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LOW-EMITTING URBAN FORESTS: A TAXONOMIC METHODOLOGY FOR ASSIGNING ISOPRENE AND MONOTERPENE EMISSION RATES

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Abstract—Large-scale tree planting programs have been proposed, and are being implemented, as a means of reducing energy demand, mitigating urban heat islands, and improving air quality. However, many species of trees emit highly photochemically reactive hydrocarbons and the rates of such emissions can vary by four orders of magnitude, depending upon the tree species. Thus, planting of high-emitting trees species on a massive scale has the potential to adversely affect air quality rather than leading to improvement. However, the selection of low-emitting trees is difficult because emission rates have been experimentally determined for only a limited number of species. The present study describes a methodology for assigning biogenic emission rates based on taxonomic relationships. Using this methodology, direct emission measurements from 124 tree and shrub species found in the California South Coast Air Basin (SoCAB) are used to assign emission rates to 253 other species found in the SoCAB but for which there are no measured emission rates. The combined listing of 377 species is ranked according to total (isoprene and monoterpenes) biogenic emission rate on an hourly basis. Although the ranking of trees developed here is specific to Southern California, the methodology described can be applied to other geographic areas to assist in the planting of low-emitting urban forests.

Key word index: Biogenic hydrocarbons, isoprene, monoterpenes, biogenic emission rates, taxonomic methodology, urban forests.

INTRODUCTION

Widespread planting of trees and shrubs in urban areas improves air quality directly by shading buildings, thus reducing cooling demand and powerplant emissions of oxides of nitrogen (NO_x). Properly located trees and shrubs have been found to reduce air conditioning electricity use by as much as 50% (Parker, 1981). In addition, increasing the size of the urban forest provides for enhanced surface deposition area for removal of labile gaseous air pollutants such as ozone, peroxyacetylnitrate (PAN), and nitric acid (HNO_3), as well as fine particulates. As an example, it has been estimated that planting 500,000 trees in Tucson would reduce airborne particulates by 6500 t yr^{-1} (McPherson, 1991).

There are also a number of indirect benefits from large-scale tree planting programs. For example, increased evapotranspiration from additional trees decreases ambient air temperature, reducing cooling demand and hence powerplant emissions. Reduced air temperature also results in lower rates of emission of volatile organic compounds (VOCs) from liquid fuels (e.g. gasoline) employed in mobile sources, as well as solvents and coatings used in a wide range of stationary sources.

A number of cities throughout the world have implemented large-scale tree planting programs in an effort to reduce the "urban heat island effect" (Landsberg, 1981; Lowry, 1967). Average summer temperatures in Nanjing, China, dropped 3°C following the planting of 34 million trees in the late 1940s (EPA, 1992). In Stuttgart, Germany, fingers of open space extending into the city are being planted with trees to convey cool night air into downtown areas and to

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help reduce daytime temperatures (EPA, 1992). In the United States, the Sacramento Municipal Utility District, in cooperation with the Sacramento Tree Foundation, has planted more than 50,000 trees to date, with the goal of planting 500,000 new shade trees by the year 2000 (Ashizawa, 1992). Trees for Tucson/Global Releaf has proposed planting 500,000 desert-adapted trees throughout the city by 1996 as a means of conserving energy and improving environmental quality (McPherson, 1992). In the Los Angeles Basin, where average temperatures have increased 3°C since 1940 (EPA, 1992), there have been suggestions to plant as many as 5 million trees (Trees, 1993).

However, against the numerous benefits cited earlier, and the additional benefit of sequestering carbon dioxide, there is a potential air quality liability associated with the addition of large numbers of trees to polluted urban airsheds. Following initial recognition (Went, 1960; Rasmussen, 1972; Westberg and Rasmussen, 1972) that hydrocarbons are emitted by vegetation, it is now well established (Zimmerman, 1979a; Tingey *et al.*, 1979, 1980; Evans *et al.*, 1982; Lamb *et al.*, 1985, 1986, 1987, 1993; Winer *et al.*, 1983, 1989, 1992; Corchnoy *et al.*, 1992) that many species of vegetation, including coniferous and deciduous trees, emit volatile organic compounds (VOCs) which react with anthropogenic oxides of nitrogen (NO_x) in a complex series of photochemical reactions to produce ozone.

