Biogenic volatile organic compounds: The state of knowledge in southern Africa and the challenges for air quality management

M. Zunckel[a*], K. Chiloane[b], M. Sowden[a] and L. Otter[c]

EMISSIONS OF BIOGENIC VOLATILE ORGANIC compounds (BVOCs) on an urban and regional scale compare with those from anthropogenic sources, both in magnitude and in their role in atmospheric photochemistry and in the formation of ozone. Despite this, research on BVOC emissions in southern Africa has been limited to relatively few plant species in savannas, woodlands and shrublands. Extrapolation of these values provides an estimated annual emission of 80 Tg C for the subcontinent. Isoprene and monoterpene emissions vary widely according to plant species, temperature, foliar density and photosynthetically active radiation, and also diurnally and with season. Savanna trees such as *Acacia nigrescens* and *Burkea africana* are high isoprene emitters, and monoterpene emissions from *Colophospermum mopane* and *Acacia tortilis* are significant. By comparison, some tree species, such as *Combretum molle* and *Sclerocarya birrea,* emit neither compound. The legal prerequisite for holistic air quality management in South Africa, together with the dearth of information on BVOC emissions and an understanding of their role in the formation of ozone, poses significant challenges for policy-makers, air quality managers and scientists in southern Africa.

Introduction

Volatile organic compounds (VOCs) play an important role in the global carbon budget, in the radiation balance of the atmosphere, and in its regional oxidant composition.[1–4] The ratio of oxides of nitrogen (NO_x) and VOCs in the lower troposphere is a determinant in the production or consumption of ozone (O_3).[5,6] The oxidation of VOCs in the lower troposphere influences the hydroxyl radical ($OH^{\cdot}$) and leads to the formation of O_3, carbon monoxide (CO), peroxyacetyl nitrate (PAN) and secondary organic aerosols.[1,7]

Anthropogenic VOC emissions result from the combustion of fossil fuels in industrial processes and by motor vehicles, from the burning of biomass, and from waste water treatment, among others.[3,5,6] Natural sources of VOCs include wild fires and biogenic emissions (BVOCs) from plants and animals.[3,8] The primary role played by BVOCs in plant form and function is to protect plants against biotic and abiotic stresses or to attract pollinators.[9] It is, however, the direct and indirect effects of BVOC emissions on atmospheric chemistry and the magnitude of their contribution that make understanding the sources of these pollutants fundamentally important for air quality management and the modelling of atmospheric chemistry at global, regional and local scales. Approximately 90% of the annual global VOC emission budget of 1150 Tg C is attributed to biogenic sources mostly in the form of isoprene and monoterpenes, which contribute 44% and 11%, respectively.[3]

Data on BVOC emissions have been determined for several regions and for various landscapes, such as on isoprene from vegetation in Australia;[10] from plants in the Amazon;[11] various landscapes in the United States;[12–15] isoprene and monoterpenes in the Mediterranean region;[16] eucalyptus forests in Portugal;[17,18] in Asia;[19] and for different tropical landscapes in central Africa.[20–23] Relatively little is known about BVOC emission rates in southern Africa except where they have been determined for shrubland and savannas,[24–26] for Kalahari woodlands[25] and mopane woodlands.[27] More recently, mapping land cover and vegetation species has been used to estimate average monthly BVOC emissions for Africa south of the equator.[8]

In South Africa, the National Environmental Management: Air Quality Act (No. 39 of 2004) promotes a holistic philosophy of air quality management at national, regional and local scales. Elsewhere in the subcontinent, air quality policies are also adopting this approach. This management philosophy requires a comprehensive understanding of all source types and their respective contributions to air quality. In this regard, BVOCs have been shown to play an important role in the formation of O_3,[29,30] yet they are generally not included in air quality planning. BVOC emissions are species specific;[3] they can have very short lifetimes (minutes or hours) and are strongly influenced by environmental conditions such as temperature, cloud cover and humidity.[21,31] These factors imply that relatively high spatial and temporal resolution may be required for BVOC emissions in air quality management activities such as modelling on a local or regional scale.

Given the renewed emphasis on air quality management in South Africa and the region as a whole, this paper provides an overview of research on BVOC emissions conducted in southern Africa to date. In so doing, we identify gaps in current understanding of the role of these compounds and discuss the challenges that are faced by researchers and air quality managers in addressing them.

