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Biogenic hydrocarbon emissions from southern African savannas

Alex Guenther,¹ Luanne Otter,² Patrick Zimmerman,¹ Jim Greenberg,¹ Robert Scholes,³ and Mary Scholes²

Abstract. Biogenic nonmethane hydrocarbon (NMHC) emissions were investigated at two field sites in the Republic of South Africa that include five important southern African savanna landscapes. Tropical savannas are a globally important biome with a high potential for biogenic emissions but no NMHC emission measurements in these regions or in any part of Africa have been reported. Landscape average hydrocarbon emissions were estimated by characterizing plant species composition and foliar density at each site, identifying and characterizing NMHC emissions of the most abundant plant species, and identifying and characterizing NMHC emissions of plant species with the highest NMHC emission rates. A hand-held portable analyzer proved to be a useful tool for identifying plants with high emission rates. A branch enclosure system, with gas chromatography and flame ionization detector, was used to quantify isoprene and monoterpene emission rates. Emission rates were species-specific and several genera had both high and low emitters. At least some species with high emission rates were identified in most savanna types. High and low emitters were found on both nutrient-rich and nutrient-poor soils. Landscape average emission capacities for the five savanna types range from 0.6 to 9 mg C m⁻² h⁻¹ for isoprene and about 0.05 to 3 mg C m⁻² h⁻¹ for monoterpenes. The savanna emission rates predicted by existing global models are within the range estimated for these five savanna types.

1. Introduction

Nonmethane hydrocarbons (NMHCs) are released into the atmosphere from surface sources and influence regional photochemical oxidant formation and acid deposition. Guenther *et al.* [1995] estimate that vegetation is the source of over 90% of all NMHCs in the global atmosphere. Other sources include organic matter decomposition [Zimmerman, 1979], oceans [Plass-Duelmer *et al.*, 1993], biomass burning [Greenberg *et al.*, 1984], fossil fuel burning, solvent use, and chemical manufacturing [Middleton *et al.*, 1990].

Improved estimates of NMHC emissions from vegetation are needed to accurately initialize global chemistry and transport models. Current estimates rely on a very limited database of NMHC emission rate measurements. Existing data demonstrate that there are large variations in emission rates for different plant species and thus for various landscapes. Most field investigations of natural NMHC emissions have been in North America and Europe [Guenther *et al.*, 1995]. Measurements have also been reported for Asia [Yokouchi and Ambe, 1984], South America [Zimmerman *et al.*, 1988], and Australia [Ayers and Gillett, 1988] but there are no measurements reported for Africa.

Guenther *et al.* [1995] estimated global NMHC emissions using the global ecosystem database developed by Olson [1992]. They found NMHC emissions data reported for 26 of the 57 global ecosystems in the Olson database. Tropical savannas are one of the ecosystems for which no NMHC emissions data were available. The high temperatures and radiation fluxes associated with tropical savannas make these regions a potentially large biogenic NMHC emissions source. Tropical savannas cover 65% of the land surface of Africa, 60% of Australia and 45% of South America [Huntley and Walker, 1982]. It is an important biome because of its potential in terms of grazing areas for livestock and crop production, and also because of the role of savannas in the global carbon cycle. The grazing and agricultural potential makes savannas susceptible to land use change. Climatic change, especially precipitation patterns, can also have a significant impact on these regions. In southern Africa the savanna biome covers 46% of all landscapes [Rutherford and Westfall, 1994]. The biome can be divided into two main types, namely the arid savannas with nutrient-rich soils and the moist, nutrient-poor savannas [Huntley, 1982]. The nutrient-rich savannas are dominated by trees of the genus *Acacia*, whereas the nutrient-poor sites are dominated by broad leaf species primarily from the families *Corsalpinaceae* and *Combretaceae* [Scholes, 1988].

The primary objective of this study was to develop a methodology for characterizing landscape average NMHC emissions and apply the method to a landscape where biogenic NMHC emissions have not been studied. Many of the landscapes where biogenic NMHC emission measurements are lacking are in regions where it is difficult and expensive to conduct field experiments. Thus, it is necessary to have emission characterization methods that require a minimum of

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field time and equipment. The four major components of the emission characterization method described in this paper include (1) characterizing plant species composition and foliar density at each site, (2) identifying and characterizing NMHC emissions of the most abundant plant species, (3) identifying and characterizing NMHC emissions of plant species with the highest NMHC emission rates, and (4) estimating landscape average NMHC emission rates. The emission characterization method is applied to two field sites in southern Africa that comprise five different tropical savanna landscapes.