Prior to a seminal modeling study conducted by Chameides and co-workers (1988), it had been assumed that the effects of biogenic hydrocarbon emissions in major urban areas were minimal or negligible when compared to anthropogenic hydrocarbons. However, the high reactivity of biogenic hydrocarbons, estimated to be 2–3 times that of a weighted average of hydrocarbons from gasoline combustion (Carter, 1994), increases their relative contribution to the formation of ozone and other secondary pollutants. The Chameides *et al.* (1988) study determined that even if all anthropogenic hydrocarbon emissions were eliminated from the Atlanta atmosphere, the flux and high photochemical reactivity of biogenic hydrocarbons (as well as the presence of anthropogenic NO_x) were sufficient to make attainment of the National Ambient Air Quality Standard for ozone (0.12 ppmv) in Atlanta difficult, if not impossible.

Biogenic emission rates are species-specific, varying by as much as four orders of magnitude depending upon the plant species. This wide range of emission rates makes the selection of low-emitting tree and shrub species critical in polluted urban airsheds where large-scale tree planting programs are being considered. However, the selection of low-emitting tree and shrub species is difficult since emission rates have been experimentally measured for only a limited number of plant species and this situation is unlikely to change in the near future due to the magnitude of resources required to make such measurements. In order to obtain a ranking of candidate tree species by biogenic emission rate, it is therefore necessary to explore various methods for assigning rates to those species for which no experimental data are available.

In this paper we propose a taxonomic methodology which can be used to assign total hourly (isoprene and monoterpene) biogenic emission rates to tree and shrub species for which there are no measured emission rates. While explicitly identifying the uncertainties and limitations inherent in this method, we believe it can assist in the selection of tree and shrub species suitable for planting in polluted urban airsheds, and aid in the development of more reliable biogenic hydrocarbon emission inventories for airsheds containing these species, until such time as direct experimental measurement data become available.

BIOGENIC HYDROCARBONS

The concept that emissions from vegetation could have a negative impact on air quality was first proposed by Went (1960) to explain the "Blue Haze" that was known to occur in unpopulated, supposedly pristine, wooded areas during late summer afternoons. Recognition that these biogenic hydrocarbons might also be contributing to urban air pollution stimulated further research. Early work identified isoprene and various monoterpenes as the predominant chemical species emitted by vegetation (Rasmussen, 1972), but recent studies have identified more than 70 hydrocarbons, including isoprene, mono- and sesquiterpenes, and a substantial number of oxygenated organics, as being emitted from ornamental, agricultural and natural plant species (Isidorov *et al.*, 1985; Winer *et al.*, 1992). Over the past two decades, however, relatively few studies have directly measured the emission rates of hydrocarbons from vegetation. The majority of those which have been conducted to date, and the measurement techniques employed, are summarized in Table 1.

The mechanisms governing the synthesis of biogenic hydrocarbons, such as isoprene and the monoterpenes, form the basis for the development of a methodology for the taxonomic assignment of biogenic hydrocarbon emission rates. The biosynthetic pathways involved in the synthesis of the more common monoterpenes are fairly well understood (Croteau, 1987; Tingey *et al.*, 1991); however, the synthesis of isoprene has not been fully elucidated and a detailed discussion is beyond the scope of this paper (Loreto and Sharkey, 1990; Monson *et al.*, 1991a, b, 1992; Sharkey *et al.*, 1991; Sharkey and Singsaas, 1995).

There is no clear consensus as to the purpose of hydrocarbon production and emission by vegetation; various hypotheses suggest that different plant species may produce biogenic hydrocarbons for different reasons, depending upon their environment and the particular type of hydrocarbon produced. It has been

Table 1. Chronological listing of studies used in compiling the present database of biogenic hydrocarbon emission rates