BVOC research in southern Africa

Total global BVOC emissions were modelled on a 0.5° by 0.5° longitude/latitude grid for 1990[3] using a global ecosystem database; non-methane hydrocarbon (NMHC) emissions were reported for 26 of the 57 global ecosystems. Natural VOCs were grouped into four categories, namely, isoprene, monoterpenes, other reactive VOCs (lifetime of less than a day under typical tropospheric conditions) and other VOCs (lifetime greater than a day). These studies concluded there was an even distribution between the northern and southern hemispheres, in the ratio of 51% and 49%, respectively, with 90% of the emissions in the southern hemisphere attributed to the region between the equator and 25°S. Because southern Africa falls within this zone, and no data had been collected here at the time, the need for BVOC emission data for the subcontinent was highlighted. Furthermore, at that stage information on BVOC emissions was not available for tropical savannas, which cover approximately 65% of Africa,[32] nor for semi-arid savannas, which cover approximately 46% of all landscapes in southern Africa.[33] Other important landscapes in the subcontinent for which no emissions data were available are the mopane, Kalahari and miombo woodlands. Without any corresponding measurements for comparison, the implication was that the estimated BVOC emissions for 1990 over Africa as a whole were likely to be inaccurate.

In 1992, the first measurements of BVOCs at two locations in South Africa

[a]CSIR Natural Resources and the Environment, P.O. Box 17001, Congella 4013, South Africa.
[b]CSIR Natural Resources and the Environment, P.O. Box 395, Pretoria 0001, South Africa.
[c]Climatology Research Group, University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa.
*Author for correspondence. E-mail: mzunckel@csir.co.za

were undertaken,[24] providing an initial record for southern African savannas. Field experiments were conducted in mid-summer at Ntoma and Nylsvlei (Fig. 1). Ntoma, which covers an area of approximately 500 km^2, is located in the Klaserie Game Reserve and consists of three savanna types, namely, *Colophospermum mopane* savanna (30%), *Combretum apiculatum* savanna (50%) and *Acacia nigrescens* savanna (20%). Nyslvlei covers approximately 30 km^2 and is represented by two landscape types, namely, *Burkea africana* savanna (80%) and *Acacia tortilis* savanna (20%). Initially, a screening study on 50 plant species in these areas was conducted using a hand-held photoionization detector (PID) system to distinguish between high and low hydrocarbon emitters.[24] Of these, 14 plant species were classified as high emitters, that is, emissions exceeding 0.5 μg C g^{-1} h^{-1}. Measurements of isoprene and monoterpenes were then conducted on the high emitters identified and on the dominant species in the area using branch enclosures. The results varied from negligible emitters of isoprene and monoterpenes (*Combretum molle, C. apiculatum* and *Sclerocarya birrea),* to species that emit isoprene only (*Burkea africana* and *Ochna pulchra*), or monoterpenes only (*Acacia tortilis, Colophospermum mopane, Grewia flavescens, Terminalia prunoides* and *T. sericea*), and those that emit both (*A. nigrescens, Phragmites mauritianum, Rhus leptodictya* and *Securinega virosa*) (Table 1).

The first estimates of regional average emissions for southern African savannas were made using species composition data at Ntoma and Nylsvlei and the measured contributions from both the dominant species and the high emitters.[24] The emission capacity of grasses was not measured and so published data were used.[3] Estimates of isoprene emission capacities ranged from 0.6 mg C m^{-2} h^{-1} for *Colophospermum mopane* savanna to 8.7 mg C m^{-2} h^{-1} for *Acacia nigrescens* savanna (Table 2). The corresponding values for monoterpenes ranged from 0.04 to about 0.06 mg C m^{-2} h^{-1} for *Combretum apiculatum, Burkea africana* and *Acacia nigrescens* savannas to more than 3 mg C m^{-2} h^{-1} for *Colophospermum mopane* and *Acacia tortilis* savannas (Table 2). For the plant species with significant monoterpene emission rates, σ-pinene, β-pinene, careen and myrcene were observed.

