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Journal
Journal of Geophysical Research, 107(D21)

ISSN
0148-0227

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Publication Date
2002-11-16

DOI
10.1029/2001jd001076

Assessment of volatile organic compound emissions from ecosystems of China

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Received 9 July 2001; revised 15 May 2002; accepted 22 May 2002; published 15 November 2002.

[1] Isoprene, monoterpene, and other volatile organic compound (VOC) emissions from grasslands, shrublands, forests, and peatlands in China were characterized to estimate their regional magnitudes and to compare these emissions with those from landscapes of North America, Europe, and Africa. Ecological and VOC emission sampling was conducted at 52 sites centered in and around major research stations located in seven different regions of China: Inner Mongolia (temperate), Changbai Mountain (boreal-temperate), Beijing Mountain (temperate), Dinghu Mountain (subtropical), Ailao Mountain (subtropical), Kunming (subtropical), and Xishuangbanna (tropical). Transects were used to sample plant species and growth form composition, leafy (green) biomass, and leaf area in forests representing nearly all the major forest types of China. Leafy biomass was determined using generic algorithms based on tree diameter, canopy structure, and absolute cover. Measurements of VOC emissions were made on 386 of the 541 recorded species using a portable photo-ionization detector method. For 105 species, VOC emissions were also measured using a flow-through leaf cuvette sampling/gas chromatography analysis method. Results indicate that isoprene and monoterpene emissions, as well as leafy biomass, vary systematically along gradients of ecological succession in the same manner found in previous studies in the United States, Canada, and Africa. Applying these results to a regional VOC emissions model, we arrive at a value of 21 Tg C for total annual biogenic VOC emissions from China, compared to 5 Tg C of VOCs released annually from anthropogenic sources there. The isoprene and monoterpene emissions are nearly the same as those reported for Europe, which is comparable in size to China. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 1615 Global Change: Biogeochemical processes (4805); 1851 Hydrology: Plant ecology; *KEYWORDS:* isoprene, succession, Gaia, grasslands, forests, peat bogs

Citation: Klinger, L. F., Q.-J. Li, A. B. Guenther, J. P. Greenberg, B. Baker, and J.-H. Bai, Assessment of volatile organic compound emissions from ecosystems of China, *J. Geophys. Res.*, *107*(D21), 4603, doi:10.1029/2001JD001076, 2002.

1. Introduction

[2] Recent work on the ecological and evolutionary relationships of plants that emit (nonmethane) volatile organic compounds (VOCs) has revealed patterns which suggest that biogenic VOCs may play adaptive roles in the metabolism and development of ecosystems. Isoprene (C_5H_8), for instance, is a highly reactive hydrocarbon emitted in large quantities by a wide variety of plants which can strongly influence concentrations of ozone (O_3), nitrogen oxides (NO_x), and hydroxyl radicals (OH) in the boundary-layer atmosphere over forested continental regions. While phylogenetic studies have revealed no clear evolutionary pattern among the major taxa that links isoprene-emitting plants [*Harley et al.*, 1999], patterns do appear when plants and their emissions are examined in an ecological context. *Klinger et al.* [1994, 1998] have shown that isoprene and monoterpene emissions appear to vary systematically along gradients of ecosystem development (i.e., succession). These and other empirical studies indicate a common spatial-temporal pattern whereby isoprene emissions are seen to be low in early successional grasslands and shrublands, increase to high rates in early to mid-successional deciduous woodlands and “secondary” forests, then decrease to moderate rates in later successional “primary” evergreen forests, and drop to low rates in late

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0148-0227/02/2001JD001076

successional peatlands [*Klinger et al.*, 1998; *Guenther et al.*, 1999a; *Helmig et al.*, 1999b; *Isebrands et al.*, 1999; *Schaab et al.*, 2000; *Westberg et al.*, 2000]. Studies using ecological models to describe VOC emissions during succession show a similar trend [*Martin and Guenther*, 1995].

[3] Such ecological patterns present opportunities to derive landscape-level VOC fluxes from models parameterized with remotely sensed vegetation data classified according to ecosystem age and/or disturbance regime. The need for a remote-sensing approach is particularly germane as scientists begin to focus on VOC emissions from the species-rich tropics. In rain forests especially, conventional ground-based methods which involve inventorying emissions of each species to characterize landscape-level VOC fluxes are time-consuming and difficult. The utility, however, of a succession-based model for predicting how VOC emissions from terrestrial ecosystems will change with time relies heavily on the degree to which the successional patterns in emissions are global.

[4] In this paper we extend to China the investigation of VOC emissions and ecosystem succession by conducting a species-by-species survey of isoprene and monoterpene emissions and characterizing vegetation composition and structure along successional gradients in boreal, temperate, subtropical, and tropical ecosystems there. Furthermore, we apply our forest and emission inventory data to a regional model to estimate VOC emissions for all of China.

2. Methods

2.1. Study Site Descriptions

[5] Study sites were located in seven regions of China in and around the following research stations: the temperate Inner Mongolia Grassland Ecosystem Research Station, (Inner Mongolia Autonomous Region), the boreal-temperate Changbai Mountain Forest Ecosystem Research Station (Jilin Province), the temperate Beijing Forest Ecosystem Research Station (Beijing Province), the subtropical Dinghu Mountain Forest Ecosystem Research Station (Guangdong Province), the subtropical Ailao Mountain Forest Ecosystem Station (Yunnan Province), the subtropical Kunming Botanical Garden (Yunnan Province), and the tropical Xishuangbanna Tropical Botanical Garden (Yunnan Province). Sampling sites were located in forests that have previously been studied and described by local ecologists. Sampling was conducted during the main growing season at each site. Table 1 lists the vegetation type, sampling period, geographic coordinates, elevation, slope, and aspect for each of the 52 study sites.

2.2. Vegetation Measurements

[6] Vegetation communities at 36 of the sites were identified, gridded, then sampled in 10-m $\times$ 10-m contiguous plots along 50-m to 100-m transects. In each plot all trees were identified, and the tree diameter at breast height (DBH) ($\sim$1.5 m from base) and tree height were recorded. All stems 4 cm DBH and 1.5 m tall were counted as trees. Tree layer and understory layer leaf area index (LAI), the ratio of leaf area to ground area, were measured at two central locations in plots using two (above and below canopy) LiCor LAI-2000 instruments. The above-canopy instrument was located at the top of a nearby tower or in a nearby forest clearing. Visual estimates of absolute cover of growth forms were made, and slope, aspect, and elevation were recorded for each plot. Details of the above methods are described by *Helmig et al.* [1999b].

[7] Leaves of the main plant species occurring in the transects, including cryptogams (mosses and lichens), were collected and photographed against a calibrated white backing. In the laboratory, dry weight of each leaf set was obtained by placing leaves in a drying oven for 24 hours at 50°C and weighing on an analytical balance. Digital photos were analyzed using an Interactive Data Language (IDL®) custom leaf area program designed to select adjacent pixels of a similar shade in an image. In each image, the leaf and 25-cm^2 calibration square pixel areas were determined, giving metric values of (one-sided) leaf area. These data were used to determine the ratio of leaf area (A_L) to leaf biomass (B_L), a parameter used in our emission equations. Species not measured were assigned A_L:B_L values based on the averages of measured species of their respective genus or of their respective growth form.

[8] Tree leaf biomass, expressed as leaf dry weight per unit ground area, was determined using generic algorithms based on DBH and canopy structure. The different algorithms were derived from measured parameters of species typifying the respective forest types of each region. The *Geron et al.* [1994] algorithms were used for the Inner Mongolia, Beijing Mountain, and Changbai Mountain forests, the *Tang et al.* [1998] and *Feng et al.* [1998] algorithms for the Xishuangbanna forests, and the *Geron et al.* [1994] and the *Qiu et al.* [1984] algorithms for the Ailao Mountain forests. Understory leafy biomass was calculated as the product of the A_L:B_L value and the fractional area cover in each plot of leafy biomass for each growth form. (We use the label ''leafy'' biomass in referring to the leaf-like, green photosynthetic tissue of all plants, including cryptogams which possess no true leaves.) The A_L:B_L values, in cm^2 per gram dry weight of leafy matter, assigned to the understory growth forms are as follows: graminoids = 121, forbs = 123, deciduous shrubs = 131, evergreen shrubs = 105, lianes = 120, bamboos = 295, ferns = 211, peat mosses = 8, other mosses = 26, and lichens = 150.

2.3. Trace Gas Sampling and Analysis

[9] Emissions of isoprene and other nonmethane VOCs were characterized for 386 of the 541 recorded species using the portable photoionization detector (PID) screening method reported by *Klinger et al.* [1998]. Measurements were taken on several different leaves and/or individual plants of a given species until a consistent result was obtained. On the basis of the semiquantitative results from the PID method, species were assigned emission potentials of high, moderate, or low as per the emission categories of *Geron et al.* [1994]. In addition, 105 species were sampled using the flow-through leaf cuvette method similar to that described by *Harley et al.* [1997] except that the cuvette system was custom-made at the National Center for Atmospheric Research (NCAR) (Boulder, CO). This system recorded flow rates, inlet and outlet air humidity, leaf temperature, and photosynthetically active radiation at 5-second intervals on a Tattletale 5F datalogger (Onset Computer Corp, Pocasset, MA). Cuvette air samples, 500 ml in volume, were collected onto absorbent cartridges using a

Table 1. Location, Sampling Period, Topographic Setting, and Vegetation Type of Study Sites

Vegetation Type[a]	Sampling Period	Latitude	Longitude	Elev, m	Slope, deg	Aspect
		Inner Mongolia				
Station area	23 July 2001	43°37.81′N	116°42.30′E	1191	0	-
Mixed grassland*	24 July 2001	43°30.38′N	116°49.39′E	1415	2.5	NNW
Stipa grassland*	24 July 2001	43°32.40′N	116°33.49′E	1174	0	-
Willow shrubland*	25 July 2001	43°09.52′N	116°06.73′E	1296	5	NE
		Beijing Mountain				
Station area forest	27 May 1998	40°01′N	115°28′E	1100	n.d.[b]	n.d.
Elm woodland	26 July 2001	40°21.30′N	116°00.39′E	644	0	-
Pine woodland*	26 July 2001	40°21.11′N	116°00.38′E	695	21	E
Locust woodland*	26 July 2001	40°21.40′N	116°00.43′E	678	15	W
		Changbai Mountain				
Alpine tundra	11 Aug. 1998	42°03.27′N	128°03.89′E	~2400	20	W
Birch woodland*	12–25 Aug. 1998	42°03.27′N	128°03.89′E	1980	12	W
Birch/larch forest*	12–25 Aug. 1998	42°03.61′N	128°03.87′E	1863	21	N
Birch/poplar forest*	20–26 Aug. 1998	42°24.26′N	128°05.97′E	700	5	SW
Birch/spruce forest*	11–25 Aug. 1998	42°03.98′N	128°03.90′E	~1700	20	N
Grass/willow shrubland*	20–24 Sept. 1998	42°24.20′N	128°06.35′E	705	0	-
Larch bog forest*	19–25 Aug. 1998	42°08.40′N	128°16.47′E	1200	0	-
Larch/pine forest*	22–25 Aug. 1998	42°11.27′N	128°13.26′E	~1000	0	-
Linden/ash forest*	14–24 Aug. 1998	42°24.18′N	128°06.35′E	705	0	-
Oak/pine forest*	15–26 Aug. 1998	42°24.26′N	128°05.97′E	745	0	-
Pine/linden/fir forest*	24–25 Aug. 1998	42°13.53′N	128°10.65′E	~900	0	-
Pine/spruce forest*	18–25 Aug. 1998	43°08.57′N	128°07.92′E	1190	0	-
Sphagnum/shrub bog*	10–21 Aug. 1998	42°01.83′N	128°25.74′E	1255	0	-
Spruce/fir forest*	12–25 Aug. 1998	42°01.61′N	128°03.85′E	1620	0	-
Spruce/larch forest*	12–25 Aug. 1998	42°04.37′N	128°03.71′E	1640	0	-
Station garden	9–22 Aug. 1998	42°24.26′N	128°05.97′E	705	0	-
		Dinghu Mountain				
Station area forest	24–25 May 1998	23°10′N	112°32′E	~400	n.d.	n.d.
		Xishuangbanna				
Botanical garden	22 Sept.–2 Nov. 1998	21°55.60′N	101°15.94′E	570	0	-
Castanopsis forest*	24 Sept.–8 Oct. 1998	21°57.66′N	101°12.02′E	820	28	W
Conservation reserve	26 Sept.–2 Nov. 1998	21°55.18′N	101°16.13′E	590	0	-
Cratoxylon moss forest*	2–8 Oct. 1998	21°57.71′N	101°12.24′E	845	10	WNW
Early primary forest*	29 Sept.–7 Oct. 1998	21°55.12′N	101°16.38′E	565	35	NNW
Early secondary forest*	29 Sept.–6 Oct. 1998	21°55.35′N	101°16.23′E	570	10	SE
Elephant reserve	23 Sept. 1998	22°10.60′N	100°51.33′E	750	0	-
Ficus garden	3–13 Aug. 2001	21°55.67′N	101°15.16′E	560	0	-
Mixed plantation	7 Oct–2 Nov 1998	21°55.35′N	101°16.23′E	570	0	-
Pometia forest*	24 Sept.–8 Oct. 1998	21°57.67′N	101°12.02′E	805	35	E
Riverside woodland*	7–10 Oct. 1998	21°55.91′N	101°15.29′E	575	10	N
Rubber tree plantation	8–10 Aug. 2001	21°55.44′N	101°16.05′E	570	0	-
Secondary forest*	30 Sept.–7 Oct. 1998	21°55.18′N	101°16.13′E	590	15	W
Shorea forest	22 Sept. 1998	21°37.59′N	101°35.28′E	~700	0	-
Trema grassland	5 Oct. 1998	22°57.95′N	102°26.28′E	910	10	W
Trema woodland*	6 Oct. 1998	21°57.95′N	101°26.28′E	915	25	W
		Ailao Mountain				
Disturbed mossy forest	29 Oct. 1998	24°19.19′N	100°47.70′E	2325	0	-
Dwarf forest*	16–24 Oct. 1998	24°31.68′N	101°01.84′E	2528	35	WNW
Heath forest*	16–24 Oct. 1998	24°31.68′N	101°01.84′E	2640	25	NW
Late *Castanopsis* forest*	17 Oct. 1998	24°32.88′N	101°02.45′E	2515	32	NE
Late primary forest*	16–26 Oct. 1998	24°32.56′N	101°01.65′E	2442	15	WNW
Lithocarpus forest/bog*	17–26 Oct. 1998	24°32.24′N	101°10.62′E	2408	9	SSW
Mossy forest*	16–26 Oct. 1998	24°31.68′N	101°01.84′E	2490	20	W
Poplar forest*	17–26 Oct. 1998	24°32.54′N	101°01.63′E	2415	20	S
Poplar woodland*	21–24 Oct. 1998	24°32.72′N	101°01.52′E	2395	23	N
Sphagnum bog*	20–24 Oct. 1998	24°32.81′N	101°01.54′E	2460	2	SW
		Kunming				
Botanical garden	5–7 Nov. 1998	25°08.27′N	102°44.32′E	1880	0	-