Investigator	Predominant technique	Predominant plant species
Flyckt (1979)	Enclosure	Oak
Zimmerman (1979b)	Enclosure	Southern Forest variety
Tingey *et al.* (1979, 1980)	Laboratory chamber	Live Oak, Slash Pine
Evans *et al.* (1982)	Total enclosure	Crops, shrubs, herbs, trees
Cronn and Nutmagul (1982)	Enclosure	Tropical shrubs and trees
Winer *et al.* (1983)	Enclosure	Natural and ornamental species
Yokouchi and Ambe (1984)	Chamber	Red Pine
Isidorov *et al.* (1985)	Branch enclosure	Oaks and pines
Lamb *et al.* (1983, 1985)	Enclosure and micrometeorological	Deciduous forest, Douglas Fir
Lamb *et al.* (1986)	Tracer flux and branch enclosure	Oregon White Oak
Winer *et al.* (1989, 1992)	Enclosure	Agricultural and natural species
Corchnoy *et al.* (1992)	Enclosure	Potential shade trees
Janson (1993)	Enclosure	Scots Pine, Norwegian Spruce
Tanner and Zielinska (1994)	Enclosure	Oak and pine
Arey *et al.* (1995)	Enclosure	Native species

hypothesized that plants tend to produce biogenic hydrocarbons because these emissions protect the plant from photosynthetic damage but are not attractive to herbivores due to their inherent toxicity (Mooney, 1972; Ross and Sombrero, 1991). In support of this hypothesis, it has been found that a large percentage of plant species in Mediterranean ecosystems emit hydrocarbons (Ross and Sombrero, 1991). However, there is growing evidence that plants may produce monoterpenes for other reasons, including as a defense against plant pathogens (Harborne, 1988; Walter *et al.*, 1989). The function of isoprene within plant tissues remains uncertain, although it is known that between 0.5 and 8% of the carbon fixed through photosynthesis (Tingey *et al.*, 1979; Monson and Fall, 1991) is in the form of isoprene. Recently, Sharkey and Singsaas (1995) have suggested that production of isoprene during photosynthetic activity occurs in order to increase the thermal tolerance of plants.

Although there remains a lack of comprehensive knowledge concerning the exact function of biogenic hydrocarbons, their distribution in plant tissues, and their emission pathways, various researchers (e.g. Seigler, 1981; Croteau, 1987) have found that biogenic hydrocarbons are emitted only by certain plant families. For example, of the approximately 400 families of flowering plants (Cronquist, 1988), only about 50 plant families produce significant quantities of monoterpenes. Findings such as these (Seigler, 1981; Charlwood and Charlwood, 1991) are the basis for the taxonomic assignment of emission rates presented in this paper.

METHODOLOGY

In the present study, average isoprene and total monoterpene emission rates for 124 species experimentally measured in previous studies (Table 1) were compiled into a single database, grouped alphabetically by plant family (Table 2). Total non-methane hydrocarbon (TNMHC) emission rates are not included in this database because only a few of the emission surveys conducted to date quantified emission rates of TNMHCs (Zimmermann, 1979b; Winer *et al.*, 1989, 1992; Arey *et al.*, 1995). Although these studies indicate that NMHCs other than isoprene and monoterpenes may account for approximately 15% of the total biogenic emissions from vegetation, the amount of information concerning these NMHCs is too limited to permit assignment of NMHC emission rates for unmeasured plant species.

Normalization of reported emission rates

Experimental studies (Tingey *et al.*, 1979; Juuti *et al.*, 1990; Guenther *et al.*, 1991; Monson and Fall, 1991) have found that biogenic emission rates vary as a function of temperature, photosynthetically active radiation (PAR) levels, humidity, and CO_2 concentration. Correction algorithms (Tingey *et al.*, 1979; Guenther *et al.*, 1991, 1993) which model the effect of these environmental factors on biogenic emissions indicate that isoprene emissions increase with increasing PAR levels and temperature (up to a certain critical temperature) while monoterpene emissions increase solely as a function of increasing temperature.