Later measurements of BVOC emissions in the subcontinent were conducted during campaigns[25–27] in savannas, Kalahari woodlands and shrublands, and mopane woodlands, as part of the SAFARI 2000 project.[34–36] Isoprene and monoterpene emissions were measured[25] at Nylsvlei (savanna) from the same species that were investigated in 1992[24] (Table 1). Differences in emission rates were attributed to seasonal and annual variation in environmental conditions, generic variability in the species and to different measurement techniques. This campaign augmented data on southern African *Acacia* species to include *A. nilotica, A. karroo* and *A. mellifera* (Table 1). Landscape isoprene emissions for *B. africana* and *A. tortilis* savannas were estimated at 5.5 and 0.7 mg C m^{-2} h^{-1}, respectively[25] (Table 2). The amount for *B. africana* compares closely with earlier estimates, [24] whereas the corresponding isoprene emission from *A. tortilis* savannas was much lower. This was because the updated *Acacia* emission capacities were included, which meant a landscape value of <0.5 μg g^{-1} h^{-1} was used[25] instead of the assumed measure for woody species of 16 μg g^{-1} h^{-1}.[24]

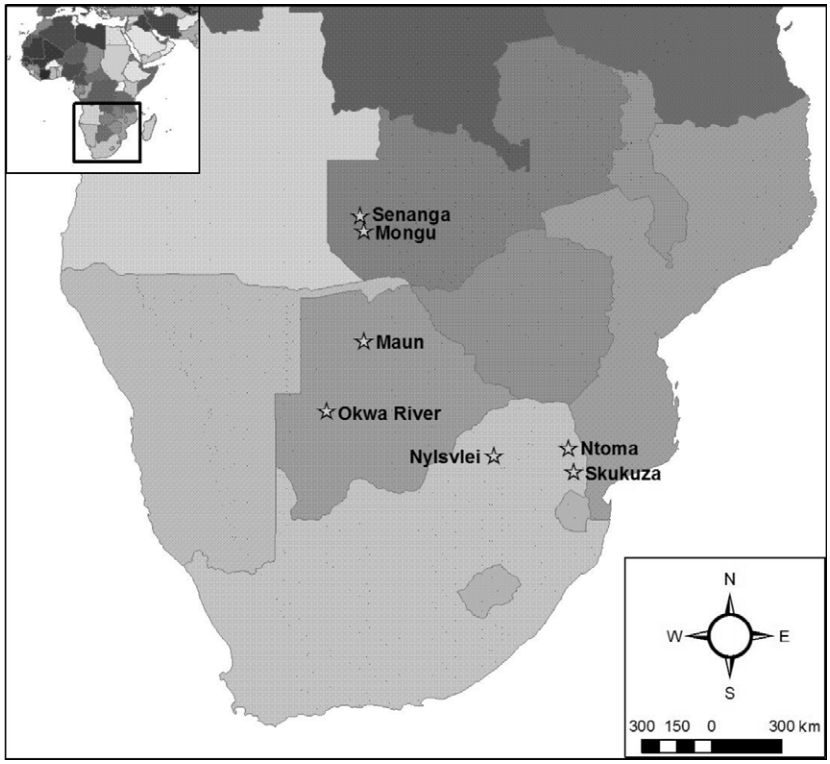

Fig. 1. Sites in southern Africa where BVOC leaf and landscape emissions have been measured.

BVOC emissions were characterized from Kalahari woodlands and shrublands and mopane woodlands by measuring 14 plant species at two sites in Zambia (Mongu and Senanga) and at two in Botswana (the Okwa River Crossing and at the Harry Oppenheimer Research Centre near Maun)[25] (Fig. 1). The two dominant species in the Kalahari woodlands, *Brachystegia spiciformis* and *Erythrophleum africanum,* proved to be non-emitters, but ten of the remaining species were identified as high isoprene emitters. *Baphia massaiensis,* an important food crop that is planted when Kalahari woodland is cleared, was also identified as a high isoprene emitter. This indicates that as land use is modified, and the species composition alters, landscape emission capacities can also change. High monoterpenes emissions of 9 and 16 μg g^{-1} h^{-1}, respectively, were measured for *Acacia erioloba* and *C. mopane.*

Landscape isoprene emissions for *B. africana* and *A. tortilis* savannas were estimated at 5.5 and 0.7 mg C m^{-2} h^{-1}, respectively[25] (Table 2). The value for *B. africana* compares closely with earlier estimates,[24] but the corresponding result for *A. tortilis* savannas was much lower than the earlier study. In calculating the landscape emission capacity, a measure of <0.5 μg g^{-1} h^{-1} was used[25] in contrast to the assumed value for woody species of 16 μg g^{-1} h^{-1}.[24]

