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Biogenic VOCs emission inventory development of temperate grassland vegetation in Xilin River Basin, Inner Mongolia, China

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Abstract: Given the key role of biogenic volatile organic compounds (VOCs) to tropospheric chemistry and regional air quality, it is important to generate accurate VOCs emission inventories. However, only a less fraction of plant species, in temperate grassland of Inner Mongolia, has been characterized by quantitative measurements. A taxonomic methodology, which assigns VOCs measurements to unmeasured species, is an applicable and inexpensive alternation for extensive VOCs emission survey, although data are needed for additional plant families and genera to further validate the taxonomic approach in grassland vegetation. In this experiment, VOCs emission rates of 178 plant species were measured with a portable photoionization detector (PID). The results showed the most of genera and some families have consistent feature of their VOCs emission, especially for isoprene, and provide the basic premise of taxonomic methodology to develop VOCs emission inventories for temperate grassland. Then, the taxonomic methodology was introduced into assigning emission rate to other 96 species, which no measured emission rates available here. A systematical emission inventory of temperate grassland vegetation in Inner Mongolia was provided and further evidence that taxonomy relationship can serve as a useful guide for generalizing the emissions behavior of many, but not all, plant families and genera to grassland vegetation.

Keywords: VOCs; PID; biogenic emission; isoprene; monoterpene; grassland vegetation; taxonomic methodology

Introduction

It is currently known that vegetation release volatile organic compounds (VOCs) into the atmosphere as products of secondary metabolism, and these VOCs emitted from terrestrial vegetation are account for more than 90% global VOCs emissions (Guenther, 1995; 1997; Bejaman, 1998). Furthermore, most VOCs emitted from vegetation are reactive and thus participate in photochemical reaction with O_3 or NOx in the lower atmospheric layers (Fesenfeld, 1992). In the past years, reports on the emission inventory from regional vegetation have increased (Benjamin, 1996; Karlik, 2001; 2002; 2003; Clark, 2001; Wang, 2002; Scott, 2003). Since Benjamin (Benjamin, 1996) have found a link between isoprene and monoterpene emissions rates and plant taxonomic relationships, and proposed that taxonomic methodology can be used to assign total hourly (isoprene and monoterpene) emission rates to other species for which no measured emission rates available. The taxonomic methodology has already been proved to be an effective means to investigate biogenic VOCs emission pattern.

The experiments are to determine specific-level isoprene and monoterpene emission rates of temperate grassland vegetation in Inner Mongolia, with a portable PID instrument. Through analyzing data of 178 plant species, there also exists a link between isoprene and monoterpene emissions rates and plant taxonomic relationship in grassland vegetation, which provides the basic premise of taxonomic methodology to develop biogenic VOCs emission inventory. Then, we introduce the taxonomic methodology into assigning emission rate to other 96 species here, which no measured emission available. Therefore, a primary goal of this study is to extend taxonomic methodology to estimate biogenic emission of grassland vegetation.

1 Materials and methods

1.1 Study area

The study area is situated in the southern part of Xilin River Basin (43°26′—44°39′N, 115°32′—117°12′E), Inner Mongolia. Details of climatological, geological and edaphic information were given in the literatures (Chen, 1988; Li, 2002).

1.2 Experimental methods

1.2.1 Calibration of the PID instruments

The study described here has been patterned after the methods of investigators who used a photoionization detector (PID) to survey vegetation (Guenther, 1996a; 1996b; Klinger, 1998; 2002; Li, 2001; Karlik, 2002). A hand-hold factory-calibrated PID (ppb RAE) was used to identify VOCs emission rate. However, the PID instrument was calibrated at the start of each day. The lower value was set to zero when a charcoal cartridge was attached to the inflow port. The upper value was set by introducing 10 ppm isobutene in a N_2 standard. Moreover, a water trap filter made of a Teflon membrane with a 10 μm pore size was utilized during a sampling period, because signal loss could occur due to condensation of water on the UV lamp (Klinger, 1998). Karlik (Karlik, 2002) reported that the lower detection limit is 150 ppb for ppb REA and the relative sensitivity ranged from 30% for methyl-butenol to 127% for Δ^3-carene. Furthermore, Li (Li, 2001) pointed out that the PID can quantitatively and accurately measured isoprene

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emission from plant but it's precision was relatively lower for monoterpene. Relative sensitivity of PID in this paper was not measured for all potential VOCs species, and the speciation of emission to particular plant sample was also unknown, so the PID values obtained from plants were considered to be a semi-quantitative index of VOCs emission rates (Guenther, 1996a; Klinger, 1998).

1.2.2 Plant sampling and VOCs measurements

It is well established that several environmental factors influence emissions of VOCs from vegetation and, among them, light and temperature are most important (Guenther, 1991; 1993; Hansen, 1997). For this reason, ambient air temperature and PAR were recorded during sampling. Temperature was measured with a general thermometer. Light intensity was measured as a 5 s average PAR value(μmol/(m^2·s)) using a quantum meter (QMSW-SS, Apogee Instruments Inc.). Samplings were usually carried out, on *in situ*, at a light intensity greater than 1000 μmol/(m^2·s), and never less than 780 μmol/(m^2·s), for isoprene emission would reach a maximum at 700—900 μmol/(m^2·s) (Guenther, 1993).

A "light run" Teflon bags were used over well-lighted branches or clumps of foliage and carefully closing the base of each bag. Background VOCs emission of Teflon bags and its effect on PAR, respectively, were checked and found which negligible. No flower or a few flowers was included in the bags. Care was taken to avoid VOCs release due to "rough handling", for damaged or crushed foliages usually increased VOCs emission remarkably (Juuti, 1990; Karlik, 2002). First, the ambient air VOCs concentration was measured for 5 replicates readings, then, after 5 min, the VOCs concentration in the bag was measured by inserting the end of Teflon sampling tube into the bag for 5 replicate readings.