Emission rates included in the database (Table 2) were measured at temperatures between 10 and 45°C and PAR levels between approximately 100 and 2000 $\mu E\,m^{-2}\,s^{-1}$. To permit comparison of the compiled emission rates, reported isoprene and monoterpene emission rates were normalized to 30°C and a light intensity level of 1000 $\mu E\,m^{-2}\,s^{-1}$, using the correction algorithms developed by Guenther *et al.* (1993). These correction algorithms were selected because they better represent isoprene and monoterpene emissions at higher temperatures and light intensities. When possible, reported PAR levels were used in normalizing emission rates. Light intensities qualitatively reported as "full", "partial", or "none" sunlight exposure were assumed to be equivalent to PAR levels of 1500, 1000, and 500 $\mu E\,m^{-2}\,s^{-1}$, respectively. For those published emission rates for which light intensities were not reported, PAR levels were assumed to be 1000 $\mu E\,m^{-2}\,s^{-1}$.

Taxonomic assignment of hourly emission rates

Based on phytochemical research (Seigler, 1981; Croteau, 1987; Charlwood and Charlwood, 1991) indicating biogenic hydrocarbons are emitted only by certain plant families,

Table 2. Tree and shrub species with measured isoprene and monoterpene emissions, listed in alphabetical order by taxonomy (family, genus species)