More than 95% of the landscape surrounding the Harry Oppenheimer Research Centre (Fig. 1) comprises *C. mopane.* Terpenes generated by these mopane woodlands were measured in January and February 2001.[27] The corresponding emission rates from leaf enclosure measurements were approximately 42 μg g^{-1} h^{-1}, whereas landscape emission rates from relaxed eddy accumulation (REA) studies were 3 mg g^{-1} h^{-1}. The emissions consisted mostly of σ-pinene (62%)

and limonene (33%). These two methods are not directly comparable. Leaf enclosure measurements are specific to individual leaves, whereas REA represents the average emission from a vegetation canopy, that is, it involves numerous leaves and possibly different plant species. Furthermore, chemical reactions can take place as soon as the VOCs are emitted into the atmosphere, thereby reducing the BVOC concentrations above the canopy. The landscape emission capacity was calculated as 5.4 mg C m^{-2} h^{-1}, which is higher than that measured earlier for a different mopane landscape[24] and also recorded for the same landscape[25] (Table 2). The discrepancies are attributed to differences in method and estimates based on different leaf sample sizes. *Colophospermum mopane* was confirmed to be a strongly light-dependent source of monoterpenes, with the emissions increasing from sunrise to late afternoon.[27]

In February 2001, isoprene generation was measured for previously unstudied savannas in South Africa's Kruger National Park[26] (Fig. 1). At a site near Skukuza, two savannas were investigated, namely a broad-leaved wooded grassland dominated by *Combretum apiculatum* and *Sclerocarya birrea* and a fine-leaved wooded grassland dominated by *A. nilotica, A nigrescens* and *S. birrea.* In the nursery at Skukuza, 120 plant species that are found throughout the game reserve were screened for isoprene emissions using leaf and branch enclosures. Emissions from isoprene emitters and non-emitters ranged from >3 μg g^{-1} h^{-1} to <1.2 μg g^{-1} h^{-1}, respectively. Species with emission rates between these values were not unanimously assigned as emitters. Importantly, several genera with isoprene emitting and non-emitting species were confirmed;[26] for example, *A. nigrescens* is an emitter, whereas *A. nilotica* is not. Emission rates for a few species may therefore not be representative of a genus. REA was used to derive an isoprene emission capacity of 0.47 mg C m^{-2} h^{-1} at Skukuza,[26] which is lower than earlier measurement for similar savannas.[24] The discrepancy is attributed to variable emissions for *A. nigrescens* (Table 1).

The importance of measuring BVOC emissions rather than applying proxy data is underlined when considering the effects of seasonal and diurnal variations. For the savannas at Nylsvlei, the predicted monoterpene emissions ranged from a maximum of about 10 mg C m^{-2} day^{-1} in late summer to minima of <1 mg C m^{-2} day^{-1} in winter, whereas isoprene emissions peaked in late summer and reached 70 mg C m^{-2} day^{-1} or more, with minimum values in winter as low as those for monoterpenes.[25] Isoprene emissions depend on foliar density, temperature and PAR, hence the diurnal and seasonal variation. Monoterpene emissions depend on foliar density and temperature, but generally not on PAR.

Table 1. Isoprene and monoterpene emissions (µg g^{-1} h^{-1}) measured during various field campaigns in southern Africa.