To measure VOCs emission from leaves darkened, sleeves with white sleeves (to avoid heating of the bags) were used to cover the sampling bags. After 5 min, we got 5 replicate readings. Then, these sample leaves were removed from the plant, placing into labeled plastic bags, and placed in a drying oven at 65℃ for 48 h. Dry weights were used for normalization of VOCs emission to leafmass.

1.2.3 Normalization of VOCs emission rate

PAR and leaf temperature can account for short-time variation in isoprene emissions, although the mechanism controlling isoprene emission is still not well known (Guenther, 1993; 1995; Kesselmeier, 1996; Hansen, 1997; Harley, 1998). Guenther (1993) have established a classic algorithm to estimates base emission of VOCs in a standard temperature (30℃) and PAR flux (1000 μmol/(m^2·s)). The algorithm have already been supported or successfully used by some other researchers (Guenther, 1995; Klinger, 1998; 2002; Li, 2001; Wang, 2002; 2003). The model is described briefly as follows:

$$I = I_s \cdot C_L \cdot C_T, \qquad (1)$$

where I is the isoprene emission rate at a temperature T and PAR flux L, I_s are the isoprene emission rate at a standard temperature T_S(30℃) and PAR flux(1000 μmol/(m^2·s)).

The factor C_L is defined by

$$C_L = \frac{\alpha C_{L1} L}{\sqrt{1 + \alpha^2 L^2}}. \qquad (2)$$

Where L is the photosynthetically active radiation (PAR), α (= 0.0027) and c_{L1} (= 1.006) are the empirical coefficients.

The factor C_T is defined by

$$C_T = \frac{\exp \dfrac{c_{T1}(T - T_s)}{RT_sT}}{1 + \exp \dfrac{c_{T2}(T - T_M)}{RT_sT}}. \qquad (3)$$

Where T is the leaf temperature, T_s is the standard temperature (303 K or 30℃), R is a constant (= 8.314 J/(K·mol)), and c_{T1} (= 95000 J/mol), c_{T2} (= 230000 J/mol), and T_M(314 K) are empirical coefficients.

Leaf temperature is usually considered the controlling factor to monoterpene emission. The model (Guenther, 1993) estimates monoterpene emission as

$$M = M_s \cdot \exp(\beta(T - T_s)), \qquad (4)$$

where M is the monoterpene emission rate at temperature T, M_s is the monoterpene emission rate at a standard temperature T_s (30℃), and β (= 0.09) is an empirical coefficient.

1.2.4 A taxonomic methodology for assigning VOCs emission rates

The basic premise of the approach is that, within broad qualitative ranges, taxonomic relationships between plant species at the lowest possible level (i.e., genus, then family level) can be used to assign measured emission rates to other species within that level for which no measurement available (Benjamin, 1996). The taxonomic methodology used in assigning isoprene and monoterpene emissions values is summarized in Fig. 1. If direct measurements are not available for a species but emission rates for other species within the same genus are measured, the mean value for that genus is assigned to the unmeasured species. If no measurements are reported for any species within the genus, but direct measurements for other species within the family

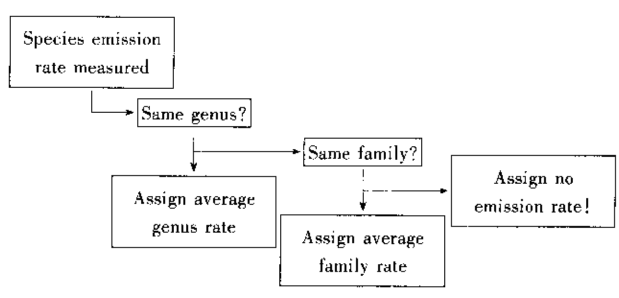

Fig.1 Flowchart showing taxonomic methodology for the assignment of emission rates to species for which measured emission rates does not exist

are available, then the mean emission rate for the family is assigned to the unmeasured species. Finally, for those species for which no measurements are reported for any other species within the family, emission rates are not assigned.

2 Results

2.1 VOCs emissions from foliage

Isoprene is the important component of VOCs emitted from plant species, and the emission rate is mainly dependent on PAR and temperature (Guenther, 1993; Kesselmeier, 1996; Hansen, 1997). However, emission of other compounds emission also shows light-dependence (Kesselmeir, 1996; Harley, 1998). Thus, there is a chance that for some plant species the emissions, reported here as isoprene, may actually be some other VOCs. We consider isoprene to likely be the dominant compounds detected by the PID, although GC confirmation is not performed. So isoprene emissions are calculated as the difference between the light and dark readings.

Monoterpenes are likely emission detected in greatest quantity from darkened foliage but no additional identification is performed. The PID instruments are less sensitive to most monoterpenes than to isoprene (Guenther, 1996; Klinger, 1998). Therefore, the monoterpenes emission is limited and tentative here.

Using these data measured, we have compared VOCs emission rates for 32 species with data reported in the literature (Klinger, 2002), and found they are relatively consistent (65.6%). However, normalized emission rates reported here is totally 2—3 times more than these emission rates measured, because the actual temperature is usually range from 20℃ to 25℃, which is far less than the standard temperature (30℃).

2.2 VOCs emission within plant genera

Results for VOCs measurements are shown in Table 1. We here will discuss firstly those genera that are most homogeneous for emission profile. For practical purposes, "low-", "moderate-", and "high-emitters" are defined as those species emitting VOCs, less than 1 μg Cg (dry leaf wt)$^{-1}$h^{-1}, between 1—10 μg Cg (dry leaf wt)$^{-1}$h^{-1}, and greater than 10 μg Cg (dry leaf wt)$^{-1}$h^{-1}, respectively (Klinger, 1998; Karlik, 2002).