[a] asterisk indicates sites sampled with transects.
[b] not determined.

large syringe [*Helmig et al.*, 1999a]. Both techniques were applied only on mature, undamaged leaves. All measurements were done around midday on in situ sunlit leaves with air temperatures ranging from 20° to 35°C. The cartridge samples were frozen and brought to NCAR for analysis using gas chromatography mass spectrometry (GC-MS) and atomic emission detection methods for VOCs [*Greenberg et al.*, 1999a].

3. Results and Interpretation

3.1. Distribution and VOC Emissions of Plant Species

[10] Table 2 lists by region the species name, family, growth form, vegetation type, emission potential, and measured emission. High, medium, and low emission potentials were assigned based on measurements in this study and/or emissions reported in the literature [*Geron et al.*, 1994; *Guenther et al.*, 1996; *Klinger et al.*, 1998; *Zhang et al.*, 2000]. For the four species where PID results differed from the leaf cuvette/GC-MS results, the latter results were used to assign emission potentials. Genus-level assignments were based on measured emissions of one or more species within a given genus. Where emission information was not available at the genus level for a given species, emission potentials were treated as missing. Monoterpene emissions for three species measured at Beijing Mountain (*Juglans mandshurica*, *Lespedeza bicolor*, and *Spiraea pubescens*) were found to be unusually high (see Table 2), probably as a result of leaf disturbance during the cuvette sampling. Thus these high values should be considered suspect.

[11] These are the first reported VOC emission measurements for most of the species sampled here. Certain genus- and family-level patterns in isoprene emission seen in Africa [*Guenther et al.*, 1996; *Klinger et al.*, 1998] are apparent in China as well. In China, 12 of the 17 species in the family Moraceae were isoprene emitters, mostly in the genus *Ficus*, a pattern similar to that in Africa. The tendency seen in Africa for species of Caesalpiniaceae and Arecaceae to emit isoprene is not as obvious in China. In the family Arecaceae, 5 of 14 species emitted isoprene and in Caesalpiniaceae, only 3 species out of 16 were isoprene emitters. One important economic species, the rubber tree *Hevea brasiliensis,* was found to be a strong, light-dependent emitter of monoterpenes. As this tree is planted widely as a monoculture in tropical China, its impact alone on the regional atmospheric chemistry may be significant.

[12] At Changbai Mountain the 56 woody species sampled for biomass and emissions account for over 95% of the forest canopy biomass in the region [*Xu et al.*, 1985; *Liu*, 1997]. At Xishuangbanna, the 278 woody species sampled for biomass include 80 to 90% of the most abundant forest species in the region according to *Cao et al.* [1996] and *Dang and Qian* [1997], respectively. The 205 woody species for which VOC emissions were sampled account for between 62 and 83% of the most abundant species in the Xishuangbanna region [*Cao et al.*, 1996; *Dang and Qian*, 1997]. In the Ailao Mountains, biomass estimates were based on 68 species, including 40 species which constitute between 80 and 95% of the forest biomass [*Qian*, 1983; *Wang*, 1983]. Emission estimates were based on 57 species, including 33 species which make up between 75 and 85% of the Ailao forest biomass [*Qian*, 1983; *Wang*, 1983; *Xie*, 1987]. For Inner Mongolia and Beijing Mountain regions, no comparable forest biomass data could be found. Overall, for those sites where inventory data are available, its appears that our emission results are based on those species that account for the majority of the woody vegetation in the study areas.

[13] Unless determined otherwise, nonwoody canopy taxa were assigned emission potentials of 0.1 μg C g^{-1} hr^{-1} for isoprene and monoterpenes, except for peat (*Sphagnum*) mosses which were assigned an emission potential of 1.0 μg C g^{-1} hr^{-1} for isoprene based on measurements of *Hanson et al.* [1999] and *Isebrands et al.* [1999]. In general, grasses, forbs, ferns, mosses, and lichens are found to emit low or no amounts of isoprene and monoterpenes. However, with only a limited inventory of the herbaceous and cryptogamic species, the actual emissions for this ground vegetation remain poorly characterized. Considering the high biomass of some of these growth forms (e.g., mosses), even a low emission could add significantly to the total emissions.

3.2. Successional Relationships of Vegetation Types

[14] Table 3 summarizes plant abundance and VOC emissions for the various vegetation types in each region according to their successional status. The successional relationships and ecosystem ages are based on previously published studies from China, recorded disturbance histories, tree size distributions, and peat depth and stratigraphy. In the Changbai Mountain region, successional stages from bare ground to spruce-fir forest were pieced together from several published field studies from this region [*Barnes et al.*, 1992; *Wu and Han*, 1992; *Deng et al.*, 1995; *Li et al.*, 1994; *Liu*, 1997] as well as field studies in nearby regions containing similar forest types [*Li*, 1991; *Tian et al.*, 1995]. The ages of the older peatland communities were based on known radiocarbon dates of basal peats at Changbai Mountain sites with peat depths comparable to those measured in this study [*Yang and Song*, 1992]. Model results of *Jiang et al.* [1999] showing biomass changes over several hundred years of ecosystem development are consistent with the pattern of gradual replacement of deciduous forest by evergreen forest shown here for Changbai Mountain. Species and biomass results of a gap model of forests on Changbai Mountain [*Yan and Zhao*, 1996], which show the succession of forest types in the sequence poplar/birch → oak → pine → spruce/fir, are also consistent with our findings. Succession at Changbai Mountain is similar to that found in other parts of China, such as in the Gongga Mountain region, western Sichuan Province, where vegetation succession from herbs to deciduous shrubs to deciduous trees to evergreen trees has been documented following glacier retreat [*Zhong et al.*, 1999].

[15] Successional patterns of the vegetation in the Xishuangbanna region follow the classification by *Zhang and Cao* [1995]. Of the ten vegetation types they report, all but one (monsoon forest over limestone) were included among the sampling sites here. Successional status was determined for the early stages (<100 years) by examining abandoned fields of known age. Later stages of succession were determined from published studies of forest composition and size structure [*Dang and Qian*, 1997; *Su*, 1997].

[16] The successional patterns in the subtropical Ailao Mountains are based on previous studies by *Wang* [1983], *Sheng and Xie* [1990], and *Young et al.* [1992], as well as on

Table 2. Taxa, Growth Forms, Vegetation Types, Emission Potentials, and Measured Emissions of All Species Sampled in 1998 and 2001

		Growth	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
Genus species	Family	Form[a]	gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
					Inner Mongolia										
Agrophyron michnoi	Poaceae	grm	✓									L	L		
Allium tenuissimum	Liliaceae	grm	✓									L	L		
Aneurolipidium chinese	Poaceae	grm	✓									L	H	*0.00*	*2.86*
Artemesia frigida	Asteraceae	frb	✓									L	H	*0.00*	*2.17*
A. pubescens	Asteraceae	frb	✓									L	L		
Aster alpinus	Asteraceae	frb	✓									L	L		
Astragalus adsurgens	Fabaceae	frb	✓									L	L		
Betula gmelinii	Betulaceae	dbt		✓								L	L		
Buplerum scorzonerifolium	Apiaceae	frb	✓												
Caragana microphylla	Fabaceae	dbs	✓	✓								L	L		
Carex korshinskyi	Cyperaceae	grm	✓									L	L		
Cleistogenes squarrosa	Poaceae	grm	✓									M	L		
Clematis hexapetala	Ranunculaceae	frb	✓									L	L		
Cotoneaster sp.	Rosaceae	dbs		✓											
Cymbaria dahurica	Scrophulariaceae	frb	✓									L	L		
Dianthus chinensis	Caryophyllaceae	frb	✓												
Filifolium sibiricum	Asteraceae	frb	✓									L	M	*0.10*	*0.59*
Galium verum	Rubiaceae	frb	✓									L	L		
Haplophyllum dauricum	Rutaceae	frb	✓									H	M		
Iris dichotoma	Iridaceae	grm	✓									L	L		
Kochia prostrata	Chenopodiaceae	frb	✓									L	L		
Koeleria cristata	Poaceae	grm	✓												
Leontopodium longifolium	Asteraceae	frb	✓									L	L		
Leymus chinensis	Poaceae	grm	✓									L	L		
Liglaria mongolica	Asteraceae	frb	✓												
Melilotoides ruthenica	Rosaceae	frb	✓									L	L		
Oxytropis hirta	Fabaceae	frb	✓									L	L		
O. myriophylla	Fabaceae	frb	✓									M	L		
Patrinia rupestris	Valerianaceae	frb	✓												
Polygonum divaricatum	Polygonaceae	frb	✓									L	H	*0.93*	*6.06*
Populus davidiana	Salicaceae	dbt		✓	✓							H	L		
Potentilla tanacetifolia	Rosaceae	frb	✓									L	H	*0.00*	*5.24*
Salix characta	Salicaceae	dbs		✓								H	M	*23.8*	*0.83*
S. gordejevii	Salicaceae	dbs		✓								L	L		
S. rosmarinifolia	Salicaceae	dbs		✓								M	L	*7.21*	*0.21*
S. sinica	Salicaceae	dbt		✓								L	L		
Salsola collina	Chenopodiaceae	frb	✓									L	L		
Sanguisorba officinalis	Rosaceae	frb	✓									L	L		
Saposhnikovia divaricata	Apiaceae	frb	✓									L	L		
Scabiosa comosa	Dipsacaceae	frb	✓												
Scutellaria baicalensis	Lamiaceae	frb	✓									L	L		
Sedum airoom	Crassulaceae	frb	✓												
Serratula centauroides	Asteraceae	frb	✓									L	M	*0.00*	*1.04*
Stellara chamaejasme	Thymelacaceae	frb	✓									L	L		
Stipa baicalensis	Poaceae	grm	✓									L	L		
S. grandis	Poaceae	grm	✓									L	M	*0.00*	*0.66*
Thalictrum petaloideum	Ranunculaceae	frb	✓									L	L		
T. squarrosum	Ranunculaceae	frb	✓												
Thermopsis lanceolata	Fabaceae	frb	✓									L	L		
Ulmus pumila	Ulmaceae	dbt		✓	✓							L	L		
					Beijing Mountain										
Acer mono	Aceraceae	dbt				✓						L	M	0.00	4.95
Ailanthus altissima	Simaroubaceae	dbt			✓										
Betula davurica	Betulaceae	dbt				✓						L	L	0.00	0.36
Biota orientalis	Cupressaceae	ent			✓							L	M	*0.03*	*0.63*
Cotinus coggygria	Anacardiaceae	dbt			✓							L	L		
Juglans mandshurica	Juglandaceae	dbt				✓						L	H	0.00	3771
Larix principis-rupprechtii	Pinaceae	dnt				✓						L	M	7.40	1.41
Lespedeza bicolor	Papilionaceae	dbt				✓						M	H	4.20	3236
Pinus tabulaeformis	Pinaceae	ent			✓	✓						L	H	*0.15*	*5.71*
Platycladus orientalis	Cupressaceae	ent				✓						L	H	0.00	61.7
Populus davidiana	Rosaceae	dbt		✓	✓							H	L		
Prunus armenica v. ansu	Rosaceae	dbt			✓							L	L		
Quercus liaotungensis	Fagaceae	dbt				✓						H	L	98.9	0.10
Robinia pseudoacacia	Papilionaceae	dbt			✓	✓						H	M	*49.8*	*2.07*
Spiraea pubescens	Rosaceae	dbt				✓						L	H	0.00	1618
Ulmus pumila	Ulmaceae	dbt		✓	✓							L	L		
Ziziphus jujuba	Rhamnaceae	dbt			✓							L	L		