Species	Isoprene	Monoterpene	Landscape	Reference
Acacia erioloba	0	9	Kalahari Woodlands	25
	0	8	Mopane woodland	27
Acacia karroo	<0.5	<0.5	Savanna	25
Acacia mellifera	5.7	<0.5	Savanna	25
Acacia nigrescens	110	0.7	Savanna	24
	4 to 20		Savanna	26
Acacia nilotica	<0.5	<0.5	Savanna	25
	BDL		Savanna	26
Acacia tortilis	<0.5	8.8	Savanna	24
	BDL		Savanna	26
Balanites maughamii	1.7		Savanna	26
Baphia massaiensis	97	0	Kalahari woodlands	25
Bauhinia petersiana	34	0	Kalahari woodlands	25
Biakiaea plurijuga	36	0	Kalahari woodlands	25
Brachystegia spiciformis	0	0	Kalahari woodlands	25
Burkea africana	36	<0.5	Savanna	24
	56.1	<0.5	Savanna	25
	62	0	Kalahari woodlands	25
Carissa edulis	BDL		Savanna	26
Colophospermum mopane	<0.5	52	Savanna	25
	0	16	Kalahari woodlands	25
	0	22	Mopane woodland	27
Combretum apiculatum	<0.5	<0.5	Savanna	24
	BDL		Savanna	26
Combertum molle	<0.5	<0.5	Savanna	24
Cryptosepalum exfoliatum	17	0	Kalahari woodlands	25
Dichrostachys cinerea	BDL		Savanna	26
Diallium engleranum	21	0	Kalahari woodlands	25
Diplorhynchus condylocarpon	25	0	Kalahari woodlands	25
Erythrophleum africanum	0	0	Kalahari woodlands	25
Euclea natalensis	BDL		Savanna	26
Grewia bicolor	BDL		Savanna	26
Grewia flavescens	<0.5	0.5	Savanna	24
	<0.5	<0.5	Savanna	25
	0	0	Mopane woodland	27
Grewia hexamita	BDL		Savanna	26
Guibourtia coleosperma	23	0	Kalahari woodlands	25
Julbernardia paniculata	34	0	Kalahari woodlands	25
Lannea schweinfurthii	BDL		Savanna	26
Lonchocarpus capassa	24.1		Savanna	26
Ochna oulchra	32	<0.5	Savanna	24
Peltophorum africanum	BDL		Savanna	26
Pterocarpus angolenis	44	0	Kalahari woodlands	25
Phragmites mauritianum	35	0.6	Savanna	24
Rhus leptodictya	54	1.1	Savanna	24
Sclerocarya birrea	<0.5	<0.5	Savanna	24
	BDL		Savanna	26
Schotia brachhypetala	BDL		Savanna	26
Securinega virosa	81	4.7	Savanna	24
Spirostachys africana	67.5		Savanna	26
Terminalia prunoides	<0.5	3.9	Savanna	24
Terminalia sericea	<0.5	1.3	Savanna	24
	<0.5	<0.5	Savanna	25
	BDL		Savanna	26
Ximenia americana	0	0	Mopane woodland	27
Ziziphus mucronata	BDL		Savanna	26

BDL, below detection limits

To estimate BVOC emissions from southern Africa and to improve on earlier estimates,[3] a comprehensive vegetation map was used for the continent south of the equator, consisting of 262 vegetation types.[8] Species-specific information combined the categories into 23 general land cover types. The average emissions

Table 2. Isoprene and monoterpene emission capacity (mg C m^{-2} h^{-1}) of various landscapes from field campaigns in southern Africa (adapted from Otter *et al.*[25]).

Landscape		Isoprene	Monoterpene	Reference
Savannas	*Acacia nigrescens*	8.7	0.06	24
	Acacia tortilis	0.7	3.0	25
	Burkea africana	5.5	0.05	25
	Colophospermum mopane	0.6	3.0	24
	Combertum apiculatum	1.0	0.04	24
		0.47		26
Kalahari woodlands	*Brachystegia erythrophleum*	3.6	2.0	25
	Brachystegia guibortia	8.2	0.1	25
	Colophospermum mopane	0.7	2.4	25
			5.4	27
Kalahari shrublands	*Acacia mellifera–Terminalia sericea*	0.70	0.20	25

for isoprene and monoterpenes was modelled for each land cover type based on leaf- and branch-level measurements obtained from various research campaigns.[20,23–27] Emissions data on important African plant genera from field measurements on other continents and in greenhouses augmented these. Isoprene estimates for approximately 400 African plant species were used, of which about 90 are also monoterpene emitters.[8] The emission data were combined with leaf area index, temperature and light data to calculate emission estimates for a representative winter and summer month.

An annual BVOC emission rate of 80 Tg C yr^{-1} was derived for southern Africa,[8] compared with 94.2 Tg C yr^{-1} in the first estimate.[3] The calculation of isoprene emissions is similar in the two studies, with 59 Tg C yr^{-1} estimated in the former and 56 Tg C yr^{-1} modelled in the later study. A large variation was found in isoprene emissions for the various land cover types, ranging from 23.4 g C m^{-2} yr^{-1} for woodlands dominated by *Diplorhynchus condylocarpon* to 3.2 g C m^{-2} yr^{-1} and less than 1 g C m^{-2} yr^{-1} for *Combretum* savannas.[8] The monoterpene emissions in this study were estimated to produce 7.2 Tg C yr^{-1} compared with 11.8 Tg C yr^{-1} in the earlier work.[3] This study[8] did improve, however, on the previous model in that it distinguished between light-dependent and non-light-dependent (or stored) monoterpenes emissions. Significant light-dependent monoterpene emissions (1769 Gg C m^{-2} yr^{-1}) and stored emissions (73 Gg C m^{-2} yr^{-1}) were derived from mopane veld, which includes shrubland, savannas and woodlands. This study shows that an understanding of species distribution and emission capacities improves the value of the emission model.