2. Field Site Description

Biogenic hydrocarbon emissions were investigated at two locations in the Republic of South Africa (RSA). Field experiments were conducted in December 1992 at Ntoma in eastern RSA (latitude 24.1° S, longitude 31.3° E) and Nylsvley (latitude 24°39' S, longitude 28°42' E).

The Ntoma site is located within the Klaserie Game Reserve that covers an area of about 500 km². The total land surface in this region consists of about 30% *Colophospermum mopane* savanna, 50% *Combretum apiculatum* savanna, and 20% *Acacia nigrescens* savanna. Each of these landscapes has been described in detail by Scholes [1988]. *Colophospermum mopane* savanna has a tree foliar density of about 80 g m² consisting of about 72% *Colophospermum mopane*, 16% *C. apiculatum*, and 6% *Grewia bicolor*. Average tree foliar densities of about 76 g m² in *C. apiculatum* savannas are 53% *C. apiculatum*, 17% *Sclerocarya birrea*, and 13% *G. bicolor*. *Acacia nigrescens* savanna has a tree foliar density of about 66 g m² consisting of about 64% *A. nigrescens*, 11% *S. birrea*, and 10% *G. bicolor*. In each of these landscapes, three to four tree species contribute over 80% of the total tree foliar density. The foliar density of grasses in these savanna regions ranges from 30 to 200 g m² with values of 100 to 150 g m² typically observed.

The Nylsvley site covers an area of about 30 km² and contains about 80% *Burkea africana* savanna and 20% *Acacia tortilis* savanna [Scholes and Walker, 1993]. *Burkea africana* savannas have tree foliar densities of about 100 g m² that consist of about 40% *B. africana*, 29% *Ochna pulchra*, and 16% *Terminalia sericea*. *Acacia tortilis* savanna have much higher foliar densities, about 485 g m², and are comprised of about 71% *A. tortilis* and 29% *A. nilotica*.

3. Methods

Isoprene and monoterpene emission rates were estimated using two field-portable enclosure measurement systems. The first system, referred to here as the hand-held emissions screening (HES) system, was used to identify plant species with high total NMHC emission rates. The HES system provides an immediate qualitative measure of total NMHC emission rate. The second system, referred to here as the branch emission measurement (BEM) system, was used to quantify isoprene and monoterpene emission rates for plant species that either were dominant in a landscape or were identified as a high emitter by the HES system.

The HES system consists of a small (approximately 0.3 L) polyethylene bag enclosure connected by Teflon tubing to a total NMHC analyzer with a photoionization detector (Thermo Environmental Instruments, model 580B). The entire

HES system weighs less than 5 kg, is battery-operated, and can easily be operated by one person. The lower detection limit of the analyzer is NMHC species-specific but is typically around 400 µg m⁻³ for terpenoid compounds. A lower detection limit of about 0.5 µg g⁻¹ h⁻¹ can be expected with about 10 g of foliage in the enclosure and a 200-mL min⁻¹ flow rate. Water vapor in the sample air is often very high due to foliar transpiration and can be a significant interference for the HES system if it condenses in the detector. This problem can be minimized by conditioning the sample flow using a water vapor trap or by reducing the pressure or heating the detector.

The BEM system uses an approximately 14-L enclosure that consists of a rigid aluminum frame covered by a flexible Teflon bag. The enclosure is suspended from a tripod to minimize contact with the vegetation. Ambient air is pushed into the enclosure through Teflon tubing from a location selected to minimize background concentrations. Samples were stored in electropolished, stainless steel canisters and transported to Boulder, Colorado, for analysis. Foliar area and dry weight were determined for the enclosed branch so that emissions could be expressed on both a foliar area and dry foliar mass basis. Whole air samples were also collected in stainless steel canisters to characterize background NMHC concentrations in ambient air.

All ambient air samples and BEM enclosure air samples were analyzed by gas chromatography (GC) with cryogenic preconcentration using a flame ionization detector (HP5890) to quantify concentrations and by comparisons with mass spectrometry to identify compounds [Greenberg et al., 1995]. This system has a lower detection limit of about 5 ppt C.