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
						Changbai Mountain									
Abies holophylla	Pinaceae	ent							✓			(L)	(H)		
A. nephrolepis	Pinaceae	ent			✓	✓	✓	✓	✓			L	H		
Acer barbinerve	Aceraceae	dbt			✓			✓				L	M	0.00	0.26
A. mandshuricum	Aceraceae	dbt					✓					(L)	(M)		
A. mono	Aceraceae	dbt			✓	✓	✓	✓				L	M	0.00	0.42
A. pseudo-sieboldiamum	Aceraceae	dbt			✓	✓						L	M		
A. tegmentosum	Aceraceae	dbt			✓	✓	✓	✓				L	M		
A. triflorum	Aceraceae	dbt			✓	✓						(L)	(M)		
A. ukurunduense	Aceraceae	dbt		✓	✓	✓						L	M		
Alnus mandshurica	Betulaceae	dbt			✓	✓			✓			L	L		
A. sibirica	Betulaceae	dbt		✓								L	L		
Betula costata	Betulaceae	dbt				✓	✓					L	L		
B. davurica	Betulaceae	dbt						✓				L	L	0.00	0.12
B. ermanii	Betulaceae	dbt		✓	✓	✓	✓	✓				L	L	0.00	0.91
B. fruticosa	Betulaceae	dbs								✓		L	L	0.00	1.40
B. platyphylla	Betulaceae	dbt		✓	✓							L	L	0.00	16.5
Carpinus cordata	Corylaceae	dbt				✓						[L]	[M]		
Chamaedaphne calyculata	Ericaceae	ebs								✓		L	H		
Corylus mandshurica	Corylaceae	dbt		✓	✓							L	L		
Fraxinus mandshurica	Oleaceae	dbt		✓	✓	✓	✓					L	L		
Hylocomnium splendens	Hylocomiaceae	mos					✓	✓				[L]			
Juglans mandshurica	Juglandaceae	dbt			✓	✓	✓					L	H		
Juniperus rigida	Cupressaceae	ent				✓						[L]	[M]		
Larix olgensis	Pinaceae	dnt			✓	✓	✓	✓	✓			L	M	0.00	3.80
Ledum palustre	Ericaceae	ebs								✓		L	H	0.00	31.5
Lonicera chrysantha	Caprifoliaceae	dbs			✓							L	L		
L. edulis	Caprifoliaceae	dbt		✓	✓							(L)	(L)		
Maackia amurensis	Papilionaceae	dbt			✓	✓	✓					H	L	136	0.00
Padus asiatica	Rosaceae	dbt					✓								
Phellodendron amurense	Rutaceae	dbt			✓							L	L		
Phyllodoce caerulea	Ericaceae	ebs							✓						
Picea jezoensis	Pinaceae	ent				✓	✓	✓				M	H	7.24	5.17
P. koreana	Pinaceae	ent					✓	✓				M	H	0.00	0.30
Pinus koraiensis	Pinaceae	ent				✓	✓	✓	✓			L	H	0.00	0.26
P. pumila	Pinaceae	ent					✓					(L)	(H)		
P. sylvestriformis	Pinaceae	ent				✓						L	H		
Populus davidiana	Salicaceae	dbt				✓	✓					H	L		
P. koreana	Salicaceae	dbt			✓		✓	✓				H	L		
P. ussuriensis	Salicaceae	dbt			✓							(H)	(L)		
Potentilla fruticosa	Rosaceae	ebs								✓		L	H		
Quercus mongolica	Fagaceae	dbt			✓	✓	✓					H	L	348	0.00
Rhododendron chrysanthum	Ericaceae	ebs							✓			L	L		
R. dahurica	Ericaceae	ebs						✓				(L)	(L)		
Rosa acicularis	Rosaceae	dbs					✓					L	L		
Rubus crataegifolius	Rosaceae	dbs				✓						L	L		
Salix sp.	Salicaceae	dbs		✓								H	L		
S. matsudana	Salicaceae	dbt		✓								H	L		
S. viminalis	Salicaceae	dbs		✓								H	L	136	0.00
Smilacina sp.	Liliacea	frb					✓	✓							
Sorbus pohuashanensis	Rosaceae	dbt				✓	✓	✓				L	L		
Sphagnum sp.	Sphagnaceae	mos							✓	✓		[M]			
Syringa reticulata	Oleaceae	dbt				✓						[L]			
Tilia amurensis	Tiliaceae	dbt			✓	✓	✓	✓				L	L		
T. mandshurica	Tiliaceae	dbt			✓	✓	✓					L	L		
Ulmus japonica	Ulmaceae	dbt				✓						L	L		
U. laciniata	Ulmaceae	dbt			✓							L	L		
U. propingua	Ulmaceae	dbt				✓						(L)	(L)		
U. pumila	Ulmaceae	dbt				✓						L	L		
Unknown grass 1	Poaceae	grm	✓									L	L		
Unknown grass 2	Poaceae	grm	✓									L	L		
Vaccinium uliginosum	Ericaceae	ebs								✓		L	L	0.00	1.13
						Dinghu Mountain									
Acacia sp.	Mimosaceae	dbt					n.d.[f]					L	M	0.38	0.36
A. auculaeformis	Mimosaceae	dbt					n.d.					L	L	0.00	0.22
A. holosericea	Mimosaceae	dbt					n.d.					L	M	0.00	1.15
A. mangium	Mimosaceae	dbt					n.d.					L	M	0.42	0.66
Alchornea tremiodes	Euphorbiaceae	dbt					n.d.					L	H	0.00	270
Bambusa textilis	Poaceae	dbt					n.d.					H	H	454	2.94
Caryota ochlandra	Arecaceae	ebt					n.d.					H	M	250	1.49

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b] gr	sh	dw	df	ef	mf	pf	pe	ex	Emission Potential[c,d] Isoprene	Terpene	Measured Emissions[e] Isoprene	Terpene
Castanopsis fissa	Fagaceae	ebt					n.d.					L	L	0.00	0.19
C. chinensis	Fagaceae	ebt					n.d.					L	M	0.00	0.70
Cinnamomum burmani	Lauraceae	ebt					n.d.					H	M	449	1.46
Cryptocarya concinna	Lauraceae	ebt					n.d.					H	H	95.9	106
Erythrophleum fordii	Caesalpiniaceae	bt					n.d.					L	M	0.43	1.03
Ficus microcarpa	Moraceae	ebt					n.d.					L	M	1.41	0.68
Garcinia oblongifolia	Hypericaceae	ebt					n.d.					L	M	0.47	0.87
Mallotus paniculatus	Euphorbiaceae	dbt					n.d.					L	M	2.28	1.40
Ormosia pinnata	Papilionaceae	ebt					n.d.					M	H	20.6	3.98
Pinus massoniana	Pinaceae	ent					n.d.					L	H	11.9	11.5
Rhus chinensis	Anacardiaceae	dbt					n.d.					M	H	4.14	4.53
Schima superba	Theaceae	ebt					n.d.					L	H	0.00	119
Syzygium jambos	Myrtaceae	ebt					n.d.					H	L	199	0.15
Taxodium ascendens	Taxodiaceae	dnt					n.d.					L	H	0.48	3.47
T. distichum	Taxodiaceae	dnt					n.d.					L	H	0.42	2.96
					Xishuangbanna										
Acacia sp.	Mimosaceae	bli			✓							M	H		
A. intsia	Mimosaceae	ebt			✓							L	L		
A. spinosa	Mimosaceae	bt										L	L		
Acrocarpus fraxinifolius	Mimosaceae	dbt			✓							L	L		
Acronychia pedunculata	Rutaceae	ebt					✓								
Actinodaphne henryi	Lauraceae	ebt					✓								
Adenanthera pavonina	Mimosaceae	dbt		✓		✓	✓					M	L	5.21	0.00
Aesculus lantsangensis	Hippocastanaceae	dbt				✓	✓					L	L		
Afzelia xylocarpa	Caesalpiniaceae	bt					✓				✓	L	L		
Aglaia abbreviata	Meliaceae	ebt					✓								
Ailanthus fordii	Simarubaceae	dbt			✓	✓						L	L		
Alangium barbatum	Alangiaceae	dbt				✓						(L)	(M)		
A. chinensis	Alangiaceae	dbt			✓							L	M		
A. kuzii	Alangiaceae	dbt			✓							L	M		
Albizia crassiramea	Mimosaceae	dbt			✓	✓						L	L		
A. lucidior	Mimosaceae	dbt			✓							H	L	26.8	0.00
Alchornea davidii	Euphorbiaceae	dbt				✓	✓					[L]	[H]		
Alocasia macrorrhiza	Araceae	frb				✓	✓					L	L		
Alpinia blepharocalyx	Zingiberaceae	frb					✓					L	L		
Alstonia scholaris	Apocynaceae	dbt			✓	✓						L	L		
Amomum villosum	Zingiberaceae	frb					✓					L	L		
Amoora dasyclada	Meliaceae	ebt					✓								
Amorphophallus virosus	Araceae	frb		✓	✓							L	L		
Anneslea fragrans	Theaceae	dbt					✓	✓				L	L		
Anogeissus acuminata	Combretaceae	bt				✓						L	L		
Anthocephalus chinensis	Rubiaceae	dbt		✓		✓						L	L		
Antiaris toxicaria	Moraceae	dbt				✓	✓					L	L		
Antidesma acidum	Euphorbiaceae	ebt					✓								
A. venosum	Euphorbiaceae	ebt				✓									
Aporusa octandra	Euphorbiaceae	ebt			✓	✓									
A. yunnanensis	Euphorbiaceae	ebt					✓								
Araucaria cunninghamii	Araucariaceae	ent						✓			✓	L	L		
Archontophoenix cunninghamiana	Arecaceae	bt										M	L		
Ardisia sp.	Myrsinaceae	ebt					✓					L	L		
A. tenera	Myrsinaceae	ebt					✓					L	L		
Arenga sp.	Arecaceae	bt										L	L		
A. candata	Arecaceae	ebs										L	L		
Baccaurea ramiflora	Euphorbiaceae	ebt		✓		✓	✓					L	L		
Barringtonia fusiocarpa	Lecythidaceae	ebt				✓	✓					L	L		
B. macrostachya	Lecythidaceae	ebt										L	L		
Bauhinia acuminata	Caesalpiniaceae	bt		✓								H	L		
B. subsessilia	Caesalpiniaceae	bt			✓							H	L		
B. variegata	Caesalpiniaceae	dbt			✓							H	L		
Beilschmiedia robusta	Lauraceae	ebt					✓								
Bischofia javanica	Euphorbiaceae	dbt					✓								
Bombax ceiba	Bombacaceae	dbt			✓							L	L		
Brassaiopsis glomerulata	Nyssaceae	ebt				✓									
Broussonetia papyrifera	Moraceae	ebt			✓							M	L		
Caesalpinia cucullata	Caesalpiniaceae	bli			✓							L	L		
C. pulcherrima	Caesalpiniaceae	ebs										L	L		
C. sappan	Caesalpiniaceae	ebt				✓					✓	L	L		
Calamus gracilis	Arecaceae	ebt				✓									
Calophyllum polyanthum	Hypericaceae	ebt										L	L		
Camellia kissi	Theaceae	ebt					✓					L	L		