The modelling study provides the most comprehensive assessment of these emissions from southern Africa to date, despite an estimated uncertainty factor of between two and three.[8] Some uncertainty (less than 10%) comes from determining the percentage cover of each species in wooded landscape types compared to landscapes with dry vegetation (≈30%). The uncertainty associated with the variability in species-specific emission rates is estimated to be about 50%. Uncertainty also derives from the taxonomic approach used. In addition, the emissions model uses standard light and temperatures, which accounts for 69% of the diurnal variation. Although emission capacity varies seasonally, a single value is assigned for the year in the model. The uncertainty associated with the measurements and the model estimates is therefore poorly characterized—whereas individual component factors have a relatively low uncertainty, the uncertainty naturally increases when they are combined.

BVOCs and air quality management in southern Africa

A holistic approach to air quality management calls for a sound understanding of all pollutants and sources that affect the region in which the state of the atmosphere is to be managed. Ozone is an important pollutant that poses a risk to human health and to vegetation on a regional and local scale. It is not source specific, however, and its formation is dependent on precursor gases and sunlight.[2,7] Sources of O_3 precursors include NO_x and VOCs of anthropogenic origin such as industry, and motor vehicles, as well as BVOC emissions from vegetation. Precursors are typically dispersed from their source region, and ozone is commonly formed at some distance. This complicates the management of ozone, which is further compounded by a generally poor understanding of the natural sources of ozone precursors and the role that they play. The primary challenge that air quality management faces in southern Africa on a regional and local scale is to improve the understanding of these sources and their contribution to air quality.

In the studies described in this article, isoprene and monoterpene generation was measured for approximately 170 plant species in three southern African savannas, and in mopane and Kalahari woodlands. These results represent a tiny fraction of the approximately 24 000 plant species found in southern African.[37] Important exceptions are the fynbos species, agricultural and forestry crops, and urban trees and shrubs. A campaign to establish emission rates for all plant species is physically and economically daunting. Accounting for emissions that vary diurnally, with season and according to rainfall,[38] compound the problem.[25] Moreover, the collection of emissions data for additional species is not necessarily appropriate,[25] but it will allow for the quantification of the relationships between emissions and the factors that control them. Researchers need to find scientifically sound, but cost-effective ways to prioritize sampling at a species and landscape level to augment the data currently available to model BVOC emissions. One approach is to screen the species that constitute the 90% of the biomass to establish the high and low BVOC emitters and then refine the estimates for high emitters.

One challenge facing modellers of how BVOCs affect ozone production is to reduce the uncertainty in their models.[8] The BVOC emission maps for Africa south of the equator[8] can thus be used to direct future research, as the areas with high emissions, or no emission data, should be the priority regions for research. However, before models are validated, it is appropriate to include a land use map in the emission model. The existing model gives emissions for potential vegetation, which is far from reality. Combining the vegetation map used in this model[8] with an updated land use map will ensure the inclusion of agriculture, forestry and urban areas without losing the species composition data for the natural vegetation zones. Initially, emission estimates for many of the land use zones will need to be used because no BVOC information has been collected from agricultural or forestry species in the subcontinent. The emission data for the model can be improved by using either species or landscape emission data. Species-specific emission factors obtained for individual plants, and then for several plants to obtain an average for a particular species, can be very time consuming. This approach is useful for modelling in regions with low

species diversity, however, or in landscapes where the biodiversity is higher but the biomass is dominated by only a few species. In regions where the biodiversity is high, the landscape emission approach is more appropriate.