Table 1 Emission rate of isoprene and monoterpenes for grassland plants in Inner Mongolia, China

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Amaranthus retroflexus	Amaranthaceae	0.23	0.55	0.78	3
Lappula redowskii	Boraginaceae	4.76	1.45	6.20	5
Lithospermum officinalis	Boraginaceae	0.56	0.44	1.00	3
Adenophora stenanthina	Campanulaceae	4.21	1.25	5.46	7
Adenophora crispata	Campanulaceae	1.60	1.27	2.87	11
Adenophora gmelinii	Campanulaceae	2.91	1.26	4.17	2[a]
Dianthus chinensis	Caryophyllaceae	0.17	1.44	1.60	2
Melandrium apricum	Caryophyllaceae	1.54	1.35	2.89	2[a]
Silene jenisseensis	Caryophyllaceae	3.57	0.39	3.96	2
Silene repens	Caryophyllaceae	6.64	3.27	9.91	4
Axyris amarantoides	Chenopodiaceae	0.22	2.08	2.30	1
Bassia dasyphylla	Chenopodiaceae	5.01	2.74	7.75	8[a]
Ceratoides arborescens	Chenopodiaceae	7.93	0.84	8.76	2
Ceratoides latens	Chenopodiaceae	7.93	0.84	8.77	1[a]
Chenopodium album	Chenopodiaceae	2.33	1.59	3.92	3[a]
Chenopodium acuminatum	Chenopodiaceae	1.95	2.34	4.29	4
Chenopodium aristatum	Chenopodiaceae	2.05	1.73	3.78	13
Chenopodium glaucum	Chenopodiaceae	2.99	0.69	3.68	8
Chenopodium hybridum	Chenopodiaceae	2.33	1.59	3.92	3[a]
Corispermum chinganicum	Chenopodiaceae	21.15	2.53	23.68	1
Kalidium foliatum	Chenopodiaceae	5.01	2.74	7.75	8[a]
Kochia prostrata	Chenopodiaceae	2.13	9.41	11.53	13
Salsola collina	Chenopodiaceae	1.69	2.33	4.02	7
Suaeda glauca	Chenopodiaceae	5.01	2.74	7.75	8[a]
Achillea asiatica	Compositae	3.57	0.41	3.98	1
Achillea ptarmicoides	Compositae	0.61	1.40	2.01	3
Artemisia pubescens	Compositae	7.26	5.68	12.94	9[a]
Artemisia arrgyi	Compositae	7.26	5.68	12.94	9[a]
Artemisia dracunculus	Compositae	3.48	0.21	3.69	1
Artemisia eriopoda	Compositae	1.81	2.07	3.89	4
Artemisia frigida	Compositae	12.32	6.93	19.25	18
Artemisia gmelinii	Compositae	7.10	12.80	19.90	1
Artemisia intramongolica	Compositae	3.70	0.40	4.10	1

(Cont'd from p.1026)

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Artemisia mongolica	Compositae	9.08	5.09	14.17	10
Artemisia scoparia	Compositae	7.17	13.19	20.36	2
Artemisia sieversiana	Compositae	1.18	11.02	12.20	1
Artemisia tanacetifolia	Compositae	19.54	2.16	21.70	3
Aster alpinus	Compositae	2.35	2.90	5.25	4
Aster tataricus	Compositae	2.35	2.90	5.25	1[a]
Bidens tripartita	Compositae	1.46	4.06	5.52	3
Crepis crocea	Compositae	3.24	3.02	6.26	35[a]
Dendranthema zawadskii	Compositae	3.24	3.02	6.26	35[a]
Echinops gmelini	Compositae	0.21	1.80	2.00	1
Erigeron acer	Compositae	3.24	3.02	6.26	35[a]
Filifolium sibiricum	Compositae	0.63	3.17	3.79	4
Heracium virosum	Compositae	3.24	3.02	6.26	35[a]
Heteropappus altaicus	Compositae	7.20	2.29	9.48	8
Inula britannica	Compositae	2.78	0.92	3.70	3
Ixeris denticulata	Compositae	3.17	2.66	5.84	3
Leontepodium ntopodioides	Compositae	2.41	2.40	4.81	7
Leontepodium longifolium	Compositae	0.86	4.63	5.48	2
Leucanthemella linearis	Compositae	0.02	1.05	1.07	1
Ligularia fischeri	Compositae	1.21	3.17	4.38	2[a]
Ligularia mongolica	Compositae	0.53	0.06	0.59	1
Ligularia sagitta	Compositae	1.89	5.25	7.14	4
Olgaea leucophylla	Compositae	0.63	0.70	1.34	7
Saussurea acuminata	Compositae	2.65	3.73	6.38	5
Saussurea amara	Compositae	2.99	2.11	5.10	3
Saussurea firma	Compositae	0.02	0.28	0.30	1
Saussurea japonica	Compositae	1.59	1.55	3.14	3[a]
Saussurea recurvata	Compositae	0.68	0.08	0.76	1
Scorzonera sinensis	Compositae	2.62	2.14	4.76	6
Senecio kirilouii	compositae	3.24	3.02	6.26	35[a]
Serratula centauroides	Compositae	1.93	1.09	3.02	8
Sonchus arvensis	Compositae	3.24	3.02	6.26	35[a]
Stemmacantha uniflora	Compositae	3.24	3.02	6.26	35[a]
Synurus deltoides	Compositae	3.24	3.02	6.26	35[a]
Takeikadzuckia lomonossowii	Compositae	0.48	4.23	4.71	1
Taraxacum leucanthum	Compositae	3.32	0.41	3.72	3
Taraxacum ohwianum	Compositae	3.32	0.41	3.72	1[a]
Xanthium sibiricum	Compositae	0.01	1.64	1.64	3
Youngia tenuifolia	Compositae	3.24	3.02	6.26	35[a]
Convolvulus arvensis	Convolvulaceae	0.88	0.68	1.55	3
Hylotelephium erythrostictum	Crassulaceae	4.79	0.53	5.31	1
Orostachys fimbriatus	Crassulaceae	1.75	0.83	2.57	3
Orostachys malacophyllus	Crassulaceae	1.52	0.75	2.27	3
Sedum aizoon	Crassulaceae	2.68	0.70	3.38	3[a]
Dontostemon microanthus	Cruciferae	2.02	0.29	2.31	1[a]
Ptilotrichum tenuifolium	Cruciferae	2.02	0.29	2.31	3
Carex duriuscula	Cyperaceae	4.21	1.44	5.65	1[a]
Carex korshinskyi	Cyperaceae	4.21	1.44	5.65	13
Carex pedifermis	Cyperaceae	4.21	1.44	5.65	1[a]
Scabiosa tschiliensis	Dipsacaceae	2.68	1.59	4.27	4
Equisetum arvense	Equisetaceae	3.10	3.66	6.76	1
Gentiana dahurica	Gentianaceae	4.43	0.62	5.05	3
Gentiana macrocarpa	Gentianaceae	4.43	0.62	5.05	1[a]
Erodium stephanianum	Geraniaceae	3.15	7.73	10.88	2
Geranium eriostemon	Geraniaceae	11.92	2.59	14.51	3
Geranium pratensis	Geraniaceae	11.92	2.59	14.51	1[a]
Achnatherum sibiricum	Gramineae	2.97	1.78	4.75	17
Achnatherum splendens	Gramineae	1.37	0.16	1.52	3