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
C. sinensis	Theaceae	ebs				✓						L	L		
Canthium horridum	Rubiaceae	dbt			✓	✓						L	L		
Carallia brachiata	Rhizophoraceae	ebt					✓					L	L		
C. lancaefolia	Rhizophoraceae	ebt				✓	✓					L	L		
Caryodaphnopsis tonkinensis	Lauraceae	ebt					✓				✓	L	L		
Caryota monostachys	Arecaceae	ebt					✓					L	L		
C. urens	Arecaceae	ebt					✓					H	L		
Cassia alata	Caesalpiniaceae	ebs			✓						✓	L	L		
C. siamea	Caesalpiniaceae	ebt				✓					✓	L	L		
Castanopsis calathiformis	Fagaceae	ebt				✓	✓					L	L		
C. hystrix	Fagaceae	ebt					✓	✓				L	L		
C. indica	Fagaceae	ebt		✓		✓	✓					L	L		
C. mekongensis	Fagaceae	ebt				✓						L	L		
Celtis tetrandra	Ulmaceae	ebt				✓						L	L		
C. wightii	Ulmaceae	ebt					✓					L	L		
Choerospondias axillaris	Anacardiaceae	dbt				✓									
Chukrasia tabularis	Meliaceae	dbt					✓					L	L		
Cinnamomum camphora	Lauraceae	ebt				✓						L	M		
C. chartophyllum	Lauraceae	ebt				✓						(L)	(M)		
C. pittosporoides	Lauraceae	ebt			✓							L	M		
Cipadessa baccifara	Meliaceae	ebt				✓						L	L		
Citrus grandis	Rutaceae	ebt			✓							L	M		
Clausena excavata	Rutaceae	ebt				✓						L	L		
Cleistanthus sumatranus	Euphorbiaceae	ebt					✓					L	L		
Cocculus laurifolius	Menispermaceae	ebt				✓						L	L		
Cocos nucifera	Arecaceae	ebt			✓							H	L		
Cratoxylon cochinchinensis	Hypericaceae	dbt		✓				✓				H	L	18.4	0.00
C. formosum	Hypericaceae	dbt		✓								(H)	(L)		
Croton argyratus	Euphorbiaceae	ebt					✓					L	L		
Crypteronia paniculata	Crypteroniaceae	ebt					✓	✓				L	L	0.02	0.00
Cycas pectinata	Cycadaceae	ebs						✓				L	L		
Cyclobalanopsis kerrii	Fagaceae	ebt					✓								
Cylindrokelupha dalatensis	Mimosaceae	ebt				✓									
Dalbergia fusca	Papilionaceae	dbt			✓	✓						H	L		
D. obtusifolia	Papilionaceae	dbt		✓								(H)	(L)		
Debergeasia libera	Urticaceae	ebt					✓								
Dendrocalamus sp.	Poaceae	dbt			✓							H	L		
D. giganteus	Poaceae	dbt			✓							H	L		
D. hamiltonii	Poaceae	dbt			✓							H	L		
D. membranaceus	Poaceae	dbt			✓							H	L		
Dillenia indica	Dilleniaceae	dbt			✓							L	L		
Diospyros kaki	Ebenaceae	dbt			✓							(L)	(L)		
D. nigrocartex	Ebenaceae	ebt					✓					L	L		
Dipterocarpus tubinatus	Dipterocarpaceae	dbt				✓					✓	L	L		
Dolichandrone stipulata	Bignoniaceae	dbt				✓						L	L		
Dracaena cambodiana	Agavaceae	frb					✓					L	L		
Dracontomelon macrocarpum	Anacardiaceae	ebt					✓					L	L		
Drypetes indica	Euphorbiaceae	ebt										L	L		
Duabanga grandiflora	Sonneratiaceae	ebt			✓							L	L		
Dysoxylum binecteriferum	Meliaceae	ebt				✓	✓					L	L		
Engelhardtia serrata	Juglandaceae	ebt						✓				L	H		
E. spicata	Juglandaceae	ebt					✓					(L)	(H)		
Epiprinus silhetianus	Euphorbiaceae	ebt					✓					L	L		
Eriolaena kwangsiensis	Sterculiaceae	dbt			✓	✓						L	L		
Erythrina lithosperma	Papilionaceae	dbt				✓						(L)	(H)		
E. stricta	Papilionaceae	dbt				✓						L	H		
Eucalyptus citriodora	Myrtaceae	dbt				✓					✓	H	H		
Eupatorium coelesticum	Asteraceae	frb	✓	✓								L	L		
E. odoratum	Asteraceae	frb	✓	✓								L	L	0.00	0.00
Ficus altissima	Moraceae	ebt			✓	✓	✓					H	L		
F. auriculata	Moraceae	dbt				✓						H	L	*139*	*0.32*
F. collosa	Moraceae	ebt					✓					H	L	*84.7*	*0.03*
F. cyrtophylla	Moraceae	ebt		✓		✓	✓					L	L	*0.06*	*0.25*
F. elastica	Moraceae	bt									✓	M	L		
F. fistulosa	Moraceae	ebt					✓					H	L	*54.3*	*0.01*
F. hirta	Moraceae	ebt			✓	✓						H	L		
F. hispida	Moraceae	ebt			✓	✓						H	L	*29.9*	*0.04*
F. langkokensis	Moraceae	ebt				✓	✓					H	L	29.7	0.00
F. racemosa	Moraceae	dbt				✓	✓					M	M	*10.4*	*1.50*
F. superba	Moraceae	ebt		✓								(H)	(L)		
Fissistigma oldhamii	Annonaceae	ebt				✓	✓					(L)	(L)		

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
F. poilanei	Annonaceae	ebt					✓					L	L		
Flemingia macrophylla	Papilionaceae	bli			✓							H	H		
Flueggea virosa	Euphorbiaceae	ebs			✓							H	L	160	0.00
Fokienia hodginsii	Cupressaceae	ent						✓				L	L		
Garcinia bracteata	Hypericaceae	ebt										L	L		
G. cowa	Hypericaceae	ebt				✓	✓					L	L	0.00	0.00
G. xanthochymus	Hypericaceae	ebt				✓	✓					M	L	2.96	0.00
G. xishuangbannaensis	Hypericaceae	ebt										L	L		
Gironniera subaequalis	Ulmaceae	ebt					✓								
Glochidion assamica	Euphorbiaceae	dbt				✓									
Gomphandra tetrandra	Icacinaceae	ebt					✓	✓							
Goniothalamus griffithii	Annonaceae	ebt				✓	✓					L	L		
Harpullia cupanioides	Sapindaceae	ebt					✓								
Heritiera angustata	Sterculiaceae	bt										L	L		
Hevea brasiliensis	Euphorbiaceae	dbt									✓	L	H	*0.17*	*20.4*
Hiptage obtusifolia	Malpighiaceae	bt										L	L		
Homalium laoticum	Samydaceae	dbt			✓							H	L		
Homonoia riparia	Euphorbiaceae	ebs			✓							H	L		
Horsfieldia amygdalina	Myristicaceae	ebt				✓						(L)	(L)		
H. kingii	Myristicaceae	ebt										L	L		
H. pandurifolia	Myristicaceae	ebt					✓					L	L		
Hypharbe lagenicaulis	Arecaceae	ebs										L	L		
Ilex godajam	Aquifoliaceae	ebt					✓	✓				[L]	[L]		
Imperata cylindrica	Poaceae	grm	✓	✓								L	L		
Itea macrophylla	Escalloniaceae	ebt				✓						L	L		
Knema cinerea	Myristicaceae	ebt					✓					(L)	(L)		
K. furfuracea	Myristicaceae	ebt					✓					L	L		
K. globularia	Myristicaceae	ebt										L	L		
Lagestroemia flos-reginae	Lythraceae	dbt										L	L		
L. intermedia	Lythraceae	dbt			✓							L	L		
L. tomentosa	Lythraceae	dbt			✓	✓						L	L		
Laurocerasus undulata	Rosaceae	ebt					✓					L	L		
Leea crispa	Vitaceae	ebt					✓					L	L		
Lindera netcalfiana	Lauraceae	ebt				✓	✓								
Linociera insignis	Oleaceae	ebt					✓					L	L		
Litchi chinenesis	Sapindaceae	ebt					✓					L	L		
Lithocarpus fenestratus	Fagaceae	dbt				✓						(L)	(L)		
L. truncatus	Fagaceae	ebt					✓	✓				L	L		
Litsea cubeba	Lauraceae	ebt			✓							(L)	(L)		
L. dilleniiefolia	Lauraceae	ebt		✓		✓						L	L		
L. elongata	Lauraceae	ebt				✓						(L)	(L)		
L. euosma	Lauraceae	ebt				✓	✓					L	L		
L. glutinosa	Lauraceae	dbt			✓	✓						L	L		
L. monopetala	Lauraceae	dbt			✓	✓						L	L		
L. panamonja	Lauraceae	ebt		✓		✓	✓					L	L		
L. pierrei	Lauraceae	ebt					✓					(L)	(L)		
Livistona saribus	Arecaceae	ebt				✓						H	L		
Lycidice rhodoslegia	Caesalpiniaceae	bt				✓					✓	L	L		
Macaranga denticulata	Euphorbiaceae	ebt			✓							L	L	*0.04*	*0.07*
M. indica	Euphorbiaceae	ebt					✓					L	L		
Machilus tenuipila	Lauraceae	ebt					✓								
Macropanax chienii	Araliaceae	ebt				✓	✓					L	L		
M. dispermus	Araliaceae	ebt					✓					(L)	(L)		
Mallotus barbatus	Euphorbiaceae	ebt				✓						(L)	(L)		
M. macrostachys	Euphorbiaceae	ebt			✓							L	L		
M. paniculatus	Euphorbiaceae	dbt					✓	✓				L	M	0.25	0.14
M. philipinensis	Euphorbiaceae	ebt			✓							L	L		
Mangifera indica	Anacardiaceae	ebt				✓						H	L		
M. sylvatica	Anacardiaceae	ebt					✓					H	L		
Manglietia wangii	Magnoliaceae	ebt					✓					L	L		
Mayodendron igneum	Bignoniaceae	dbt				✓						L	L		
Maytenus hookeri	Celastraceae	ebt				✓						L	L		
Melia azedarach	Meliaceae	dbt				✓						L	L		
M. toosanden	Meliaceae	dbt			✓	✓						L	L		
Meliosma sp.	Sabiaceae	ebt					✓					L	L		
Memecylon polyanthum	Melastomaceae	ebt					✓								
Metadina trichotoma	Rubiaceae	ebt					✓	✓							
Mezzettiopsis creaghii	Annonaceae	ebt					✓								
Microcos nervosa	Tiliaceae	ebt				✓						H	L	32.6	0.00
Millettia leptobotrya	Papilionaceae	ebt		✓		✓	✓					L	L	0.00	0.00
M. pulchra	Papilionaceae	dbt				✓	✓	✓				H	L	20.8	0.00

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
Mitrephora wangii	Annonaceae	ebt					✓					L	L		
Morinda angustifolia	Rubiaceae	ebt			✓	✓						L	L		
Morus macroura	Moraceae	dbt			✓	✓						[L]	[L]		
Musa acuminata	Musaceae	ebt			✓	✓						L	L		
Mycetia gracilis	Rubiaceae	ebt					✓								
Myristica yunnanensis	Myristicaceae	ebt					✓					H	L	37.8	0.00
Neocinnamomum caudatum	Lauraceae	ebt				✓						L	L		
Neonauclea griffithii	Rubiaceae	ebt					✓								
Nephelium chryseum	Sapindaceae	ebt					✓					L	L		
Olea rosea	Oleaceae	ebt					✓					L	L		
Ormosia henryi	Papilionaceae	ebt						✓							
Oroxylum indicum	Bignoniaceae	dbt					✓					L	L		
Paramichelia baillonii	Magnoliaceae	ebt				✓						L	L		
Phlogacanthus curviflorus	Acanthaceae	ebt					✓					L	L		
Phoebe lanceolata	Lauraceae	ebt				✓	✓					L	L		
P. puwenensis	Lauraceae	dbt				✓	✓					L	L		
Phoenix roebelinii	Arecaceae	ebt			✓							L	L		
P. sylvestris	Arecaceae	bt										L	L		
Phyllanthus emblica	Euphorbiaceae	dbt		✓			✓					(L)	(L)		
P. flexuosus	Euphorbiaceae	ebt				✓						L	L		
Pithecellobium clypearia	Mimosaceae	bt			✓		✓					[L]			
Pittosporopsis sp.	Icacinaceae	ebt					✓					(L)	(L)		
P. kerrii	Icacinaceae	ebt					✓					L	L		
Platea latifolia	Icacinaceae	ebt					✓								
Podocarpus imbricatus	Podocarpaceae	ent						✓				L	L		
P. macrophylla	Podocarpaceae	ent						✓				L	L		
P. nagi	Podocarpaceae	ent						✓				L	L		
P. neriifolius	Podocarpaceae	ent						✓				L	L		
Poikilospermum lanceolatum	Urticaceae	bli					✓					L	L		
Polyalthia cheliensis	Annonaceae	ebt					✓					[L]			
Polyscias balfourniana	Araliaceae	ebs										L	L		
Pometia tomentosa	Sapindaceae	ebt				✓	✓					L	L	*0.20*	*3.89*
Pouteria grandiflora	Sapotaceae	ebt					✓					L	L		
Premna flavescens	Verbenaceae	dbt				✓						(L)	(L)		
P. fulva	Verbenaceae	dbt				✓						L	L		
Psidium guajava	Myrtaceae	ebt				✓					✓				
Pterocarya tonkinensis	Juglandaceae	dbt				✓						L	L		
Pterospermum sp.	Sterculiaceae	bt										L	L		
P. lanceaefolium	Sterculiaceae	ebt					✓								
Radermachera microcalyx	Bignoniaceae	ebt					✓								
Randia acuminatissima	Rubiaceae	ebt					✓								
R. wallichii	Rubiaceae	ebt				✓	✓								
Rauvolfia verticillata	Apocynaceae	ebt					✓					(L)	(L)		
R. vomitoria	Apocynaceae	ebt				✓					✓	L	L		
Rhus chinensis	Anacardiaceae	dbt		✓								L	M	0.18	1.56
Ricinus communis	Euphorbiaceae	ebt			✓							L	L		
Sapium baccatum	Euphorbiaceae	ebt					✓					L	L		
S. eugeniaefolium	Euphorbiaceae	ebt				✓						(L)	(L)		
Saraca declimata	Caesalpiniaceae	ebt					✓					L	L		
S. dives	Caesalpiniaceae	bt										L	L		
S. indica	Caesalpiniaceae	bt										L	L		
Schima wallichii	Theaceae	ebt		✓		✓	✓	✓				L	L		
Schizomussaenda dehiscens	Rubiaceae	dbt				✓						L	L		
Scleropylum wallichianum	Santalaceae	ebt					✓								
Shorea wangtanshuea	Dipterocarpaceae	dbt					✓					L	L		
Sindora glabra	Caesalpiniaceae	bt									✓	L	L		
Solanum verbacifolium	Solanaceae	ebt		✓		✓	✓					L	L		
Spondias pinnata	Anacardiaceae	dbt						✓				H	L		
Sterculia lanceolata	Sterculiaceae	dbt				✓						L	L		
Stereospermum colais	Bignoniaceae	dbt										L	L		
Streblus asper	Moraceae	dbt				✓						H	L		
Suregada glomerulata	Euphorbiaceae	dbt										L	L		
Syzygium balsameum	Myrtaceae	ebt					✓					(H)	(L)		
S. fluviatile	Myrtaceae	ebt				✓						(H)	(L)		
S. forrestii	Myrtaceae	ebt		✓		✓	✓	✓				(H)	(L)		
S. latilimbum	Myrtaceae	ebt					✓					L	L		
S. oblatum	Myrtaceae	ebt					✓					H	L		
S. polypetaloideum	Myrtaceae	ebt					✓					(H)	(L)		
Talauma gitingensis	Magnoliaceae	dbt					✓				✓	L	L		
Tapiscia yunnanensis	Staphyleaceae	dbt					✓								
Terminalia bellirica	Combretaceae	dbt				✓						L	L		