Family	Botanical name	Common name	Isoprene (μg(g dry leaf wt)$^{-1}$ h^{-1})	monoterpenes (μg(g dry leaf wt)$^{-1}$ h^{-1})	Reference
Aceraceae	*Acer floridanum*	Silver Maple	BDL	2.0	Winer *et al.* (1983)
	Acer rubrum	Red Maple	NED	3.5	Zimmerman (1979)
	Acer saccharinum	Silver Maple	NED	2.2	Evans *et al.* (1982)
	Acer saccharinum	Silver Maple	NR	3.5	Lamb *et al.* (1983)
Anacardiaceae	*Pistacia vera*	Kerman Pistachio	NED	9.0	Winer *et al.* (1992)
	Rhus ovata	Sugarbush	BDL	BDL	Winer *et al.* (1983)
	Schinus molle	California Pepper	NED	3.7	Corchnoy *et al.* (1992)
	Schinus molle	California Pepper	NED	NED	Winer *et al.* (1983)
	Schinus terebinthifolius	Brazilian Pepper	NED	1.3	Corchnoy *et al.* (1992)
	Schinus terebinthifolius	Brazilian Pepper	BDL	10.4	Winer *et al.* (1983)
Apocynaceae	*Carissa macrocarpa*	Natal Plum	BDL	BDL	Winer *et al.* (1983)
	Nerium oleander	Oleander	BDL	BDL	Winer *et al.* (1983)
	Nerium oleander	Oleander	NED	NED	Zimmerman (1979)
Aquifoliaceae	*Ilex cassine*	Dahoon Holly	NED	NED	Zimmerman (1979)
Arecaceae	*Elaeis guineensis*	Palm Oil Tree	172.9	NR	Cronn and Nutmagul (1982)
	Phoenix dactylifera	Date Palm	15.8	BDL	Winer *et al.* (1983)
	Sabel palmetto	Sabel Palmetto	4.7	0.4	Zimmerman (1979)
	Serenoa repens	Saw Palmetto	8.9	BDL	Zimmerman (1979)
	Washingtonia filifera	California Fan Palm	9.9	BDL	Winer *et al.* (1983)
	Xylosma congestum	Shiny Xylosma	6.8	BDL	Winer *et al.* (1983)
Berberidaceae	*Nandina domestica*	Heavenly Bamboo	25.1	BDL	Winer *et al.* (1983)
Bignoniaceae	*Jacaranda mimosifolia*	Jacaranda	NR	BDL	Corchnoy *et al.* (1992)
	Jacaranda mimosifolia	Jacaranda	NED	NED	Winer *et al.* (1983)
	Tecomaria capensis	Cape-Honeysuckle	BDL	BDL	Winer *et al.* (1983)
	Trichostema lanatum	Woolly Blue Curls	0.0	17.7	Winer *et al.* (1983)
Caprifoliaceae	*Sambucus simponii*	Elderberry	NED	BDL	Zimmerman (1979)
	Viburnum rufidulum	Viburnum	NED	0.2	Zimmerman (1979)
Compositae	*Artemisia californica*	California Sagebrush	0.0	47.0	Arey *et al.* (1995)
	Artemisia californica	California Sagebrush	BDL	9.6	Winer *et al.* (1983)
Cupressaceae	*Cupressus forbesii*	Tecate Cypress	0.0	1.7	Arey *et al.* (1995)
	Cupressus sempervirens	Italian Cypress	0.0	0.1	Winer *et al.* (1983)
	Juniperus chinensis	Chinese Juniper	0.0	0.6	Winer *et al.* (1983)
Ericaceae	*Arctostaphylos glandulosa*	Peninsular Manzanita	NED	NED	Arey *et al.* (1995)
	Arctostaphylos glauca	Bigberry Manzanita	BDL	BDL	Winer *et al.* (1983)
Euphorbiaceae	*Hevea brasiliensis*	Rubber Tree	7.5	0.5	Cronn and Nutmagul (1982)
	Macaraunga triloba	Macauranga	45.3	0.7	Cronn and Nutmagul (1982)
	Mallotus paniculatis	Mallotus	NR	0.8	Cronn and Nutmagul (1982)
Fagaceae	*Quercus agrifolia*	Coast Live Oak	35.3	BDL	Winer *et al.* (1983)
	Quercus alba	White Oak	7.8	1.5	Lamb *et al.* (1983)
	Quercus borealis	Red Oak	19.7	0.0	Evans *et al.* (1982)
	Quercus borealis	Red Oak	40.4	NR	Flyckt (1979)
	Quercus coccinea	Scarlet Oak	20.1	3.2	Lamb *et al.* (1983)
	Quercus douglasii	Blue Oak	8.7	0.0	Tanner and Zielinska (1994)
	Quercus dumosa	California Scrub Oak	5.2	0.0	Arey *et al.* (1995)
	Quercus dumosa	California Scrub Oak	54.4	BDL	Winer *et al.* (1983)
	Quercus garryana	Oregon White Oak	59.2	NR	Lamb *et al.* (1986)
	Quercus incana	Bluejack Oak	45.6	0.2	Zimmerman (1979)
	Quercus laevis	Scrub Oak	24.3	0.8	Zimmerman (1979)
	Quercus laurifolia	Diamond Leaf Oak	10.4	0.2	Zimmerman (1979)
	Quercus lobata	Valley Oak	3.4	0.0	Winer *et al.* (1992)
	Quercus myrtifolia	Myrtle Oak	15.2	0.2	Zimmerman (1979)
	Quercus nigra	Water Oak	24.6	BDL	Zimmerman (1979)
	Quercus phellos	Willow Oak	32.2	NED	Zimmerman (1979)
	Quercus prinus	Chestnut Oak	6.5	1.5	Lamb *et al.* (1983)
	Quercus robur	European Oak	76.6	NR	Isidorov *et al.* (1985)
	Quercus rubra	Northern Red Oak	14.8	1.8	Lamb *et al.* (1983)
	Quercus velutina	Black Oak	18.9	1.0	Lamb *et al.* (1983)
	Quercus virginiana	Virginia Live Oak	30.9	NR	Tingey *et al.* (1979)
	Quercus virginiana	Virginia Live Oak	9.5	0.3	Zimmerman (1979)
	Quercus wislizenii	Interior Live Oak	12.5	0.0	Arey *et al.* (1995)
Ginkgoaceae	*Ginkgo biloba*	Ginkgo	NED	3.0	Corchnoy *et al.* (1992)
Hamamelidaceae	*Liquidambar styraciflua*	Liquidambar	35.3	3.0	Corchnoy *et al.* (1992)
	Liquidambar styraciflua	Liquidambar	17.8	2.9	Evans *et al.* (1982)
	Liquidambar styraciflua	Liquidambar	3.5	51.5	Zimmerman (1979)
Juglandaceae	*Carya aquatica*	Water Hickory	NED	0.7	Zimmerman (1979)
	Juglans regia	English Walnut	NED	1.8	Winer *et al.* (1992)
Lamiaceae	*Salvia mellifera*	Black Sage	0.0	5.0	Arey *et al.* (1995)
	Salvia mellifera	Black Sage	BDL	11.7	Winer *et al.* (1983)
Lauraceae	*Cinnamomum camphora*	Camphor	NED	0.0	Corchnoy *et al.* (1992)
	Cinnamomum camphora	Camphor	NED	0.0	Winer *et al.* (1983)
	Persea americana	Avocado	BDL	BDL	Winer *et al.* (1983)
	Persea borbonia	Red Bay	NED	1.2	Zimmerman (1979)