Leaf temperature, enclosure temperature, relative humidity, photosynthetically active radiation (PAR), and general sampling conditions were recorded for each BEM enclosure measurement. A LICOR 6200 with a 4-L chamber was used to measure photosynthesis, transpiration, and stomatal conductance from representative leaves of each tree. These measurements were recorded between 800 LST and 1200 LST. Xylem pressure potentials were measured just after sunrise at 730 LST with a Scholander pressure chamber. The average midday temperatures of around 36°C are typical of southern African savannas in summer (December).

4. Isoprene and Monoterpene Emission Rates

Guenther et al. [1995] have estimated that the global annual NMHC flux from vegetation is about 1 Gg (10¹⁵ g) of carbon and consists primarily of isoprene (44%) and monoterpenes (11%). Investigations of NMHC emission rates described in this section include NMHC screening of a large variety of plant species and quantitative estimates of isoprene and monoterpene emission rates for important plant species.

4.1. Vegetation Screening

Fifty plant species were screened with the HES system. Plants were considered to be high NMHC emitters if qualitative results with the HES system indicated that NMHC emissions exceeded about 0.5 µg C g⁻¹ h⁻¹. Fourteen (28%) of the species shown in Table 1 were classified as high emitters. Trees have been the focus of most NMHC emission studies but shrubs and grasses contribute significantly to the total LAI in most savanna landscapes and should be included in future investigations of biogenic NMHC. The percentage of the total

Table 1. Description of the Occurrence and Form of the Savanna Species and Results of HES Total NMHC Emission Screening

Family	Species	Growth Form	Soil Nutrient Status	Ntoma LAI, %	Nylsvley LAI, %	Total NMHC Emission
Mimosoideae	<i>Acacia caffra</i>	Tree	Fertile	< 1	< 1	Low
Mimosoideae	<i>A. karroo</i>	Tree	Fertile	< 1	< 1	Low
Mimosoideae	<i>A. mellifera</i>	Tree	Fertile	< 1	< 1	High
Mimosoideae	<i>A. nigrescens</i>	Tree	Fertile	17	< 1	High
Mimosoideae	<i>A. nilotica</i>	Tree	Fertile	< 1	4	Low
Mimosoideae	<i>A. tortilis</i>	Tree	Fertile	< 1	7	High
Caesalpinioideae	<i>Bauhinia galpinii</i>	Shrub	Infertile	< 1	< 1	Low
Capparaceae	<i>Boscia albitrunca</i>	Tree	Fertile	4	< 1	Low
Caesalpinioideae	<i>Burkea africana</i>	Tree	Infertile	< 1	32	High
Apocynaceae	<i>Carissa bispilowsa</i>	Shrub	Fertile	< 1	< 1	Low
Caesalpinioideae	<i>Cassia abbreviata</i>	Shrub	Infertile	< 1	< 1	Low
Celastraceae	<i>Cassine transvaalensis</i>	S/T ^a	Fertile	< 1	< 1	Low
Vitaceae	<i>Cissus cornifolia</i>	Shrub	F/IF ^b	2	< 1	Low
Caesalpinioideae	<i>Colophospermum mopane</i>	Tree	F/IF	18	< 1	High
Combretaceae	<i>Combretum apiculatum</i>	Tree	Infertile	32	5	Low
Combretaceae	<i>C. heteroense</i>	Tree	Infertile	< 1	< 1	Low
Combretaceae	<i>C. imberbe</i>	Tree	Infertile	2	< 1	Low
Combretaceae	<i>C. molle</i>	Tree	Infertile	< 1	< 1	Low
Combretaceae	<i>C. zeyherii</i>	Tree	Infertile	< 1	2	Low
Mimosoideae	<i>Dichrostachys cinerea</i>	Tree	Fertile	< 1	< 1	Low
Ebenaceae	<i>Diospyros mespiliformis</i>	Tree	Fertile	< 1	< 1	Low
Apocynaceae	<i>Diplorynchus condylocarpon</i>	S/T	Infertile	< 1	< 1	High
Sterculiaceae	<i>Dombeya rotundifolia</i>	Tree	F/IF	< 1	< 1	Low
Mimosoideae	<i>Elephantorrhiza burkei</i>	Shrub	Infertile	< 1	< 1	Low
Papilionoideae	<i>Erythrina lysistemon</i>	Tree	Infertile	< 1	< 1	Low
Ebenaceae	<i>Euclea natalensis</i>	S/T	Infertile	< 1	< 1	Low
Ebenaceae	<i>E. undulata</i>	Shrub	Infertile	< 1	< 1	Low
Rubiaceae	<i>Gardenia volkensii</i>	Tree	Infertile	< 1	< 1	Low
Tiliaceae	<i>Grewia flavescens</i>	Shrub	F/IF	11	5	High
Flacourtiaceae	<i>Kiggelaria africana</i>	Tree	Fertile	< 1	< 1	Low
Anacardiaceae	<i>Lannea discolor</i>	Tree	Infertile	< 1	< 1	Low
Anacardiaceae	<i>L. stuhlmanni</i>	Tree	Infertile	< 1	< 1	Low
Papilionoideae	<i>Lonchocarpus capassa</i>	Tree	Infertile	< 1	< 1	Low
Celastraceae	<i>Maytenus heterophylla</i>	S/T	F/IF	< 1	< 1	Low
Ochnaceae	<i>Ochna pulchra</i>	Tree	Infertile	< 1	32	High
Anacardiaceae	<i>Ozoroa paniculosa</i>	Tree	Infertile	< 1	< 1	Low
Caesalpinioideae	<i>Peltophorum africanum</i>	Tree	Infertile	< 1	< 1	High
Graminae	<i>Phragmites mauritianum</i>	Reed	wetland	< 1	< 1	High
Anacardiaceae	<i>Rhus leptodictya</i>	S/T	F/IF	< 1	< 1	High
Anacardiaceae	<i>R. pyroides</i>	S/T	Infertile	< 1	< 1	Low
Caesalpinioideae	<i>Schotia brachypetala</i>	Tree	Fertile	< 1	< 1	Low
Anacardiaceae	<i>Sclerocarya birrea</i>	Tree	Infertile	8	2	Low
Euphorbiaceae	<i>Securinea virosa</i>	S/T	Infertile	< 1	< 1	High
Loganiaceae	<i>Strychnos pungens</i>	Tree	Infertile	< 1	< 1	Low
Combretaceae	<i>Terminalia prunoides</i>	Tree	Infertile	< 1	< 1	High
Combretaceae	<i>T. sericea</i>	Tree	Infertile	< 1	9	High
Ulmaceae	<i>Trema orientalis</i>	S/T	Infertile	< 1	< 1	Low
Meliaceae	<i>Trichilia emetica</i>	Tree	Fertile	< 1	< 1	Low
Verbenaceae	<i>Vitex rehmanni</i>	Shrub	Infertile	< 1	< 1	Low
Rhamnaceae	<i>Ziziphus mucronata</i>	Tree	F/IF	< 1	< 1	Low