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
T. myriocarpa	Combretaceae	dbt				✓	✓					L	L	*0.02*	*0.18*
Tetrameles nudiflora	Tetramelaceae	dbt				✓						L	L		
Theobroma cacao	Sterculiaceae	ebt					✓				✓	L	L		
Toona ciliata	Meliaceae	ebt			✓	✓						L	L		
Toxicodendron succedaceum	Anacardiaceae	dbt					✓								
Trema orientalis	Ulmaceae	ebt		✓			✓					L	L	0.00	0.00
Trevesia palmata	Araliaceae	ebt					✓					L	L		
Trigonostemon thyrsoideum	Euphorbiaceae	ebt					✓					L	L		
Unknown epiphytic moss		mos					✓	✓				M	L		
Unknown grass	Poaceae	grm	✓	✓								L	L		
Urena lobata	Malvaceae	ebs			✓							L	L		
Vatica guangxiensis	Dipterocarpaceae	ebt					✓					L	L		
Wallichia caryotoides	Arecaceae	ebt				✓						L	L		
W. densiflora	Arecaceae	ebt				✓						L	L		
Walsura robusta	Meliaceae	ebt					✓								
Wendlandia tinctoria	Rubiaceae	ebt						✓							
Winchia calophylla	Apocynaceae	ebt					✓								
Woodfordia fruticosa	Lythraceae	dbt			✓							L	L		
Wrightia laevis	Apocynaceae	dbt					✓								
Xanthophyllum siamensis	Xanthophyllaceae	ebt				✓	✓								
Zenia insignis	Caesalpiniaceae	dbt				✓					✓	L	L		
					Ailao Mountain										
Acanthopanax evodiaefolius	Araliaceae	bt				✓	✓	✓	✓			L	L		
Acer heptalobum	Aceraceae	dbt				✓	✓	✓				(L)	(M)		
Alnus nepalensis	Betulaceae	dbt						✓				L	L		
Berberis sp.	Berberidaceae	ebs			✓							[M]	[L]		
Betula luminifera	Betulaceae	dbt						✓				L	L		
Camellia forrestii	Theaceae	ebt				✓	✓	✓	✓			(L)	(L)		
Carex sp.	Cyperaceae	grm								✓					
C. nubigena	Cyperaceae	grm								✓					
C. teimogyna	Cyperaceae	grm							✓	✓					
Castanopsis orthocantha	Fagaceae	ebt					✓	✓				L	L	0.00	0.00
C. wattii	Fagaceae	ebt				✓	✓	✓				(L)	(L)		
Cinnamomum pittosporoides	Lauraceae	ebt					✓	✓				(L)	(M)		
Dichapetalum gelonioides	Dichapetalaceae	bt				✓		✓							
Dichotomanthus tristaniaecarpa	Rosaceae	ebs								✓		L	L		
Eriobotrya bengalensis	Rosaceae	bt				✓	✓	✓				[L]	[H]		
Eurya obliquifolia	Theaceae	bt						✓				L	L		
Gaultheria forrestii	Ericaceae	ebs							✓			(L)	(L)		
G. griffithiana	Ericaceae	ebs				✓						L	L		
Hartia sinensis	Theaceae	ebt						✓				L	L		
Hypericum patulum	Hypericaceae	ebs				✓						(M)	(L)		
H. petiolulatum	Hypericaceae	frb								✓		M	L		
H. uralum	Hypericaceae	frb								✓		(M)	(L)		
Ilex sp.	Aquifoliaceae	ebt					✓					[L]	[L]		
I. corallina	Aquifoliaceae	ebt						✓	✓			[L]	[L]		
I. micrococca	Aquifoliaceae	ebt					✓	✓				[L]	[L]		
I. szechwanensis	Aquifoliaceae	ebt					✓	✓	✓			[L]	[L]		
I. wardii	Aquifoliaceae	ebt				✓	✓	✓	✓			[L]	[L]		
Illicium sp.	Illiciaceae	ebt					✓					(L)	(L)		
I. macranthum	Illiciaceae	ebt				✓	✓	✓				L	L		
Impatiens rubro-striata	Balsaminaceae	frb								✓					
Juncus effusus	Juncaceae	gra								✓		L	L	0.00	0.00
J. inflexus	Juncaceae	gra								✓		(L)	(L)		
J. minimus	Juncaceae	gra								✓		(L)	(L)		
Lithocarpus chintungensis	Fagaceae	ebt				✓	✓	✓	✓			(L)	(L)		
L. hypoviridis	Fagaceae	ebt				✓	✓	✓				L	L		
L. pachyphylloides	Fagaceae	ebt							✓			(L)	(L)		
L. xylocarpa	Fagaceae	ebt					✓	✓				L	L	0.00	0.00
L. yunnanensis	Fagaceae	ebt						✓				L	L		
Litsea elongata	Lauraceae	ebt					✓	✓	✓			L	L		
Lyonia ovalifolia	Ericaceae	ebt				✓	✓	✓	✓			L	L		
Machilus viridis	Lauraceae	ebt						✓							
Mahonia converta	Berberidaceae	ebs		✓								M	L		
Manglietia insignis	Magnoliaceae	ebt					✓	✓	✓			L	L		
Neolitsea homilantha	Lauraceae	ebt						✓							
N. polycarpa	Lauraceae	ebt						✓							
Oenanthe dielsii v. stenophylla	Apiaceae	frb								✓					
Pinus armandi	Pinaceae	ent						✓	✓			L	H		
P. yunnanensis	Pinaceae	ent			✓	✓	✓	✓				L	H		

Table 2. (continued)

Genus species	Family	Growth Form[a]	Recorded Vegetation Type[b]									Emission Potential[c,d]		Measured Emissions[e]	
			gr	sh	dw	df	ef	mf	pf	pe	ex	Isoprene	Terpene	Isoprene	Terpene
Poa khasiana	Poaceae	grm								✓		(L)	(L)		
Populus bonatii	Salicaceae	dbt				✓	✓					H	L		
Potentilla griffithii	Rosaceae	frb								✓		L	L		
Primula deflexa	Primulaceae	frb								✓		(L)	(L)		
Prunus cerasoides	Rosaceae	dbt					✓		✓			[L]	[L]		
P. maximiwiczii	Rosaceae	dbt				✓	✓					[L]	[L]		
Pteridium revolutum	Pteridiaceae	frn			✓							L	L		
Rhododendron decorum	Ericaceae	ebt						✓				(L)	(L)		
R. delavayi	Ericaceae	ebs				✓	✓	✓				L	L		
R. irroratum	Ericaceae	ebt				✓	✓	✓	✓			L	L	0.00	0.00
R. leptothrium	Ericaceae	ebt						✓				(L)	(L)		
Rosa longicuspis	Rosaceae	dbs		✓								(L)	(L)		
Salix sp.	Salicaceae	dbt			✓	✓						H	L		
Schefflera delavayi	Araliaceae	ebt				✓	✓	✓	✓						
S. hypoleuca	Araliaceae	ebt					✓		✓						
S. shweliensis	Araliaceae	ebt							✓						
Schima argentea	Theaceae	ebt						✓				(L)	(L)		
S. norohae	Theaceae	ebt				✓	✓	✓	✓			(L)	(L)		
Senecio scandens	Asteraceae	frb							✓	✓		(L)	(L)		
Sinarundinaria nitida	Poaceae	dbt								✓		L	L		
Skimmia arborescens	Rutaceae	ebt						✓							
Smilax lebrunii	Smilacaceae	bli		✓											
Sorbus ferruginea	Rosaceae	dbt					✓		✓			(L)	(L)		
Sphagnum junghuhnianum	Sphagnaceae	mos								✓		[M]	[L]		
Spiraea japonica	Rosaceae	dbs		✓								L	H	0.00	5.28
Stachys kouyangesis	Labiaceae	frb								✓					
Stranvaesia davidiana	Rosaceae	bt					✓		✓						
Styrax perkinsiae	Styraceae	ebt				✓	✓	✓				[L]			
Swertia bimaculata	Gentianaceae	frb								✓					
Symplocos anomala	Symploceae	ebt						✓				(L)	(L)		
S. botryantha	Symploceae	ebt					✓	✓				(L)	(L)		
S. dryophila	Symploceae	ebt					✓	✓	✓			L	L		
S. poilanei	Symploceae	ebt					✓	✓				(L)	(L)		
Tapiscia yunnanensis	Staphyleaceae	dbt						✓							
Ternstroemia gymnanthera	Theaceae	ebt				✓	✓	✓	✓			L	L		
Vaccinium duclouxii	Ericaceae	ebt				✓	✓	✓	✓			L	L	0.00	0.00
Viburnum cylindricum	Caprifoliaceae	ebt					✓	✓				[L]	[L]		
V. foetidum	Caprifoliaceae	ebs					✓					[L]	[L]		
					Kunming										
Acanthopanax evodiaefolius	Araliaceae	bt				✓						L	L	0.00	0.00
Alangium kuzii	Alangiaceae	dbt				✓						L	L	0.00	0.00
Anneslea fragrans	Theaceae	dbt				✓						L	L	0.00	0.00
Broussonetia papyrifera	Moraceae	ebt				✓						M	L	6.16	0.00
Celtis tetrandra	Ulmaceae	ebt				✓						L	L	0.00	0.00
Dichotomanthus tristaniaecarpa	Rosaceae	ebs				✓						L	L	0.00	0.00
Dolichandrone stipulata	Bignoniaceae	dbt				✓						L	L	0.00	0.00
Illicium macranthum	Illiciaceae	ebt				✓						L	L	0.00	0.00
Mahonia converta	Berberidaceae	ebs				✓						M	L	4.63	0.00
Melia toosanden	Meliaceae	dbt				✓						L	L	0.00	0.00
Pinus armandi	Pinaceae	ent				✓						L	H	0.00	0.39
P. yunnanensis	Pinaceae	ent				✓						L	H	0.00	0.17
Podocarpus imbricatus	Podocarpaceae	ent				✓						L	L	0.00	0.00
Schima wallichii	Theaceae	ebt				✓						L	L	0.00	0.00
Shorea wangtanshuea	Dipterocarpaceae	dbt				✓						L	L	0.00	0.00
Symplocos dryophila	Symploceae	ebt				✓						L	L	0.00	0.00
Terminalia bellirica	Combretaceae	dbt				✓						L	L	0.00	0.00

[a] dbs, deciduous broadleaved shrub; ebs, evergreen broadleaved shrub; bli, broadleaved liana; bt, broadleaved tree; dbt, decidous broadleaved tree; ebt, evergreen broadleaved tree; dnt, deciduous needleleaved tree; ent, evergreen needleleaved tree; grm, graminoid; frb, forb; mos, moss.
[b] gr, grassland; sh, shrubland; dw, deciduous woodland; df, deciduous forest; ef, evergreen forest; mf, moss forest; pf, peat forest; pe, peatland; ex, exotic.
[c] isoprene emission potentials (μg C g^{-1} hr^{-1}): H = 70, M = 14, L = 0.1; terpene emission potentials (μg C g^{-1} hr^{-1}): H = 3.0, M = 0.6, L = 0.1.
[d] parentheses indicate genus-based assignments; brackets indicate literature-based assignments.
[e] units: μg C g^{-1} hr^{-1}; 2001 measurements in italics.
[f] not determined.

observed forest structure, peat depth, and gross peat stratigraphy. The successional patterns shown here, to about 500 years, are consistent with successions described from other subtropical forests of China [*Ming*, 1987; *Zhou et al.*, 1999; *Chau and Marafa*, 1999; *An et al.*, 2001]. *Wang* [1983] further proposes that, in this region, succession occurs from peatland to *Populus* forest, although no data in support of this pathway are presented. In our study we found unambiguous evidence that, in the absence of large-scale disturbance, peatlands are replacing the *Lithocarpus* forest in the region,

Table 3. Means (±S. E.) of Leafy Biomass, Leaf Area Index, and Emission Potentials According to Vegetation Type and Ecosystem Age Class