Table 2. (*Continued*)

Family	Botanical name	Common name	Isoprene (μg(g dry leaf wt)$^{-1}$ h^{-1})	monoterpenes	Reference
Leguminosae	*Acacia farnesiana*	Sweet Acacia	NED	4.7	Zimmerman (1979)
	Cercis canadensis	Redbud	0.0	NED	Evans *et al.* (1982)
	Glycine max		0.0	0.0	Evans *et al.* (1982)
	Pueraria lobata		9.6	0.0	Evans *et al.* (1982)
	Robinia pseudoacacia	Black Locust	13.5	4.7	Lamb *et al.* (1983)
	Robinia pseudoacacia	Black Locust	10.1	0.0	Winer *et al.* (1983)
Lythraceae	*Lagerstroemia indica*	Crape Myrtle	NED	NED	Corchnoy *et al.* (1992)
	Lagerstroemia indica	Crape Myrtle	NED	NED	Winer *et al.* (1983)
Magnoliaceae	*Liriodendron tulipifera*	Tulip Tree	4.1	NR	Lamb *et al.* (1983)
	Magnolia grandiflora	Magnolia	BDL	5.9	Winer *et al.* (1983)
Moraceae	*Ficus fistulosa*	Fig	27.0	0.2	Cronn and Nutmagul (1982)
	Morus rubra	Red Mulberry	NED	1.6	Zimmerman (1979)
Myrtaceae	*Callistemon citrinus*	Bottlebrush	16.0	BDL	Winer *et al.* (1983)
	Eucalyptus globulus	Blue Gum Eucalyptus	57.0	9.2	Evans *et al.* (1982)
	Eucalyptus viminalis	Ribbon Gum	8.0	BDL	Winer *et al.* (1983)
	Eugenia grandis	Eugenia	12.1	NR	Cronn and Nutmagul (1982)
	Myrtica cerifera	Wax Myrtle	NED	1.1	Zimmerman (1979)
	Myrtus communis	Common Myrtle	34.0	BDL	Winer *et al.* (1983)
Oleaceae	*Fraxinus caroliniana*	Carolina Ash	NED	NED	Zimmerman (1979)
	Fraxinus uhdei	Evergreen Ash	BDL	BDL	Winer *et al.* (1983)
	Ligustrum lucidum	Glossy Privet	BDL	BDL	Winer *et al.* (1983)
	Olea europaea	Olive	BDL	0.5	Winer *et al.* (1983)
	Olea europaea	Olive	NED	0.1	Winer *et al.* (1992)
Pinaceae	*Cedrus deodara*	Deodar Cedar	NED	0.3	Corchnoy *et al.* (1992)
	Cedrus deodara	Deodar Cedar	BDL	0.9	Winer *et al.* (1983)
	Picea abies	Norwegian Spruce	NR	1.2	Janson (1993)
	Picea engelmannii	Engelmann Spruce	16.3	3.4	Evans *et al.* (1982)
	Picea sitchensis	Sitka Spruce	4.0	1.1	Evans *et al.* (1982)
	Pinus canariensis	Canary Island Pine	NED	1.7	Corchnoy *et al.* (1992)
	Pinus canariensis	Canary Island Pine	BDL	2.6	Winer *et al.* (1983)
	Pinus clausa	Sand Pine	NED	11.5	Zimmerman (1979)
	Pinus densiflora	Red Pine	NR	0.2	Yokouchi and Ambe (1984)
	Pinus ellotii	Slash Pine	NED	6.9	Evans *et al.* (1982)
	Pinus ellotii	Slash Pine	NED	6.2	Tingey *et al.* (1979)
	Pinus ellotii	Slash Pine	NED	5.0	Tingey *et al.* (1980)
	Pinus ellotii	Slash Pine	NED	3.2	Zimmerman (1979)
	Pinus halepensis	Aleppo Pine	NR	0.2	Corchnoy *et al.* (1992)
	Pinus halepensis	Aleppo Pine	BDL	0.5	Winer *et al.* (1983)
	Pinus palustris	Longleaf Pine	NED	5.9	Zimmerman (1979)