The status of the soil in which they are found in the field is also indicated. NMHC is nonmethane hydrocarbon and HVS is hand-held NMHC screening system.

^aShrub and tree.

^bFertile and infertile.

LAI contributed by tree and shrub species at each of the two field sites is shown in Table 1. Only nine species contribute more than 5% of the LAI of woody species in either of the two areas. Seven of these dominant species were identified as high emitters by the HES system.

Negligible NMHC emissions were observed for all of the *Combretum* spp., *Lannea* spp., and *Euclea* spp. tested in the study areas, but the genera *Acacia* and *Rhus* each included both high and low emitters. *Acacia caffra*, *A. karroo*, *A. nilotica*, and *Rhus pyroides* were identified as low emitters, whereas *A. mellifera*, *A. nigrescens*, *A. tortilis*, and *Rhus leptodictya* were high emitters. These results indicate that emissions are species-specific and all important species in a genus should be investigated.

High NMHC emissions were observed for 23% of the species from nutrient-rich and 25% from nutrient-poor soils. All of the *Acacia* species are found on nutrient-rich soils yet three species emit hydrocarbons and three species do not. *A. mellifera*, *A. nigrescens*, and *A. tortilis* on nutrient-rich soils were classified as high emitters, as were *Burkea africana* and *Ochna pulchra* which grow on nutrient-poor soils. *Colophospermum mopane*, *Rhus leptodictya*, and *Grewia flavescens* are species which can be found on both nutrient-rich and nutrient-poor soils and they all emit hydrocarbons. NMHC emissions can thus occur from a species, regardless of the soil nutrient availability.

The qualitative HES measurements and the quantitative BEM measurements are compared in Table 2. The HES results indicated that 11 of the 14 species have significant total NMHC emission rates. This result is validated by the BEM measurements. This finding demonstrates that the HES system is a valuable tool for identifying plant species with high NMHC emission rates.