(Cont'd from p.1027)

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Agropyron cristatum	Gramineae	1.30	1.06	2.36	12
Agropyron michnoi	Gramineae	1.86	2.30	4.16	6
Agrostis gigantea	Gramineae	2.01	0.90	2.91	1[a]
Agrostis trinii	Gramineae	2.01	0.90	2.91	1
Alopecurus aequalis	Gramineae	1.69	1.84	3.53	19[a]
Bromus inermis	Gramineae	2.21	0.31	2.52	3
Calamagrostis epigeios	Gramineae	1.13	9.91	11.04	2
Calamagrostis macrolepis	Gramineae	1.13	9.91	11.04	1[a]
Chloris virgata	Gramineae	1.69	1.84	3.53	19[a]
Cleistogenes squarrosa	Gramineae	1.28	3.22	4.50	15
Digitaria ischaemum	Gramineae	1.69	1.84	3.53	19[a]
Echinochloa crusgalli	Gramineae	1.69	1.84	3.53	19[a]
Elymus nutans	Gramineae	1.49	2.51	4.01	1
Elymus sibiricus	Gramineae	1.49	2.51	4.01	1[a]
Eragrostis minor	Gramineae	1.69	1.84	3.53	19[a]
Festuca dahurica	Gramineae	2.60	0.87	3.47	4
Festuca rubra	Gramineae	2.60	0.87	3.47	1[a]
Hierochloe glabra	Gramineae	1.69	1.84	3.53	19[a]
Hordeum roshevitzii	Gramineae	1.69	1.84	3.53	19[a]
Koeleria cristate	Gramineae	1.96	0.88	2.83	17
Leymus chinensis	Gramineae	1.87	0.89	2.76	19
Leymus secalinus	Gramineae	4.16	1.31	5.47	6
Melica scabrosa	Gramineae	1.69	1.84	3.53	19[a]
Pennisetum centrasiatieum	Gramineae	1.69	1.84	3.53	19[a]
Phragmites australis	Gramineae	0.42	3.81	4.23	1
Poa ochotensis	Gramineae	1.04	1.61	2.64	1[a]
Poa pratensis	Gramineae	1.04	1.61	2.64	4
Psammochloa villosa	Gramineae	1.18	0.14	1.32	1
Setaria glauca	Gramineae	2.14	1.08	3.22	1[a]
Setaria viridis	Gramineae	2.14	1.08	3.22	3
Stipa gobica	Gramineae	0.57	1.13	1.70	2[a]
Stipa baicalensis	Gramineae	0.14	1.47	1.61	3
Stipa grandis	Gramineae	1.00	0.79	1.79	17
Stipa krylovii	Gramineae	0.57	1.13	1.70	2[a]
Iris dichotoma	Iridaceae	0.08	0.72	0.81	1
Iris tenuifolia	Iridaceae	1.14	0.21	1.34	4
Iris ventricosa	Iridaceae	2.15	0.47	2.62	9
Leonurus sibiricus	Labiatae	7.41	0.83	8.24	3
Mentha haplocalyx	Labiatae	4.94	2.89	7.83	6[a]
Phlomis tuberosa	Labiatae	4.94	2.89	7.83	6[a]
Schizonepeta multifida	Labiatae	7.79	11.59	19.38	7
Scutellaria baicalensis	Labiatae	3.22	0.57	3.79	1
Scutellaria ikonnikovii	Labiatae	1.19	1.40	2.59	1
Scutellaria scordifolia	Labiatae	3.17	0.30	3.47	3
Scutellaria viscidula	Labiatae	2.53	0.75	3.28	3[a]
Stachys riederi	Labiatae	4.94	2.89	7.83	6[a]
Thymus serpyllum	Labiatae	3.44	1.53	4.97	5
Nepeta sibirica	Labiatae	10.83	1.15	11.99	1
Astragalus adsurgens	Leguminosae	1.22	2.68	3.90	4
Astragalus dahuricus	Leguminosae	2.10	7.25	9.35	3
Astragalus galactiters	Leguminosae	1.66	4.97	6.63	2[a]
Astragalus melilotoides	Leguminosae	1.66	4.97	6.63	2[a]
Astragalus mongolicus	Leguminosae	1.66	4.97	6.63	2[a]
Caragana microphylla	Leguminosae	2.93	0.93	3.85	10
Glycyrrhiza uralensis	Leguminosae	12.66	2.47	15.14	3
Gueldenstaedtia multiflora	Leguminosae	1.99	1.25	3.24	4
Hedysarum fruticosum	Leguminosae	3.65	1.24	4.89	3
Hedysarum gmelinii	Leguminosae	3.39	1.35	4.75	3