Another approach is to use landscape emissions because fewer measurements then need to be made across a region; however, BVOC generation over a landscape is complex because only two cases of such measurements have been made in our region, one at a savanna site in the Kruger National Park and one in mopane woodlands at Maun.[27] BVOC concentrations measured at the landscape level are low compared with branch or leaf records, due to complex chemical reactions and atmospheric movement. The transport of emissions from the leaves to the boundary layer is not only influenced by wind but also by the canopy structure. The size and number of leaves, and the openness and height of the canopy, all affect the air movement across a leaf and through the whole canopy layer. This in turn influences the amount and rate of BVOC emissions from the leaf and the entire canopy. Canopy structure also affects the distribution and concentration of other atmospheric gases in the boundary layer, which ultimately influences VOC reactions and thus concentration in the canopy layer. For example, NO_x and O_3 concentrations differ from the bottom to the top of a forest canopy and this affects the amount of BVOCs (emitted from leaves) reaching the atmosphere above the canopy.[39] In most cases, REA measurements are taken in landscapes where the canopy is relatively even, such as closed canopy forests. In southern Africa, however, the dominant vegetation types are savannas and woodlands, which have a more open canopy with trees interspersed in grasslands. This has major implications for wind speed, direction, velocity and turbulence in the boundary layer, and little is known about how this vegetation structure affects the overall landscape emission capacity. This is an instance where species emission capacities can be measured alongside landscape emissions to determine their mutual relationship. There is thus much research that can be done, specifically for southern African vegetation, to improve our understanding of landscape emissions and the interactions of BVOCs with other trace gases in the canopy layer.

None of the current air quality management plans for South Africa considers the potential effect of biogenic sources of VOCs. Such management activities are generally poorly resourced in South Africa in terms of personnel and funding. The focus therefore falls on managing primary pollution sources that are relatively easily identified and where the biggest returns with respect to air quality improvement can be made, namely, industrial emissions, those from vehicles, and the burning of domestic fuel. The inclusion of BVOCs in South African emissions inventories in the management of urban air quality poses several obstacles. The first is the lack of baseline data for urban vegetation and the practical and logistical complexities associated with augmenting these data. The second is the incorporation of photochemical dispersion models into air quality management systems that, with air quality monitoring, help to develop an understanding of the roles that the different precursor sources play in the production of ozone, photochemical smog and other secondary pollutants.

The Dynamic Air Pollution Prediction System (DAPPS) is the only South African example to date where BVOC generation has been included in an urban emissions inventory and modelling study (M. Sowden *et al.*, in prep.). In Cape Town, these emissions are of the same order as those from motor vehicles, and both exceed those from industry.[41] BVOCs in the West Midlands metropolitan area of the U.K. were shown to compare with anthropogenic VOC emissions.[41] In Barcelona, 34% of the total VOCs is attributed to vegetation and 51% to traffic; high O_3 concentrations also result from anthropogenic NO_x and biogenic VOC.[42] Biogenic emissions have also been included in air quality planning in the Houston–Galveston area of Texas.[43] In modelling the effects of increased urban tree cover on ozone concentrations, from Washington D.C. to Massachusetts in the United States, emissions from trees generally reduce ozone concentrations in the cities, but increase the average concentrations in the overall modelling domain.[41] It has been suggested that replacing urban trees with low VOC-emitting species could help to reduce ozone levels.[44]

Urbanization, forestation and deforestation, loss of biodiversity, and changing agricultural practices as a result of forces such as climate change or industrial expansion continually modify landscapes. As a result, the composition of landscape vegetation is continually changing, thereby affecting the nature of BVOC emissions. This results in changes in atmospheric chemistry and thus in air quality. Such changes in turn have implications for researchers and for the authorities with responsibility for air quality, whether with a regional or much smaller focus, or with medium- or long-term objectives.

Conclusion

On an urban and regional scale, BVOC emissions are recognized as being as important as other sources of VOCs due to their fundamental role in the chemistry of the lower troposphere. In southern Africa, however, understanding these emissions is limited; research has been conducted only in savannas, woodlands and shrublands. Plant-level emissions have been recorded on approximately 170 of southern Africa's nearly 24 000 plant species. Extrapolation of these results to landscapes and scaling-up for the subcontinent provides an estimate of 80 Tg C per annum from vegetation, with some landscapes (such as those featuring *Acacia nigrescens, Burkea africana* and *Colophospermum mopane*) being identified as strong emitters.

Hydrocarbons play a crucial role in the formation of atmospheric ozone, so an understanding of BVOC generation is important to any initiative to manage air quality. The dearth of information on these emissions at a plant species level therefore poses a challenge to both researchers and to those responsible for air quality. A most pressing requirement is the augmentation of existing data, in particular on these gaseous emissions from fynbos, urban trees, commercial forestry and agriculture. Understanding the factors that control emissions at the plant level is basic to extending models to a landscape and ultimately to a regional scale. In turn, these landscapes are being altered under the influence of urbanization, agricultural practices, and climate change. No air quality management plan in southern Africa currently takes BVOC emissions into account. Such planning is therefore fundamentally compromised until they are.

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