4.2. Emission Rate Measurements

Emission rates for the 14 plant species sampled with the BEM system are shown in Table 2. *C. molle*, *C. apiculatum*, and *Sclerocarya birrea* emitted negligible ($< 0.5 \mu\text{g g}^{-1} \text{hr}^{-1}$) amounts of isoprene and monoterpenes. Only isoprene was emitted from *B. africana* and *O. pulchra*. Five species emitted only monoterpenes including *A. tortilis*, *C. mopane*, *G. flavescens*, *T. prunoides*, and *T. sericea*. The remaining four species emitted both isoprene and monoterpenes: *A. nigrescens*, *Phragmites mauritianum*, *R. leptodictya*, and *Securinega virosa*. In order to use these measurements to initialize emission models, the emission capacity at a leaf temperature of 30°C and PAR of 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was estimated using the temperature and PAR dependent emission algorithms of Guenther et al. [1993]. Guenther et al. [1994] reviewed field measurements of NMHC emissions from North American plant species and considered plants to be high emitters of isoprene if branch-level isoprene emissions were around $40 \pm 20 \mu\text{g g}^{-1} \text{hr}^{-1}$. Six of the species listed in Table 2 have isoprene emission rates ranging from 32 to 110 $\mu\text{g g}^{-1} \text{hr}^{-1}$, including four that fall within the range of $40 \pm 20 \mu\text{g g}^{-1} \text{hr}^{-1}$ and two species with higher rates (81 and 110 $\mu\text{g g}^{-1} \text{hr}^{-1}$).

Eight different monoterpenes were observed in enclosure air samples including α -pinene, β -pinene, camphene, myrcene, carene, cymene, d-limonene, and terpinolene. Only α -pinene, β -pinene, carene, myrcene and terpinolene were a major portion of the emission rate from the eight plants with significant monoterpene emission rates.

Guenther et al. [1994] considered North American plant species to be high total monoterpene emitters if emissions were about $3 \pm 1.5 \mu\text{g C g}^{-1} \text{hr}^{-1}$. The 14 African savanna plant species included five with emission rates $< 0.5 \mu\text{g C g}^{-1} \text{hr}^{-1}$, five with rates ranging from 0.5 to 1.3 $\mu\text{g C g}^{-1} \text{hr}^{-1}$, and three

Table 2. Isoprene and Monoterpene Emission Rate Capacities Estimated With the BEM System and Total NMHC Emission Capacity Determined Using the HES System

Species	Isoprene, ^a $\mu\text{g g}^{-1} \text{h}^{-1}$	Monoterpene, ^a $\mu\text{g g}^{-1} \text{h}^{-1}$	Total NMHC, ^b Emissions	Specific Leaf Area, $\text{cm}^2 \text{g}^{-1}$
<i>Acacia nigrescens</i>	110	0.7	High	174
<i>Acacia tortilis</i>	< 0.5	8.8	High	64
<i>Burkea africana</i>	36	< 0.5	High	123
<i>Colophospermum mopane</i>	< 0.5	52 ^c	High	114
<i>Combretum apiculatum</i>	< 0.5	< 0.5	Low	131
<i>Combretum molle</i>	< 0.5	< 0.5	Low	111
<i>Grewia flavescens</i>	< 0.5	0.5	High	139
<i>Ochna pulchra</i>	32	< 0.5	High	171
<i>Phragmites mauritianum</i>	35	0.6	High	51
<i>Rhus leptodictya</i>	54	1.1	High	130
<i>Sclerocarya birrea</i>	< 0.5	< 0.5	Low	101
<i>Securinega virosa</i>	81	4.7	High	217
<i>Terminalia prunoides</i>	< 0.5	3.9	High	163
<i>Terminalia sericea</i>	< 0.5	1.3	High	90

^aEmission rate capacities, representative of a leaf temperature of 30°C and PAR of 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$, measured with the BEM system.

^bTotal NMHC emissions measured with the HES system.