(Cont'd from p.1028)

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Hedysarum mongolicum	Leguminosae	3.52	1.30	4.82	2[a]
Lathyrus humilis	Leguminosae	4.42	1.88	6.30	23[a]
Lespedeza bicolor	Leguminosae	2.63	2.46	5.09	2[a]
Lespedeza davurica	Leguminosae	3.51	0.91	4.41	1
Lespedeza hedysaroides	Leguminosae	1.75	4.02	5.77	3
Medicago falcata	Leguminosae	3.52	0.45	3.97	3
Medicago lupulina	Leguminosae	7.08	2.86	9.94	3
Medicago sativa	Leguminosae	6.40	1.33	7.73	4
Melilotoides ruthenica	Leguminosae	3.72	1.36	5.08	5
Melilotus albus	Leguminosae	9.38	2.23	11.61	3
Melilotus dentatus	Leguminosae	5.32	1.09	6.41	3
Melilotus suaveolens	Leguminosae	6.45	1.25	7.70	7
Oxytropis filiformis	Leguminosae	3.04	0.80	3.84	2[a]
Oxytropis hirta	Leguminosae	3.04	0.80	3.84	2[a]
Oxytropis myriophylla	Leguminosae	3.31	0.51	3.82	1
Oxytropis ochrantha	Leguminosae	2.76	1.09	3.85	6
Sphaerophysa salsula	Leguminosae	4.42	1.88	6.30	23[a]
Thermopsis lanceolata	Leguminosae	3.49	2.26	5.75	5
Trifolium lupinaster	Leguminosae	1.94	1.23	3.16	2
Vicia amoena	Leguminosae	4.20	2.33	6.53	4
Vicia cracca	Leguminosae	4.20	2.33	6.53	1[a]
Vicia unijuga	Leguminosae	7.38	1.31	8.69	1
Allium anisopodium	Liliaceae	3.72	2.15	5.87	5[a]
Allium bidentatum	Liliaceae	1.97	1.17	3.13	2
Allium condensatum	Liliaceae	4.60	1.45	6.06	7
Allium ledebourianum	Liliaceae	3.72	2.15	5.87	5[a]
Allium ramosum	Liliaceae	7.07	3.39	10.46	10
Allium senescens	Liliaceae	3.00	1.08	4.08	6
Allium tenuissimum	Liliaceae	1.95	3.66	5.61	2
Anemarrhena asphodeloides	Liliaceae	0.93	1.48	2.41	6
Asparagus dauricus	Liliaceae	1.49	2.19	3.67	6
Asparagus schoberioides	Liliaceae	1.62	2.56	4.18	3
Hemerocallis minor	Liliaceae	0.30	0.05	0.35	1
Lilium concolor	Liliaceae	2.75	3.69	6.44	1[a]
Lilium pumilum	Liliaceae	2.75	3.69	6.44	1
Polygonatum humile	Liliaceae	0.32	2.88	3.20	2
Polygonatum odoratum	Liliaceae	0.57	3.61	4.18	2[a]
Polygonatum sibiricum	Liliaceae	0.82	4.34	5.17	3
Veratrum nigrum	Liliaceae	2.83	0.30	3.13	1
Linum perenne	Linaceae	0.40	2.81	3.21	4
Hippophae rhamnoides	Lythraceae	1.35	0.87	2.22	1
Malva verticillate	Malvaceae	6.16	3.31	9.47	3
Cannabis ruderalis	Moraceae	23.59	34.10	57.69	2
Spiranthes sinensis	Orchidaceae	0.14	1.28	1.42	1
Papaver nudicaule	Papaveraceae	0.87	0.09	0.96	1
Plantago asiatica	Plantaginaceae	2.98	0.83	3.81	1
Plantago depressa	Plantaginaceae	5.05	2.37	7.43	3
Plantago marritima	Plantaginaceae	4.01	1.60	5.61	2[a]
Limonium bicolor	Plumbaginaceae	0.37	0.04	0.41	1
Polygonum aviculare	Polygonaceae	3.30	1.16	4.46	3[a]
Polygonum convolvulus	Polygonaceae	3.91	1.59	5.50	6
Polygonum divaricatum	Polygonaceae	2.22	1.51	3.73	8
Polygonum laxmanni	Polygonaceae	3.30	1.16	4.46	3[a]
Polygonum sibiricum	Polygonaceae	3.77	0.40	4.17	1
Rumex acetosella	Polygonaceae	0.55	4.85	5.40	2[a]
Rumex hadroocarpus	Polygonaceae	0.55	4.86	5.41	2[a]
Rumex patientia	Polygonaceae	0.95	8.19	9.14	1
Rumex thyrsiflorus	Polygonaceae	0.15	1.51	1.66	1

(Cont'd from p.1029)