Veg Type[a]	N Plots	Ecosystem Age Class, years	Graminoids, $g\ m^{-2}$	Forbs, $g\ m^{-2}$	Shrubs, $g\ m^{-2}$	Deciduous Trees, $g\ m^{-2}$	Evergreen Trees, $g\ m^{-2}$	Ferns, $g\ m^{-2}$	Cryptogams, $g\ m^{-2}$	Total, $g\ m^{-2}$	Leaf Area Index, $m^2\ m^{-2}$	Standardized Isoprene Flux, $mg\ C\ m^{-2}\ hr^{-1}$	Standardized Terpene Flux, $\mu g\ C\ m^{-2}\ hr^{-1}$
						Inner Mongolia/Beijing Mountain							
gr	10	1–10	78 ± 4	31 ± 10	0.3 ± 0.2	0	0	0	<0.1	109 ± 12	1.3 ± 0.1	0.1 ± <0.1	37 ± 6
sh	10	10–25	23 ± 5	28 ± 5	39 ± 6	2 ± 2	0	0	1 ± 1	93 ± 11	1.2 ± 0.1	0.9 ± 0.2	14 ± 2
dw	10	25–100	7 ± 1	17 ± 2	121 ± 9	54 ± 16	19 ± 12	0	6 ± 2	224 ± 19	2.6 ± 0.1	3.0 ± 0.9	111 ± 32
						Changbai Mountain							
gr	6	1–10	27 ± 5	23 ± 8	36 ± 6	0	0	0	25 ± 16	110 ± 30	1.2 ± 0.1	0.2 ± 0.2	2 ± 1
sh	13	10–25	9 ± 1	11 ± 2	66 ± 4	6 ± 4	0	0	76 ± 23	169 ± 25	2.4 ± 0.3	0.8 ± 0.3	4 ± 1
dw	18	25–100	10 ± 2	12 ± 2	54 ± 6	214 ± 18	0	0	121 ± 30	411 ± 40	3.5 ± 0.4	1.7 ± 0.7	48 ± 11
df	11	100–200	5 ± 1	13 ± 2	45 ± 5	277 ± 50	63 ± 14	0	92 ± 31	498 ± 49	4.7 ± 0.1	5.6 ± 2.6	225 ± 43
ef	15	200–300	7 ± 2	17 ± 1	38 ± 5	100 ± 14	254 ± 43	0.1 ± <0.1	82 ± 17	498 ± 56	5.2 ± 0.2	1.1 ± 0.3	785 ± 129
mf	27	300–500	6 ± 1	12 ± 1	23 ± 3	51 ± 10	645 ± 76	0	285 ± 13	1022 ± 69	5.7 ± 0.2	3.1 ± 0.5	1948 ± 225
pf	10	500–1000	10 ± 3	8 ± 1	44 ± 5	68 ± 15	23 ± 8	0	541 ± 48	712 ± 41	2.7 ± 0.1	0.4 ± 0.1	102 ± 27
pe	5	1000+	4 ± 0.3	2 ± 1	15 ± 5	0	0	0	738 ± 58	902 ± 61	2.9 ± 0.1	0.5 ± 0.1	47 ± 20
						Xishuangbanna							
gr	1	1–2	48	5	0	0	0	0	<0.1	52	1.1	<0.1	1
sh	3	2–10	13 ± 4	21 ± 10	69 ± 3	13 ± 7	33 ± 22	2 ± 2	1 ± 1	152 ± 31	2.7 ± 0.6	0.3 ± 0.3	<0.1 ± <0.1
dw	8	10–20	6 ± 2	7 ± 2	67 ± 15	350 ± 90	23 ± 7	0.1 ± <0.1	8 ± 3	461 ± 90	4.2 ± 0.4	7.2 ± 5.5	6 ± 3
df	10	20–100	6 ± 2	9 ± 2	60 ± 7	446 ± 93	147 ± 39	3 ± 2	8 ± 4	679 ± 102	5.2 ± 0.2	1.6 ± 0.8	139 ± 96
ef	33	100–300	1 ± 0.2	7 ± 1	58 ± 3	51 ± 14	435 ± 39	9 ± 2	22 ± 3	582 ± 44	4.9 ± 0.2	1.5 ± 0.6	20 ± 9
mf	7	300+	0.3 ± 0.1	4 ± 0.3	35 ± 2	54 ± 25	96 ± 30	2 ± 1	167 ± 12	358 ± 47	2.1 ± 0.2	2.2 ± 0.7	98 ± 56
						Ailao Mountain							
df	9	100–200	8 ± 4	6 ± 2	39 ± 7	60 ± 25	79 ± 21	7 ± 3	111 ± 23	311 ± 22	4.0 ± 0.3	1.4 ± 0.5	15 ± 10
ef	10	200–300	9 ± 3	5 ± 1	30 ± 4	28 ± 14	215 ± 42	8 ± 2	87 ± 21	381 ± 51	4.3 ± 0.1	0.1 ± <0.1	5 ± 2
mf	36	300–500	4 ± 1	4 ± 1	30 ± 4	3 ± 2	286 ± 37	5 ± 1	128 ± 10	460 ± 35	4.3 ± 0.1	<0.1 ± <0.1	10 ± 4
pf	6	500–1000	2 ± 6	3 ± 4	35 ± 8	10 ± 2	126 ± 26	2 ± 1	380 ± 33	570 ± 26	4.4 ± 0.2	0.1 ± <0.1	2 ± 1
pe	5	1000+	1 ± 3	2 ± 3	2 ± 1	0	0	0.1 ± <0.1	817 ± 98	873 ± 94	2.4 ± 0.2	0.6 ± 0.2	6 ± 3

[a] vegetation type: gr, grassland; sh, shrubland; dw, deciduous woodland; df, deciduous forest; ef, evergreen forest; mf, moss forest; pf, peat forest; pe, peatland.

and we found no evidence of succession from peatland to *Populus* forest. This evidence can be seen in the oldest (500-1000 years) *Lithocarpus* forests (the so-called "dwarf forests") where we find peatland plants, particularly *Sphagnum* mosses, colonizing the forest floor. Also, in the dwarf forests along the margins of peatlands, the peat bog vegetation is overgrowing forest plants and soils. Here there is an abundance of dead and dying trees, with logs and stumps buried under the peat. Measured peat depths in these bogs range from 205 to 404 cm, which suggests that the oldest parts of these peatlands are several thousands of years in age.

[17] The successional patterns described here for China are consistent with successional studies elsewhere that show, in the absence of disturbance, pathways of ecosystem development going from evergreen forest to peat forest to peatland [*Klinger et al.*, 1990; *Klinger*, 1996a, 1996b; *Klinger and Short*, 1996]. However, other studies suggest different successional pathways and relationships among the ecosystem types described here, thus leaving the matter open to further investigation.

3.3. Leafy Biomass, Leaf Area, and VOC Emissions

[18] Mean values of leafy biomass, leaf area, and VOC emissions according to successional status of plots in each of the study areas are also listed in Table 3. The biomass values reported here are generally consistent with values reported from comparable sites in China. Measured leafy biomass of *Stipa*-dominated grasslands in northern China is reported by *Gao and Yu* [1998] as 153 g (leaf dry weight) per m^{-2} (ground area) compared to 109 g m^{-2} determined in this study. At Changbai Mountain, *Xu et al.* [1985] reported canopy leafy biomass values of 262 and 269 g m^{-2} for two deciduous forest types, and 240 and 326 g m^{-2} for two evergreen forest types, compared to canopy leafy biomass for deciduous forests of 340 g m^{-2} and for evergreen forests of 353 g m^{-2} measured here. *Cao et al.* [1995] reported cryptogam biomass of 400 to 558 g m^{-2} for moss forests and 534 g m^{-2} for a peatland compared to values of 351 and 480 g m^{-2} measured here, respectively. *Shao et al.* [1992] found an herb (graminoid + forb) leafy biomass of 42.2 g m^{-2} in deciduous forest compared to 17.5 g m^{-2} found here. Tree leaf biomass reported for a Xishuangbanna primary rain forest is 791 g m^{-2} [*Dang et al.*, 1997] compared to tree leaf biomass of primary rain forest found here to be 486 g m^{-2}. Estimates of leafy biomass for subtropical broad-leaved evergreen forest, similar to Ailao Mountain forests, range from 128 [*Chen et al.*, 1993] to 346 g m^{-2} [*Qiu et al.*, 1984], compared to 243 g m^{-2} reported here. At Ailao Mountain, *Qiu et al.* [1984] reported moss forest canopy leafy biomass of 346 g m^{-2} compared to 289 g m^{-2} here.

[19] The only comparable measurements of LAI found in the literature are for the Changbai Mountain region, reported as 6.9 for deciduous forest and 4.7 for evergreen forest [*Xu et al.*, 1985], compared to values found here of 4.7 and 5.2, respectively. There are no known measurements of VOC emissions for comparable forests in China.

[20] Figure 1a shows the mean values of total leafy biomass for each plot according to successional stage. The trend in group means shows that leafy biomass of plants increases sigmoidally with ecosystem age, consistent with *Odum*'s [1971] principles of ecosystem development. While the curve in Figure 1a shows leafy biomass continuing to increase during succession, Table 3 indicates that the leafy biomass in later successional stages is composed largely of cryptogams.

[21] Calculated isoprene and monoterpene emissions for each plot according to successional stage are shown in Figures 1b and 1c. Isoprene values were adjusted for leaf area index and standardized for a sun zenith angle of 57 degrees, an above-canopy PAR of 1500 μmoles m^{-2} s^{-1}, and a leaf temperature of 30°C. The curve of isoprene mean group values indicates that isoprene emissions are highest in the early successional forest stages (3–4 mg C m^{-2} hr^{-1}) and drop to lower levels in the late successional forests and peatlands (0.1–2 mg C m^{-2} hr^{-1}). The group means for monoterpene emissions indicate highest monoterpene emissions (~2 mg C m^{-2} hr^{-1}) in the late successional moss forests and declining somewhat in the peatland stages. These patterns are very similar to those found in previous successional studies of VOC emissions in Africa [*Klinger et al.*, 1998], in North America [*Guenther et al.*, 1999a; *Helmig et al.*, 1999b], and in Europe [*Schaab et al.*, 2000].

3.4. VOC Emission Estimates for China

[22] VOC emissions for all of China were computed using the model of *Guenther et al.* [1995], parameterized and modified for China in the following ways. The percentage of forest types by province was calculated from forest inventory results reported by *Wu* [1997]. From this inventory we utilized data on two forest classifications to arrive at province-level forest composition and cover (Table 4). One data set provided province-level areas for the following categories: coniferous forest, broadleaved forest, bamboo forest, economic forest, total forest, and total area. A second data set gave provincial presence-absence and nationwide percentage cover for 15 forest types: *Quercus, Betula, Populus, Larix, Picea, Abies, Cunninghamia lanceolata, Pinus massoniana, P. tabulaeformis, P. yunnanensis,* mixed conifer, mixed broadleaf, broadleaf, sclerophyll, and other. These latter forest types were condensed to 12 by combining the three *Pinus* types to a single *Pinus* type and combining the *Abies* and *Cunninghamia lanceolata* types to a single fir type. The first data set provided area-weighted indices for these 12 forest types according to the percentage composition of "conifer," "broadleaf," or "other" ("bamboo" + "economic") forest cover. Characterizations of species composition, leafy biomass density, and emissions data collected at the Changbai, Xishuangbanna, and Ailao locations in areas representative of nearly all these forest types were then applied to the values in Table 4. The results (Table 5) show the canopy leafy biomass, isoprene emission factors, monoterpene emission factors, and emission factors of other volatile organic compounds (OVOCs) calculated from *N* samples (plots) in each forest type, except sclerophyll forest. OVOC emission factors were based on a value of 1.5 μg C g^{-1} hr^{-1} assigned for all canopy species [*Geron et al.*, 1994]. These results were then used to weight, proportional to the magnitude of leafy biomass and emission rates, the forest emission factors for each province in the regional VOC emissions model of *Guenther et al.* [1999b]. Inputs of temperature and light in the Guenther model are based on monthly average values from a 0.5° × 0.5° gridded meteorological database.

[23] Model results of VOC annual emissions from forested areas of China by province are given in Table 6. These

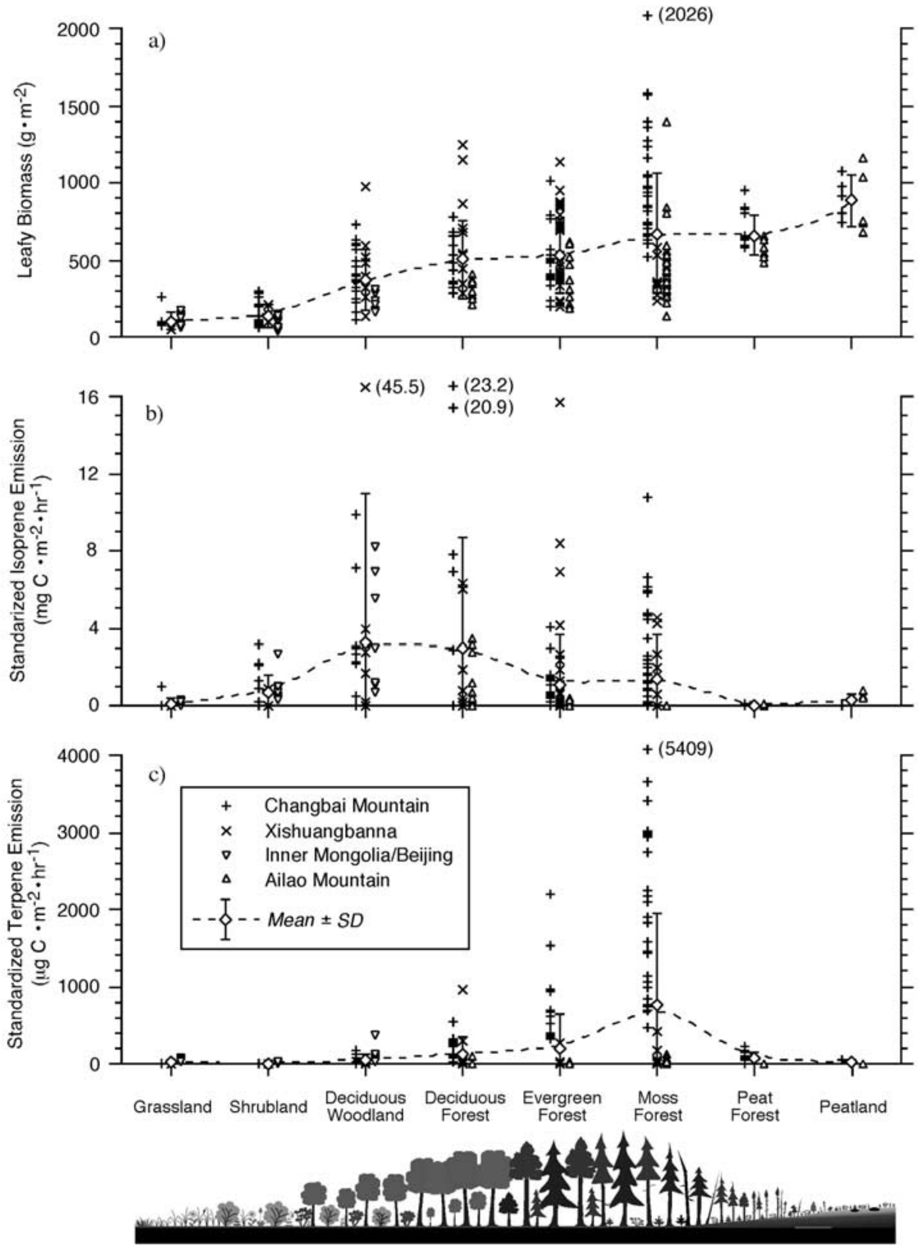

Figure 1. Individual plot means and group means (± S. D.) of (a) total leaf/green biomass, (b) standardized isoprene emissions, and (c) standardized monoterpene emissions for all plots grouped according to successional stage.