^cMay be overestimated due to disturbance of secretory cells.

with rates between 3.9 and 8.8 $\mu\text{g C g}^{-1} \text{ hr}^{-1}$. Much higher monoterpene emission rate capacities were estimated for *C. mopane* (52 $\mu\text{g g}^{-1} \text{ hr}^{-1}$). There are at least two possible explanations for these high rates. Some plants, such as *Quercus ilex*, produce and release monoterpenes at rates of tens of $\mu\text{g g}^{-1} \text{ hr}^{-1}$ [Kesselmeier et al., 1996]. The monoterpenes are not stored in the plant and the high emission is not a result of disturbances during the enclosure measurement. Other plants store monoterpenes externally in specialized secretory cells or internally to the plant in resin ducts [Tingey et al., 1991]. These plants have relatively low monoterpene emission rates under natural conditions but enclosure measurements are susceptible to extreme overestimation when stored monoterpenes are disturbed by an enclosure. Additional measurements are required to determine if the high rates observed for *C. mopane* are representative of undisturbed conditions.

5. Landscape Average Emission Rates

Surface emission models are essential for incorporating the impact of emissions into regional and global atmospheric chemistry models. The estimated emission rates can be used to assess potential changes in atmospheric chemical constituents. Early estimates of global biogenic NMHC emission rates used a single emission factor to represent all terrestrial landscapes [Zimmerman, 1979]. Recent efforts have resulted in global models with high resolution ($0.5^\circ \times 0.5^\circ$ latitude/longitude) that can generate hourly average emission estimates [Guenther et al., 1995]. The accuracy of these estimates in most regions is severely limited by the emissions data used to develop these models. In this section NMHC emissions for southern African savannas are estimated

based on the data described above and compared to the estimates of Guenther et al. [1995].

The two field sites comprise a total of five distinct landscapes: *C. mopane* savanna (CM), *C. apiculatum* savanna (CA), *A. nigrescens* savanna (AN), *Burkea africana* savanna (BA), and *A. tortilis* savanna (AT). Landscape average emission capacities were determined for each of the five landscapes using the species composition data in Table 1 and the emission capacities for species listed in Table 2. The emission capacities for grasses (5 $\mu\text{g C g}^{-1} \text{ hr}^{-1}$ for isoprene and 0.2 $\mu\text{g C g}^{-1} \text{ hr}^{-1}$ for monoterpenes) and for woody plants (16 $\mu\text{g C g}^{-1} \text{ hr}^{-1}$ for isoprene and 0.8 $\mu\text{g C g}^{-1} \text{ hr}^{-1}$ for monoterpenes) not listed in Table 2 are based on values reported by Guenther et al. [1995]. The resulting isoprene emission capacities shown in Table 3 range from about 0.6 $\text{mg C m}^{-2} \text{ h}^{-1}$ for CM to almost 9 $\text{mg C m}^{-2} \text{ h}^{-1}$ for AN. *A. nigrescens* is responsible for over 90% of the isoprene emission capacity from AN. *B. africana* contributes about half and *O. pulchra* about a third of the emission capacity of BA. Monoterpene emission capacities range from about 0.05 $\text{mg C m}^{-2} \text{ h}^{-1}$ for CA, AN and BA to about 3 $\text{mg C m}^{-2} \text{ h}^{-1}$ for CM and AT. If the very high monoterpene emission rate observed for *C. mopane* was caused by disturbances to secretory cells then the monoterpene emission capacity for CM would be around 0.2 $\text{mg C m}^{-2} \text{ h}^{-1}$. The single dominant species in both CM (*C. mopane*) and AT (*A. tortilis*) is estimated to be responsible for over 95% of the landscape average monoterpene emission capacity.

Table 4 contains estimates of foliar densities and emission capacity estimates for the Ntoma and Nylsvley field sites, based on the relative areas of each of the five savanna types in Table 3, and from the global model developed by Guenther et al. [1995]. The isoprene emission capacity, per gram of dry

Table 3. Contribution of Each Vegetation Species to the Area Average Isoprene and Monoterpene Emission Capacity of Five Savanna Types

Species	Isoprene, $\mu\text{g C m}^{-2} \text{ h}^{-1}$					Monoterpene, $\mu\text{g C m}^{-2} \text{ h}^{-1}$				
	CM	CA	AN	BA	AT	CM	CA	AN	BA	AT
<i>Acacia nigrescens</i>	<1	290	8130	<1	<1	<1	1	30	<1	<1
<i>Acacia tortilis</i>	<1	<1	<1	<1	60	<1	<1	<1	<1	3030
<i>Acacia nilotica</i>	<1	<1	<1	<1	2250	<1	<1	<1	<1	110
<i>Burkea africana</i>	<1	<1	<1	2520	<1	<1	<1	<1	4	<1
<i>Colophospermum mopane</i>	10	<1	<1	<1	<1	3000	<1	<1	<1	<1
<i>Combretum</i> spp.	2	7	1	1	<1	1	4	<1	1	<1
<i>Grewia flavescens</i>	4	9	8	4	<1	2	5	4	2	<1
<i>Ochna pulchra</i>	<1	<1	<1	1620	<1	<1	<1	<1	3	<1
<i>Sclerocarya birrea</i>	<1	2	1	<1	<1	<1	1	1	<1	<1
<i>Terminalia sericea</i>	<1	<1	<1	3	<1	<1	<1	<1	21	<1
Other woody spp.	77	164	63	88	<1	4	8	3	4	<1
Grass spp.	500	500	500	500	500	20	20	20	20	20
Total	593	975	8700	4740	2811	3020 ^a	40	58	55	3160