	Pinus pinea	Italian Stone Pine	NED	0.4	Corchnoy *et al.* (1992)
	Pinus pinea	Italian Stone Pine	BDL	BDL	Winer *et al.* (1983)
	Pinus radiata	Monterey Pine	NED	0.9	Corchnoy *et al.* (1992)
	Pinus radiata	Monterey Pine	BDL	0.7	Winer *et al.* (1983)
	Pinus sabiniana	Foothill Pine	NED	0.6	Tanner and Zielinska (1994)
	Pinus sylvestris	Scots Pine	NED	12.1	Isidorov *et al.* (1985)
	Pinus sylvestris	Scots Pine	NR	0.8	Janson (1993)
	Pinus taeda	Loblolly Pine	NR	5.1	Lamb *et al.* (1985)
	Pseudotsuga macrocarpa	Bigcone Douglas Fir	0.0	1.1	Arey *et al.* (1995)
Pittosporaceae	*Pittosporum tobira*	Japanese Pittosporum	BDL	BDL	Winer *et al.* (1983)
	Pittosporum undulatum	Victorian Box	BDL	BDL	Winer *et al.* (1983)
Platanaceae	*Platanus occidentalis*	American Sycamore	27.5	NED	Evans *et al.* (1982)
	Platanus racemosa	Western Sycamore	10.9	BDL	Winer *et al.* (1983)
Podocarpaceae	*Podocarpus gracilior*	Fern Pine	BDL	BDL	Winer *et al.* (1983)
Polygonaceae	*Eriogonum fasciculatum*	California Buckwheat	BDL	BDL	Winer *et al.* (1983)
Polypodiaceae	*Thelypteris decursive-pinnata*		24.5	0.0	Evans *et al.* (1982)
Rhamnaceae	*Ceanothus crassifolius*	Hoaryleaf Ceanothus	BDL	BDL	Winer *et al.* (1983)
	Ceanothus leucodermis	Chaparral Whitehorn	NED	5.4	Winer *et al.* (1992)
	Ceanothus spinosus	Greenbark	0.0	1.8	Arey *et al.* (1995)
	Rhamnus californica	Coffeeberry	29.3	NED	Evans *et al.* (1982)
	Rhamnus crocea	Redberry	54.4	BDL	Winer *et al.* (1983)
Rosaceae	*Adenostoma fasciculatum*	Chamise	NED	NED	Arey *et al.* (1995)
	Adenostoma fasciculatum	Chamise	NED	NED	Winer *et al.* (1983)
	Adenostoma fasciculatum	Chamise	NED	0.4	Winer *et al.* (1992)
	Cercocarpus betuloides	Mountain Mahogany	NED	NED	Arey *et al.* (1995)
	Cotoneaster pannosus	Cotoneaster	BDL	BDL	Winer *et al.* (1992)
	Prunus armeniaca	Blenheim Apricot	NED	0.1	Winer *et al.* (1992)
	Prunus avium	Bing Cherry	NED	0.1	Winer *et al.* (1992)
	Prunus domestica	Santa Rosa Plum	NED	0.0	Winer *et al.* (1992)
	Prunus dulcis	Nonpareil Almond	NED	0.0	Winer *et al.* (1992)
	Prunus persica	Halford Peach	NED	0.1	Winer *et al.* (1992)
	Pyrus kawakamii	Evergreen Pear	BDL	BDL	Winer *et al.* (1983)
	Rhaphiolepis indica	India Hawthorne	BDL	BDL	Winer *et al.* (1983)
Rutaceae	*Citrus limon*	Lisbon Lemon	NED	3.2	Winer *et al.* (1989)
	Citrus limon 'Meyer'	Meyer Lemon	BDL	BDL	Winer *et al.* (1983)
	Citrus sinensis	Navel Orange	NED	1.8	Winer *et al.* (1992)
	Citrus sinensis 'Valencia'	Valencia Orange	NED	0.9	Winer *et al.* (1992)

Table 2. (*Continued*)