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Aconitum kusnezoffii	Ranunculaceae	1.23	10.33	11.56	1
Caltha palustris	Ranunculaceae	5.39	2.67	8.06	8[a]
Clematis hexapetala	Ranunculaceae	5.41	0.58	5.99	1
Delphinium grandiflorum	Ranunculaceae	5.87	0.92	6.80	6
Halerpestes ruthenica	Ranunculaceae	0.06	0.60	0.66	1
Paeonia lactiflora	Ranunculaceae	5.39	2.67	8.06	8[a]
Pulsatilla tunczaninovii	Ranunculaceae	1.37	1.27	2.64	4
Ranunculus gmelinii	Ranunculaceae	10.65	3.42	14.07	3
Ranunculus japonicus	Ranunculaceae	10.65	3.42	14.07	1[a]
Thalictrum petaloideum	Ranunculaceae	3.92	2.62	6.54	5
Thalictrum simplex	Ranunculaceae	14.61	1.59	16.20	1
Thalictrum squarrosum	Ranunculaceae	9.27	2.10	11.37	2[a]
Agrimonia pilosa	Rosaceae	3.98	2.42	6.40	13[a]
Chamaerhodos canescens	Rosaceae	3.98	2.42	6.40	13[a]
Cotoneaster integerrimus	Rosaceae	7.23	0.64	7.87	4
Cotoneaster melanocarpus	Rosaceae	4.63	1.62	6.25	2[a]
Cotoneaster mongolicus	Rosaceae	2.04	2.61	4.64	4
Crataegus sanguinea	Rosaceae	3.98	2.42	6.40	13[a]
Dracocephalum moldavicum	Rosaceae	3.98	2.42	6.40	13[a]
Malus baccata	Rosaceae	3.98	2.42	6.40	13[a]
Potentilla acaulis	Rosaceae	3.56	1.08	4.64	14
Potentilla anserina	Rosaceae	3.93	1.75	5.67	6
Potentilla betonicaefolia	Rosaceae	7.58	0.87	8.45	3
Potentilla bifurca	Rosaceae	2.88	1.70	4.58	8
Potentilla conferta	Rosaceae	3.86	1.82	5.68	7[a]
Potentilla longifolia	Rosaceae	1.57	0.17	1.74	1
Potentilla sericea	Rosaceae	3.86	1.82	5.68	7[a]
Potentilla supina	Rosaceae	3.86	1.82	5.68	7[a]
Potentilla tanacetifolia	Rosaceae	5.50	3.46	8.96	11
Potentilla verticillaris	Rosaceae	1.99	3.73	5.72	7
Prunus padus	Rosaceae	3.98	2.42	6.40	13[a]
Rosa acicularis	Rosaceae	3.98	2.42	6.40	13[a]
Rosa davurica	Rosaceae	3.98	2.42	6.40	13[a]
Rubus saxatilis	Rosaceae	3.98	2.42	6.40	13[a]
Sanguisorba officinalis	Rosaceae	6.21	1.14	7.35	6
Sibbaldia adpressa	Rosaceae	2.48	1.80	4.28	7
Spiraea aquilegifolia	Rosaceae	1.48	6.01	7.49	4
Spiraea pubescens	Rosaceae	5.33	6.58	11.92	4
Galium boreale	Rubiaceae	3.34	3.26	6.60	1[a]
Galium verum	Rubiaceae	3.34	3.26	6.60	10
Rubia cordifolia	Rubiaceae	3.34	3.26	6.60	1[a]
Haplophyllum dauricum	Rutaceae	9.68	2.88	12.56	1
Populus davidiana	Salicaceae	5.84	6.25	12.09	1[a]
Populus nigra	Salicaceae	5.84	6.25	12.09	3
Salix rosmarinifolia	Salicaceae	8.42	1.56	9.98	3
Salix microstachya	Salicaceae	8.42	1.56	9.98	1[a]
Parnassia palustris	Saxifragaceae	1.54	1.91	3.45	2
Cymbarria dahurica	Scrophulariaceae	5.05	0.72	5.76	4
Euphrasia hirtella	Scrophulariaceae	10.97	1.42	12.39	3
Linaria vulgaris	Scrophulariaceae	5.04	0.53	5.58	3
Omphalothrix longipes	Scrophulariaceae	5.78	0.87	6.65	5[a]
Pedicularis striata	Scrophulariaceae	1.91	1.01	2.91	1
Veronica incana	Scrophulariaceae	5.95	0.69	6.63	1
Veronicastrum sibirica	Scrophulariaceae	5.78	0.87	6.65	5[a]
Hyoscyamus niger	Solanaceae	0.61	0.39	1.00	1
Stellera chamaejasme	Thymelaeaceae	7.91	1.40	9.31	8
Ulmus macrocarpa	Ulmaceae	0.80	0.13	0.93	1
Antriscus sylvestris	Umbelliferae	2.56	2.54	5.10	4[a]

(Cont'd from p.1030)

Genus species	Family	Isoprene	Monoterpenes	Iso. + mono.	No. of specimens sampled
		μg Cg (dry leaf wt)$^{-1}$h^{-1}			
Bupleurm bicaule	Umbelliferae	1.22	1.93	3.15	12
Bupleurm scorzonerifolium	Umbelliferae	4.21	0.84	5.05	3
Cicuta virosa	Umbelliferae	2.56	2.54	5.10	4[a]
Ferula bungeana	Umbelliferae	2.56	2.54	5.10	4[a]
Saposhnikovia divaricata	Umbelliferae	2.50	1.18	3.68	11
Sphallerocarpus gracilis	Umbelliferae	2.50	1.18	3.68	1[a]
Carum carvi	Umbelliferae	2.30	6.22	8.52	3
Urtica cannabina	Urticaceae	1.16	0.22	1.38	2
Patrinia rupestris	Valerianaceae	2.62	0.22	2.84	1

Notes: Emission rate, expressed as μg C g(dry leaf wt)$^{-1}$ h^{-1}, corrected to a standard temperature (30℃) and standard PAR flux (1000 μmol/(m^2·s); a. indicates the emission rates are assigned from other species or genera

Many genera are notably uniform of low, moderate, or high emission categorizations, for example, *Adenophora*, *Astragalus*, *Hedysarum*, *Melilotus*, *Agropyron*, *Vicia*, *Allium*, *Asparagus*, and *Spiraea*, containing species with moderate isoprene and monoterpene emissions. Moreover, *Orstachys* contains species with moderate isoprene emissions and low monoterpene emissions; *Ploygonatum* and *Rumex* contain species with low isoprene emissions and moderate monoterpene emissions.