Savanna types include *Colophospermum mopane* savanna (CM), *Combretum apiculatum* savanna (CA), *Acacia nigrescens* savanna (AN), *Burkea africana* savanna (BA), and *Acacia tortilis* savanna (AT).

^aThis is an overestimate if disturbances to *C. mopane* secretory cells caused the very high emission rate observed for this species.

Table 4. Comparison of Isoprene and Monoterpene Emission Capacities and Foliar Densities Estimated for Savanna Areas

Savanna region	Foliar		Emission Capacity			
	Area, 10 ³ km ²	Density, g m ⁻²	Isoprene ^a	Terpene ^a	Isoprene ^b	Terpene ^b
Nylsvley field site	0.03	277	16	2.4	4.35	0.68
Ntoma field site	0.5	175	14	5.3	2.41	0.94
^c Southern African savannas	160	603	16	0.8	9.65	0.48
^c All savannas	6680	805	16	0.8	12.9	0.64

^aμg C g⁻¹h⁻¹;^bmg C m⁻²h⁻¹;^cEstimates reported by *Guenther et al.* [1995].

weight foliar mass, assumed by *Guenther et al.* [1995] is similar to the estimates calculated for each of the two field sites. The monoterpene emission capacity estimated for the Nylsvley site is a factor of 3 higher and the estimate for the Ntoma site is a factor of 6 higher than the value used by *Guenther et al.* [1995]. As discussed above, enclosure measurements of monoterpene emission capacities are susceptible to overestimation and further study is required to validate this result.

Estimates of foliar densities at the two field sites are 175 and 277 g dry weight m⁻² which are considerably less than the *Guenther et al.* [1995] estimates (603±181 g m⁻²) for southern African savannas. *Guenther et al.* [1995] estimate that the average foliar density of southern African savannas is about 75% of the average estimate for all savannas. The higher foliar density estimates and lower monoterpene emission capacity (per gram foliage) results in good agreement between the emission capacities (per square meter) estimated for the two field sites and by *Guenther et al.* [1995]. The good agreement between the per gram foliage isoprene emission capacities results in a factor of 2 to 4 higher per square meter isoprene emission capacity estimated by *Guenther et al.* [1995]. These results demonstrate the importance of accurate estimates of both foliar density and per gram foliage emission capacity.

6. Summary and Conclusions

Tropical savannas are one of many globally important biomes for which biogenic NMHC emissions data are lacking. The study described in this paper provides an initial characterization of NMHC emissions from southern African savannas and demonstrates a methodology that can be used to characterize emissions from other regions.

Species with high isoprene or monoterpene emissions were identified in most savanna types. Emission rates were species-specific and several genera were found to have both high and low emitters. High and low emitters were also found to occur on both nutrient-rich and nutrient-poor soils.

Landscape average emission capacities for the five savanna types range from 0.6 to 9 mg C m⁻² h⁻¹ for isoprene and about 0.05 to 3 mg C m⁻² h⁻¹ for monoterpenes. *Guenther et al.*

[1995] assumed that southern African savannas have an isoprene emission capacity of almost 10 mg C m⁻² h⁻¹ and a monoterpene emission capacity of about 0.5 mg C m⁻² h⁻¹. On a unit foliar mass basis, the isoprene emission capacity assumed by the global model agrees with field measurements while the monoterpene emission capacity is lower. The factor of 2 to 3 higher foliar density calculated by the global model, however, results in higher area average isoprene emissions estimated by the global model.

Tropical and subtropical savannas clearly have the potential to make a significant impact on global NMHC budgets. Additional studies are required to accurately estimate foliar densities, species composition, and emission capacities for these globally important landscapes.

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