results give annual VOC emissions for China (except Taiwan) of 4.1 Tg C as isoprene, 3.5 Tg C as monoterpenes, and 13 Tg C as OVOCs. The isoprene emissions found in this study are substantially lower than the value of 15.0 Tg C yr^{-1} of isoprene obtained using the *Guenther et al.* [1995] model (Table 7). This discrepancy is mainly due to the differences in model input values for the forest cover and isoprene emission factors, which *Guenther et al.* [1995] obtained from data sets that contained little or no information specific to China on forest species composition or VOC emissions. The isoprene + monoterpene annual emissions of 7.6 Tg C found here are similar to the isoprene + monoterpene annual emissions of 8.3 Tg C calculated for China by *Bai et al.* [1995] using an extrapolation method based on branch measurements of VOC emissions from 15 representative tree species. The annual biogenic VOC emissions are considerably higher than the annual anthropogenic VOC emissions reported for China to be 5.3 Tg C [*Piccot et al.*, 1992], although we expect that the relative amounts of anthropogenic and biogenic emissions vary widely from region to region in China.

[24] Figures 2a, 2b, and 2c show the distribution across China of modeled July noonday emission rates of isoprene, monoterpenes, and OVOCs, respectively. These figures reveal marked differences in distributions and rates of VOC emissions compared to those shown by *Guenther et*

Table 4. Percentage of Forested Area of the 12 Forest Types Used in the Emission Estimates Listed by Province

		Forest Type											
Province	Forested Area, km^2	*Betula*	Broadleaf	Fir	*Larix*	Mixed Broadleaf	Mixed Needleleaf	Other[a]	*Picea*	*Pinus*	*Populus*	*Quercus*	Sclerophyll
Anhui	22561	0	4.8	18.3	0	0	0	27.2	0	23.0	5.9	14.0	6.8
Beijing	2671	9.2	0	0	9.3	0	0	45.5	0	7.0	6.0	15.9	7.1
Fujian	61484	0	8.4	23.2	0	0	0	23.9	0	29.1	0	15.3	0
Gansu	19486	12.0	4.7	4.6	8.1	8.0	4.2	10.5	5.3	4.4	6.7	23.0	8.6
Guangdong	65431	0	7.6	19.1	0	9.0	11.0	18.7	0	25.4	0	0	9.2
Guangxi	60217	0	6.0	13.5	0	0	0	20.4	0	26.7	7.3	17.5	8.5
Guizhou	26028	6.5	2.5	14.5	0	4.4	7.1	15.7	0	28.5	3.7	12.5	4.7
Hainan	10663	0	26.0	0.8	0	29.0	0	43.2	0	1.0	0	0	0
Hebei	24806	8.7	3.4	0	5.4	5.9	3.1	38.5	3.8	3.2	4.9	16.8	6.2
Heilongjiang	161620	12.1	4.7	7.8	12.6	8.1	7.2	0.3	8.7	0	6.8	23.2	8.6
Henan	17527	0	0	4.6	4.6	0	0	25.2	0	8.7	13.5	28.2	15.1
Hubei	39522	7.9	3.6	14.1	10.2	0	0	15.7	0	23.4	4.8	14.3	5.9
Hunan	69490	0	1.7	16.7	0	0	0	39.9	0	32.0	2.1	5.1	2.5
Inner Mongolia	140657	12.9	6.0	0	14.1	0	0	6.2	10.5	9.4	7.9	23.4	9.7
Jiangsu	4122	0	3.4	14.9	0	0	0	44.3	0	18.7	4.1	9.8	4.7
Jiangxi	67277	0	3.0	24.3	0	4.1	0	25.0	0	30.4	0	8.9	4.3
Jilin	63469	14.5	5.6	5.0	8.0	9.7	4.6	0.7	5.6	0	8.1	27.8	10.4
Liaoning	39186	9.2	3.6	3.7	6.4	6.2	3.3	30.8	4.2	3.5	5.1	17.6	6.6
Ningxia	1020	15.3	7.1	0	6.0	0	0	18.4	0	4.6	9.4	27.7	11.5
Qinghai	2501	15.7	0	14.9	24.0	0	0	1.4	16.6	14.2	13.3	0	0
Shaanxi	12700	10.9	5.0	0	14.9	0	0	13.6	11.1	9.9	6.7	19.7	8.2
Shandong	16288	0	0	0	9.7	0	0	60.6	0	7.3	5.3	11.1	6.0
Shanhai	147	0	0	0	0	0	19.7	78.9	0	0	0	0	1.4
Shanxi	49735	15.7	7.2	4.8	3.4	0	0	12.9	0	6.3	9.6	28.4	11.8
Sichuan	115318	5.8	2.7	16.7	12.5	0	0	10.3	5.8	28.0	3.5	10.5	4.3
Taiwan	19695						(data not available)						
Tianjing	858	0	7.4	0	0	0	0	46.7	0	4.8	9.0	21.6	10.5
Tibet	71699	0	0	24.6	0	9.5	0	0	26.5	23.9	0	15.4	0
Xinjiang	13056	11.4	7.2	16.7	24.4	0	0	4.3	18.1	0	8.4	0	9.4
Yunnan	94042	8.9	3.4	18.5	12.2	5.9	0	8.5	7.4	6.7	5.0	17.0	6.3
Zhejiang	43759	0	1.3	26.1	0	0	0	32.4	0	32.8	1.6	3.9	1.9
Total	1337035	8.5	3.6	11.3	8.4	5.8	2.1	10.5	3.9	18.9	5.0	15.9	6.2

[a] mainly economic and bamboo forest areas.

al. [1995]. Our results differ mostly with respect to isoprene emissions, which here are highest mainly in the temperate woodland savannas and forests of central and northeastern China. *Guenther et al.* [1995] report the highest isoprene emissions occurring in the subtropical and tropical forests of southeast China, at overall rates several times higher than we find here. Overall monoterpene and OVOC emissions for China are shown here to be near or slightly lower than those reported by *Guenther et al.* [1995], with the highest emissions coming similarly from the subtropical forests of southeast China. Our results, however, show monoterpene and OVOC emissions to be relatively high in the temperate and boreal forest areas of central and northeast China compared to the results of *Guenther et al.* [1995].

4. Discussion

4.1. VOC Emissions and Ecosystem Succession

[25] The above results extend to China the occurrence of a successional pattern in VOC emissions where the highest

Table 5. Assigned Biomass and Emission Factors for China Forest Types

Forest Type	N Plots[a]	Canopy Leafy Biomass, $g\ m^{-2}$	Emission Factors: Isoprene, $\mu g\ C\ m^{-2}\ hr^{-1}$	Terpene, $\mu g\ C\ m^{-2}\ hr^{-1}$	OVOC, $\mu g\ C\ m^{-2}\ hr^{-1}$
Betula	9	259	1960	24.6	388
Broadleaved	108	426	2990	36.4	639
Fir	7	430	3160	1040	644
Larix	16	174	221	188	261
Mixed Broadleaved	20	274	725	68.3	411
Mixed Needleleaved	11	440	2310	831	660
Other[b]	-	350	1860	52.3	525
Picea	19	792	9530	2220	1190
Pinus	11	448	1300	870	672
Populus	11	266	5980	270	399
Quercus	4	423	23600	202	634
Sclerophyll	0	n.m.[c]	n.m.	n.m.	n.m.

[a] number of plots used in calculation of assigned factors.
[b] average of broadleaved and mixed broadleaved forest types.
[c] not measured.

Table 6. Forest Area, Leafy Biomass, and Estimated Annual VOC Emissions by Province

Province	Total Area, km^2	Forest Area, km^2	Tree Leaf Biomass of Forest Areas, $g\ m^{-2}$	Isoprene Emissions, $10^9 g\ C\ yr^{-1}$	Monoterpene Emissions, $10^9 g\ C\ yr^{-1}$	OVOC[a] Emissions, $10^9 g\ C\ yr^{-1}$
Anhui	138165	22561	372	92.5	82.7	359
Beijing	17821	2671	314	13.9	7.80	26.3
Fujian	121500	61484	414	140	205	366
Gansu	449734	19486	338	167	119	482
Guangdong	177901	65431	367	103	159	596
Guangxi	237600	60217	368	195	129	709
Guizhou	176471	26028	378	80.5	70.5	370
Hainan	34104	10663	349	16.8	12.0	124
Hebei	185879	24806	339	99.2	50.9	321
Heilongjiang	454608	161620	346	328	257	517
Henan	167000	17527	310	97.7	50.3	403
Hubei	185862	39522	347	139	132	435
Hunan	211835	69490	389	113	159	505
Jiangsu	102600	4122	370	21.2	16.0	216
Jiangxi	166723	67277	390	116	201	447
Jilin	188869	63469	329	152	51.7	235
Liaoning	145739	39186	342	89.7	33.1	221
Inner Mongolia	1158402	140657	350	528	344	1518
Ningxia	66400	1020	307	28.3	12.9	96.3
Qinghai	721514	2501	381	56.5	53.1	346
Shaanxi	156623	12700	357	204	157	396
Shandong	152221	16288	323	38.9	27.8	345
Shanhai	5956	147	363	0.02	0.02	0.27
Shanxi	205977	49735	317	86.4	81.0	253
Sichuan	566079	115318	381	245	351	786
Taiwan	35760	19695	n.a.[b]	n.a.	n.a.	n.a.
Tianjing	11493	858	332	2.59	1.42	22.2
Xinjiang	1647000	13056	356	398	197	1487
Tibet	1228436	71699	514	61.1	92.7	424
Yunnan	382644	94042	359	382	288	746
Zhejiang	101800	43759	399	62.6	120	257
All China	9602716	1337035	360	4057	3462	13010

[a] OVOC, other volatile organic compound.
[b] data not available.

isoprene emissions occur in pioneer and early secondary forests, and the highest monoterpene emissions occur in late secondary and primary forests [cf. *Li and Klinger*, 2001]. Lower isoprene and monoterpene emissions are found in early successional grasslands and late successional peatlands. We suggest that the systematic patterns in the VOC emissions found here in the forests and peatlands of China and elsewhere [*Klinger et al.*, 1994, 1998; *Guenther et al.*, 1999a; *Helmig et al.*, 1999b; *Isebrands et al.*, 1999; *Schaab et al.*, 2000; *Westberg et al.*, 2000] are indicative of deterministic, self-organizing behavior in ecosystems, consistent with theories and concepts in systems ecology, complexity, and Gaia theory [*Lovelock*, 1995]. The validity of this view, as applied to the ecosystems of China, is backed by several Chinese ecologists [*Han*, 1992; *Chang*, 2000]. From a systems perspective, the successional patterns in isoprene found here point toward a possible functional role of isoprene at the ecosystem level. As postulated by *Klinger et al.* [1998], isoprene may enhance the formation of available nitrogen (N) in the canopy atmosphere, thus promoting the assimilation of N into an N-limited early successional forest ecosystem.