Genera found to have moderate isoprene emission, included *Silene*, *Chenopodium*, *Achnatherum*, *Leymus*, *Stipa*, *Scutellaria*, *Lespedeza*, *Plantago*, *Medicago*, *Oxytropis*, *Polygonum*, *Cotoneaster*, *Potentilla*, *Bupleurm*, however, have monoterpene emissions ranged from low to moderate. Moreover, some genera have relatively consistent monoterpene emissions but their isoprene emissions change from low to moderate, such as *Leontepodium*, *Iris* and *Thalictrum*.

Species measured of some genera are dissimilar in quantity of emissions, including *Achillea*, *Ligularia* and *Saussurea*. The most troublesome genus for VOCs inventories in grassland vegetation of Inner Mongolia in terms of range and variability of emission is *Achillea*. In *Achillea* genus, two species (*A. frigida* and *A. tanacetifolia*) have high isoprene emission, others species moderate. Furthermore, three species(*A. gmelinii*, *A. scoparia* and *A. sieversiana*) have high monoterpene emission, and other species range from low to moderate. Totally, based above discussion, most of genera have the consistent feature of their emission behavior, especially for isoprene emission.

2.3 VOCs emissions within plant families

Within the *Campanulaceae* family, all of the three species measured have moderate isoprene and monoterpenes. The *Rosaceae* family is similar to the *Campanulaceae* in emission profile, although three of thirteen have low-emitting monoterpene. Based on this limited samples, the two families appear to moderate-emitting species. The *Crassulaceae* contains plants with medium isoprene emission and low monoterpene emission. For the *Gramineae*, *Iridaceae*, *Liliaceae*, and *Polygonaceae* families, isoprene emissions and monoterpene emission range from low to medium among genera.

Several families, such as *Chenopodiaceae*, *Compositae*, *Labiatae*, *Leguminosae*, *Ranunculaceae* and *Scrophulariaceae*, contain species less homogeneous in emission behavior than the families discussed above. Emission rate of plants in these families range from low to high. So it would not be surprising to find another species within those families with measurable high emission rate.

Therefore, genera represent a more certain basis for inferring emission of VOCs for unmeasured plant species than do families, and are useful to inferring VOCs inventory in grassland vegetation. However, generalization might also be possible for some familes, in which genera and their species appear to be uniform in emission behavior.

3 Discussion

Basing the emissions measured, most of vegetation in temperate grassland vegetation have low or moderate VOCs emission rate, except some of *Achillea* plants. Moreover, many genera and some families have the consistent feature of their VOCs emission, especially for isoprene, which provide the basic premise of taxonomic methodology to develop VOCs emission inventories for grassland vegetation. The taxonomic methodology has already been used to estimate VOCs forest vegetation and savanna vegetation(Benjamin, 1996; 1997; Csiky, 1999; Karlik, 2002; 2003). Then, we introduce the taxonomic relationship into developing VOCs emission inventory of grassland vegetation. The experiments have further test the feasibility of taxonomic methodology for grassland vegetation, although there are a few breakthroughs on methodology herself. Compared with some developed countries, relatively few plants of VOCs have been investigated in the past decade or two in China(Mu, 1999; Li, 2001; Klinger, 2002; Wang, 2002; 2003). Therefore, taxonomic approach may be applicable to gain emission inventory in China, where plant species in natural landscapes are very rich but measurements have been not done for most of species.

Up to now, most of VOCs measurement mainly has focused on trees or woody shrubs, less is known of families with mostly herbaceous plants. Generally, a taxonomic method here has been used to assign VOCs emission rate measurements to unmeasured species in temperate grassland vegetation, but more detailed data are needed for additional plant families and genera to further develop and validate the taxonomic approach in the future. The PID instrument, due to its short response time and simplicity, may be useful for extensive VOCs emission surveys.

VOCs emitted from vegetation play important roles in tropospheric ozone formation, global tropospheric chemistry (Guenther, 1995; 2002). Biogenic emission inventory development will be helpful to estimate accurately the magnitude of VOCs emission in Inner Mongolia region. Furthermore, some researchers (Fesenfeld, 1992; Hansen, 1997; Lerdau, 1999; Clark, 2001; Guenther, 2002; Kesselmeier, 2002) recently have been mentioned that, those VOCs, as a loss of photosynthetic fixed carbon, should be potentially significant in analysis of carbon budgets to terrestrial ecosystem, and found the amount of carbon lost as VOCs emissions are significant relative or comparable to net ecosystem carbon fluxes in particular regions, while VOCs flux estimates are small in relation to total carbon emission or deposition. Therefore, how to use the emission inventory to answer or discuss the question, that is, whether is the contribution of biogenic VOCs to carbon cycles of mature grassland ecosystem important or not, will be our mainly interest in the future.

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References:

Benjamin M T, Sudol M, Bloch L *et al*., 1996. Low-emitting urban forests: A taxonomic methodology for assigning isoprene and monoterpene emission rates [J]. Atmos Environ, 30: 1437—1452.

Benjamin M T, Sudol M, Vorsatz D *et al*., 1997. A spatially and temporally resolved biogenic hydrocarbon emissions inventory for the California south coast air basin[J]. Atmos Environ, 31: 3087—3100.

Benjamin M T, Winer A M, 1998. Estimating the ozone-forming potential of urban trees and shrubs[J]. Atmos Environ, 32: 53—68.

Chen Z Z, 1988. Physiographic and climatological features of the Xilin River Basin[M]. Research Grassland Ecosystem. 3 ed. Bejing: Science Press. 13—22.

Clark D A, Brown S, Kicklighter D W *et al*., 2001. Net primary production in tropical forests: an evaluation and synthesis of existing field data[J]. Ecol Appl, 11: 371—384.

Csidy O, Seufert G, 1999. Terpenoid emissions of Mediterranean oaks and their relation to taxonomy[J]. Ecol Appl, 9: 1138—1146.

Fesenfeld F, Calvert J, Fall R *et al*., 1992. Emission of volatile organic compounds from vegetation and the implications for atmospheric chemistry[J]. Global Biogeochem Cycle, 6: 389—430.

Guenther A, Monson R K, Fall, R, 1991. Isoprene and monoterpene emission rate variability: observations with eucalyptus and emission rate algorithm development[J]. J Geophy Res, 96: 10799—10808

Guenther A B, Zimmerman P R, Harley P C, 1993. Isoprene and monoterpene emission rate variability: Model evaluations and sensitivity analyses[J]. J Geophy Res, 98: 12609—12617.

Guenther A, Hewitt C, Erickson D *et al*., 1995. A global model of natural volatile organic compound emissions[J]. J Geophy Res, 100: 8873—8892.

Guenther A, Otter L, Zimmerman P *et al*., 1996a. Biogenic hydrocarbon emissions from southern African savannas[J]. J Geophy Res, 101(D2): 25859—25865.

Guenther A, Zimmerman P, Klinger L *et al*., 1996b. Estimates of regional natural volatile organic compound fluxes from enclosure and ambient measurements[J]. J Geophy Res, 101(D1): 1345—1359.

Grenther A, 1997. Seasonal and spatial variations in the natural volatile organic compound emissions[J]. Ecol Appl, 7: 34—45.

Guenther A, 2002. The contribution of reactive carbon emissions from vegetation to the carbon balance of terrestrial ecosystem[J]. Chemosphere, 49: 837—844.

Hansen U, Eijk J V, Bertin N *et al*., 1997. Biogenic emissions and CO_2 gas exchange investigated on four Mediterranean shrubs[J]. Atmos Environ, 31: 157—166.

Harley P C, Fridd V, Greenberg J *et al*., 1998. Emission of 2-methyl-3-buten-2-ol by pines: a potentially large natural source of reactive carbon to the atmosphere[J]. J Geophy Res, 103: 25479—25486.

Karlik J F, Winer A M, 2001. Measured isoprene emission rates of plants in California landscapes: comparison to estimates from taxonomic relationships [J]. Atmos Environ, 35: 1123—1131.

Karlik J F, Mckay A H, Welch J M *et al*., 2002. A survey of California plant species with a portable VOC analyzer for biogenic emission inventory development[J]. Atmos Environ, 36: 5221—5230.

Karlik J F, Chung Y J, Winer A M, 2003. Biogenic emission inventory development: field assessment of the GAP vegetation database in California [J]. Phys Chem Earth(B), 28: 315—325.

Kesselmeier J, Schafer L, Ciccioli P *et al*., 1996. Emission of monoterpenes and isoprene from a Mediterranean oak species *Quercus iles* L. measured within the BEMA project[J]. Atmos Environ, 30: 1841—1850.

Kesselmeier J, Ciccioli P, Kuhn U *et al*., 2002. Volatile organic compound emissions in relation to plant carbon fixation and the terrestrial carbon budget [J]. Global Biogeochem Cycles, 16(4): (73) 1—9.

Klinger L F, Grenberg J, Guenther A *et al*., 1998. Patterns in volatile organic compound emissions along a savanna-rainforest gradient in central Africa[J]. J Geophy Res, 103: 1443—1454.

Klinger L F, Li Q J, Guenther A B *et al*., 2002. Assessment of volatile organic compound emissions from ecosystems of China[J]. J Geophy Res, 107 (ACH16): 1—21.

Juuti S, Arey J, Atkinson R, 1990. Monoterpene emission rates measurements from a Monterey pine[J]. J Geophy Res, 95: 7515—7519.

Lerdau M T, Throop H L, 1999. Isoprene emission and photosynthesis in a tropical forest canopy: implications for model development[J]. Ecol Appl, 9: 1109—1117.

Li L H, Han X G, Wang Q B *et al*., 2002. Correlation between plant biomass and soil respiration in a Leymus chinensis community in the Xilin River Basin of Inner Mongolia[J]. Acta Bot Sin, 44: 593—597.

Li Q J, Klinger L F, 2001. The correlation between the volatile organic emissions and the vegetation succession of the ecosystems in different climate zones of China[J]. Acta Bot Sin, 43: 1065—1071.

Mu Y J, Song W Z, Zhang X S *et al*., 1999. Study on emissions of isoprene from deciduous and broadleaf trees[J]. Environ Chem, 18: 21—27.

Scott K I, Benjamin M T, 2003. Development of a biogenic volatile organic compounds emission inventory for the SCOS97- NARSTO domain[J]. Atmos Environ, 37(Sup): S39—S49.

Wang X K, MU Y J, Ouyang Z Y *et al*., 2002. Study on emission of isoprene from major plants living in Tao-Hu basin[J]. Chin Bullet Bot, 19: 224—230.

Wang Z H, Bai Y H, Zhang S Y, 2003. A biogenic volatile compounds emission inventory for Beijing[J]. Atmos Environ, 37: 3771—3782.

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