4.2. VOC Emissions From China

[26] Refining the magnitudes and distributions of biogenic VOC emissions in China is important in order to better understand potential feedbacks of these emissions on the vegetation via ozone. Ozone levels are found to be high in several urban and nonurban areas of China and may be affecting crop yields [*Chameides et al.*, 1999; *Shao et al.*, 2000]. Models indicate that biogenic VOCs significantly affect ozone production in these regions [*Luo et al.*, 2000; *Shao et al.*, 2000] and may even be limiting for ozone production in the rural areas of northern China. Our results

Table 7. Comparison of Regional and Global VOC Emission Estimates

Region	Area, $10^6\ km^2$	Isoprene Emissions, $Tg\ C\ yr^{-1}$	Monoterpene Emissions, $Tg\ C\ yr^{-1}$	OVOC Emissions, $Tg\ C\ yr^{-1}$	Area Average Isoprene Emis., $g\ C\ m^{-2}\ yr^{-1}$	References
China	9.6	4.1	3.5	13	0.43	This study
China	9.6	15.0	4.3	9.1	1.56	*Guenther et al.* [1995]
Europe	9.9	4.6	3.9	5.0	0.46	*Simpson et al.* [1999]
North America	24.7	29.3	21.0	33.6	1.19	*Guenther et al.* [2000]
Central Africa	4.54	35.4	-	-	7.80	*Guenther et al.* [1999b]
Central South America	14.2	108	12	-	7.61	*Greenberg et al.* [1999b]
Global (Land)	146.8	503	127	517	3.43	*Guenther et al.* [1995]

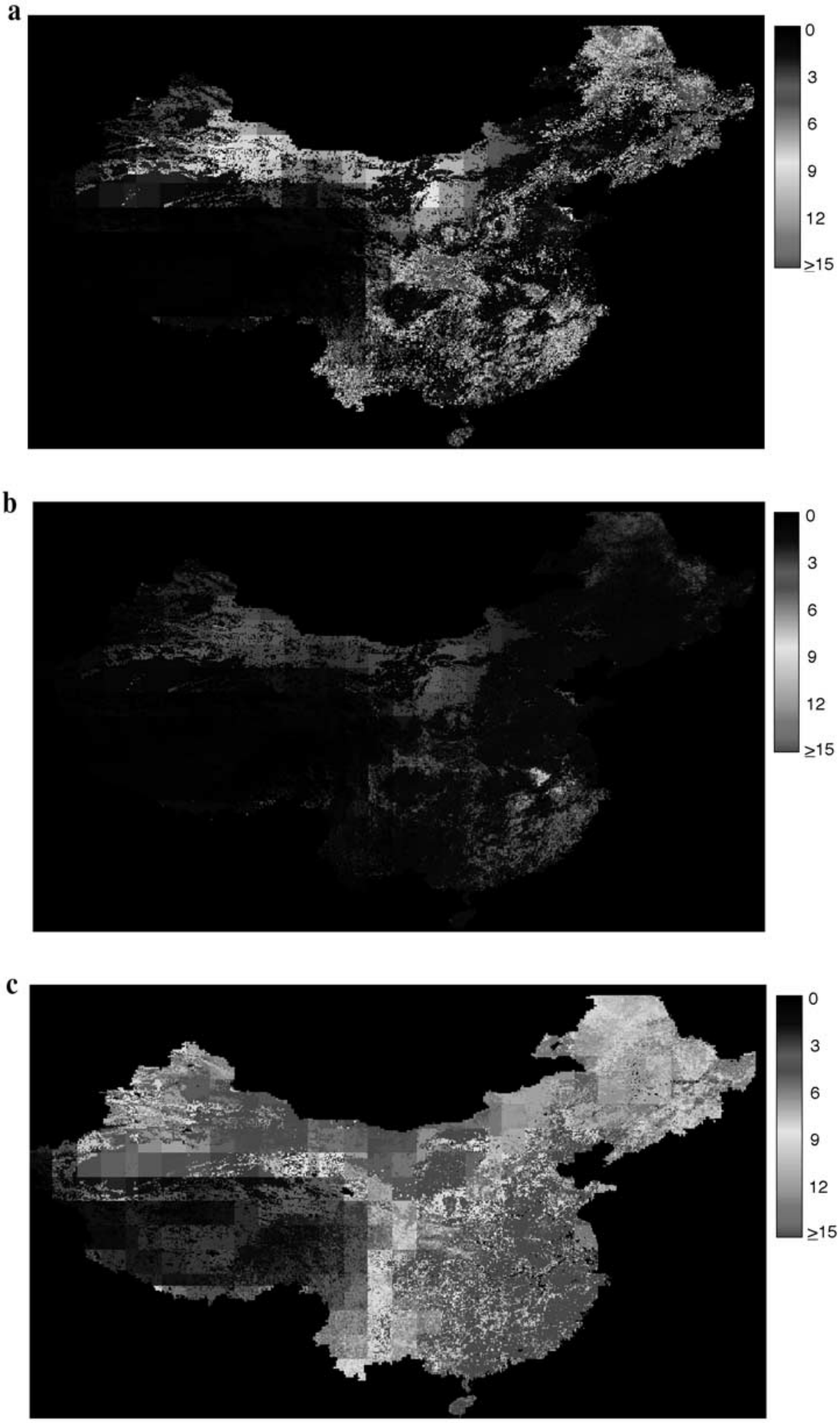

Figure 2. Modeled average July noonday emissions (mg C m^{-2} d^{-1}) for China of (a) isoprene, (b) monoterpenes, and (c) other volatile organic compounds. See color version of this figure at back of this issue.

give higher-than-previous estimates of isoprene emission for northern China, and hence greater potential for ozone production there.

[27] Comparing our VOC emission estimates for China with estimates for Europe, central Africa, central South America, and North America (Table 7), we find that China and Europe are quite similar with respect to isoprene and monoterpene emissions. Our OVOC emission estimates for China, however, are considerably higher than those for Europe, reflecting the large extent of grasslands in China. North America, central Africa, and central South America exhibit higher isoprene emissions on a per-area basis than do China and Europe, suggesting that early successional forest cover is relatively high in the former regions. Discrepancies between our VOC emission results and those of *Guenther et al.* [1995] for China (Table 7), as in the fourfold difference in isoprene emissions discussed in section 3.3, highlight the importance of conducting field studies in regions that are poorly characterized with respect to forest cover and VOC emissions.

4.3. Uncertainties

[28] The major uncertainties of these findings arise from observational errors in plot measurements and from inaccuracies of key assumptions used in the extrapolation. Uncertainty in the VOC emission potential assigned for a given species can occur from species misidentification, from inaccurate determinations of VOC emission, and from an unrealized discrepancy between assigned versus actual emission potentials. Such a discrepancy can result from assigning unmeasured species of a given genus the same emission potential as the measured species. Error from misidentification is likely quite low as botanical experts were employed for all identifications. The frequency of incorrect assessment of emission potentials (i.e., determining the emission potential of a plant is high when it is actually moderate), based on comparing PID screening results with leaf cuvette method, is about 10% [*Klinger et al.*, 1998]. It is possible that some plants identified as isoprene emitters with the PID may instead be emitting monoterpenes or methyl butenol in a light-dependent manner. *Hevea brasiliensis* (rubber tree), for example, exhibits light-dependent VOC emissions which, when sampled using the leaf cuvette/GC-MS method, are found to be mainly monoterpenes. However, in other plants with light-dependent monoterpene emissions, the values tend to be low [*Kesselmeir et al.*, 1996]. Methyl butenol emissions have been found only in the *Pinus* species of North America. Because the pines here were found to have low or no isoprene emissions, it appears that methyl butenol is not contributing to any overestimate in isoprene emissions. Uncertainty of assigned versus actual emission potentials, based on the degree to which species emission potentials were derived from genus assignments versus actual measurements, is estimated at 10% for Changbai Mountain, 20% for Ailao Mountain, and 25% for Xishuangbanna. As discussed in section 3.2, there is an added uncertainty (10%) in the emission potentials of the nonwoody vegetation.

[29] Uncertainties in the determination of vegetation abundance (LAI and leafy biomass) arise from both error in measurement and error in the forest algorithms. The optical sensing methods employed for LAI are accurate to about 20% for the range of LAIs found in this study. The forest algorithms are not reported with uncertainty levels, so their error, based on comparing our leafy biomass results with other studies in China (see section 3.2), is estimated to be 20% for trees and 50% for understory vegetation (mainly as an underestimation).

[30] The VOC emission estimates for China rely largely on the accuracy of the national forest inventory data [*Wu*, 1997], on the degree to which our plots are representative of a given forest type, and on the validity of model assumptions. All of our study sites were located with the assistance of local scientists in typical forest types in and around ecological research stations of the Chinese Academy of Sciences. An uncertainty factor of about three has been associated with regional model estimates of biogenic VOC emission rates, but this uncertainty is not based on a quantitative evaluation. The error associated with emissions predicted for a specific landscape can be evaluated using above-canopy eddy flux measurements [e.g., *Guenther and Hills*, 1998], but there is currently no method for evaluating or even constraining these flux estimates. The uncertainties associated with specific model procedures can be evaluated for particular circumstances, such as a quantitative test of the response of isoprene emission to changes in temperature, but it is not possible to assign rigorous uncertainty estimates to the regional results because of the limited data. A factor of three is probably a reasonable estimate of the uncertainty associated with annual total VOC estimates for China, but predictions for specific times, locales, and compounds can be much more uncertain.

[31] **Acknowledgments.** We wish to thank the staff of the Inner Mongolia Grassland Ecosystem Research Station, the Changbai Mountain Forest Ecosystem Research Station, the Beijing Forest Ecosystem Research Station, the Dinghu Mountain Forest Ecosystem Research Station, the Ailao Mountain Forest Ecosystem Station, the Kunming Botanical Garden, and the Xishuangbanna Tropical Botanical Garden. For field, technical, and logistical assistance we especially thank at Inner Mongolia, Cheng Yun-Xiang, Kawadu Kiyokazu, and Sun Xin-Wen; at Changbai, Dai Limin, Wang Xiaochun, Xu Hao, Yang Liyun, Liu Qingwei, Wang Chenrui, and Yun Yangli; at Xishuangbanna, Zhang Jinhou, Xia Yong-Mei, Wang Hong, Tang Jianwei, Bo Wen Bian, Hu Jiang-Xiang, Zhang Ling, Xiang Hui, Wang Zhi-Hui, Ava Klinger, and Sonya Klinger; at Ailao, Zhang Xing-Wei, Yang Gou-Ping, He Yong-Tao, Tang Yong, Li Da-Weng, and Yang Weng-Zheng; and at Kunming, Shui Yu-Ming and Gong Xun. Special thanks go to Hu Zaichun and Lou Zhi-Ping of the Chinese Academy of Sciences, who arranged and greatly facilitated this China-United States research collaboration. Thanks to Bill Baugh at NCAR who provided the IDL program used to measure leaf area. Many thanks to Peter Harley, Janne Rinne, Daniel McKenna, and three anonymous reviewers for providing valuable comments on the manuscript. Part of the support for this work came from NSFC grants (39700019 and 40075027) to Q.-J. Li and from an NSF grant (INT-0116879) to B. Baker. The National Center for Atmospheric Research is sponsored by the U.S. National Science Foundation.

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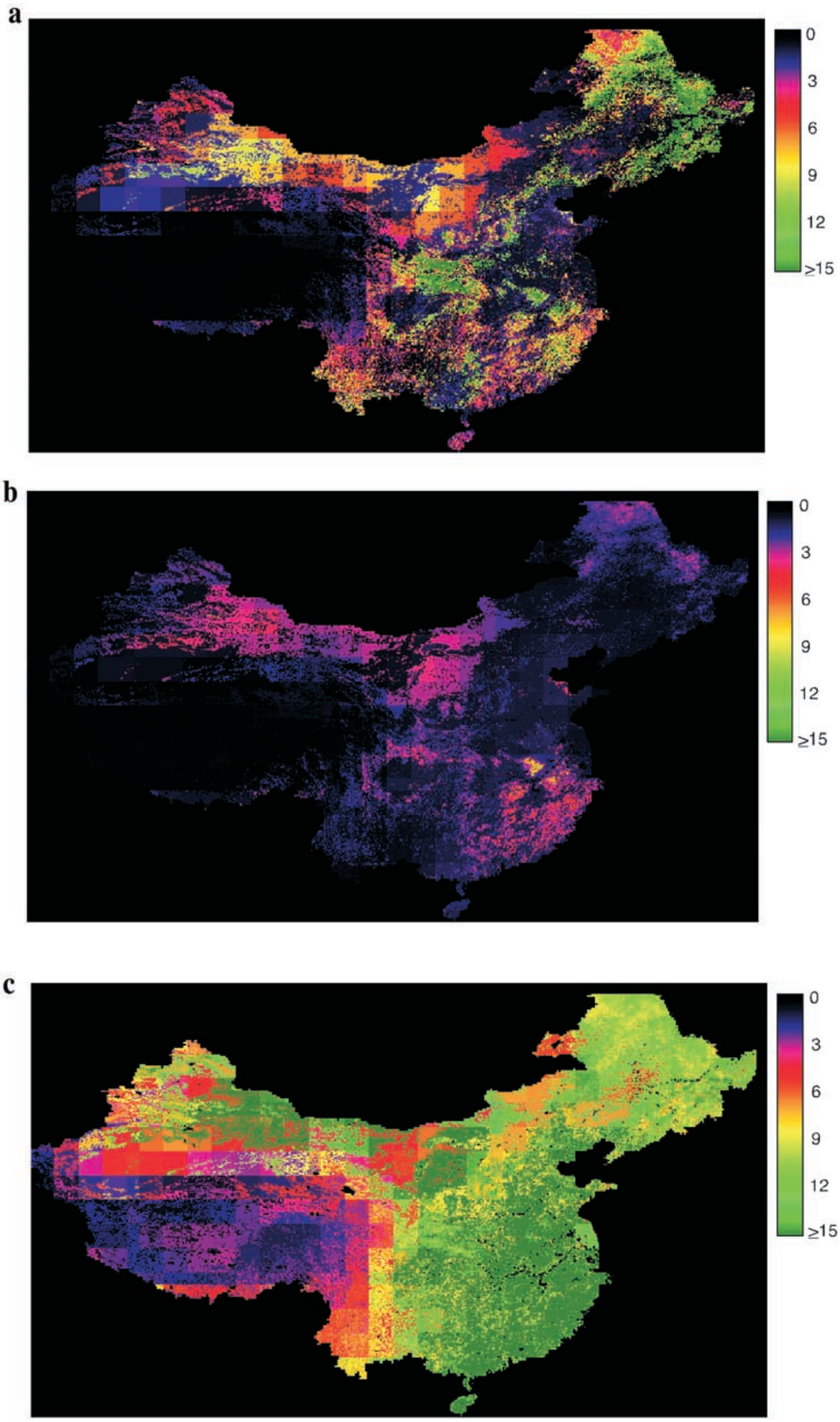

Figure 2. Modeled average July noonday emissions (mg C m^{-2} d^{-1}) for China of (a) isoprene, (b) monoterpenes, and (c) other volatile organic compounds.