Family	Botanical name	Common name	Isoprene (μg(g dry leaf wt)$^{-1}$ h^{-1})	monoterpenes	Reference
Salicaceae	*Populus deltoides*	Eastern Cottonwood	37.0	NED	Evans *et al.* (1982)
	Populus tremuloides	Quaking Aspen	50.2	NED	Evans *et al.* (1982)
	Salix babylonica	Weeping Willow	115.0	NED	Winer *et al.* (1983)
	Salix caroliniana	Coast Plain Willow	12.5	BDL	Zimmerman (1979)
	Salix nigra	Black Willow	25.2	NED	Evans *et al.* (1982)
Sapindaceae	*Cupaniopsis anacardioides*	Carrotwood	50.9	NED	Corchnoy *et al.* (1992)
Taxodiaceae	*Taxodium sp.*	Cypress	NED	8.5	Zimmerman (1979)
Ulmaceae	*Ulmus americana*	American Elm	BDL	BDL	Winer *et al.* (1983)
	Ulmus americana	American Elm	NED	NED	Zimmerman (1979)
	Ulmus parvifolia	Chinese Elm	BDL	BDL	Winer *et al.* (1983)

All emissions, expressed in μg(g dry leafwt)$^{-1}$ h^{-1}, normalized at 30°C using Guenther *et al.* (1993) algorithms. NR = not reported; BDL = below detection limit; NED = no emissions detected.

several researchers (Horie *et al.*, 1990; Sidawi and Horie, 1992; Sudol and Winer, 1992; Tanner *et al.*, 1992) have employed a taxonomic methodology for assigning emission rates to species for which no measurements exist. The basic premise of this 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 measurements exist.

In the present study, the taxonomic method was applied to the compilation of measured emission rates for 124 tree and shrub species (Table 2) in order to assign emission rates to 253 other species which might be considered for planting in the SoCAB. The resulting database of emission rates for 377 tree and shrub species was then grouped into genus and family clusters. Since detection limits were not reported in all of the previous studies, emission rates shown in Table 2 as "BDL" (below detection limit) or "NED" (no emissions detected) were assumed to be zero, while emission rates shown as "NR" (not reported) were assumed to be missing and therefore not used in assigning emission rates. For those plant species for which emission rates were reported by multiple investigators, mean emission rates were calculated.

The taxonomic methodology used in assigning isoprene and monoterpene emissions values is summarized in Fig. 1. For those species for which direct measurements were reported, the individual or mean (if more than one measurement was available) emission rate for that species was assumed. If direct measurements were not available for a species but were reported for other species within the same genus, the mean value for that genus was assigned to the unmeasured species. If no measurements were reported for any of the species within the genus, but direct measurements for other species within the family were available, then the mean emission rate for the family was assigned to the unmeasured species. Finally, for those species for which no measurements were reported for any other species within the family, emission rates were not assigned.

RESULTS AND DISCUSSION

Ranking of species

As shown in Fig. 1, direct measurements accounted for 33% of the emission rates in the combined database (124/377). Genus relationships were used in assigning 30% of the emission rates (114/377) while family relationships accounted for 21% (79/377) of the emission rates. The remaining 16% (62/377) of the species were not assigned emission rates because there were no direct measurements made within their families.

The resulting database of emission rates for 377 tree and shrub species (Table 3) was ranked by the sum of the hourly emission rates of isoprene and monoterpenes, expressed as μg emissions (g dry leaf wt)$^{-1}$ h^{-1}. A plot of the cumulative fraction of species vs total emission rate (Fig. 2) shows that emission rates for the 316 species for which emission rates could be assigned vary by approximately four orders of magnitude. In addition, emission rates for the species examined are skewed towards low and moderate emitters. In Fig. 2, a detection limit of 0.01 μg (g dry leaf wt)$^{-1}$ h^{-1} was assumed for species reported in Table 3 as having zero emissions.

Based upon the distribution of emission rates shown in Fig. 2, the 316 tree and shrub species for which emission rates were measured or could be assigned were classified as being "low-", "moderate-", and "high-emitters". For practical purposes, "low-", "moderate-", and "high-emitters" were defined as those species emitting less than 1 μg total emissions (g dry leaf wt)$^{-1}$ h^{-1}, between 1–10 μg total emissions (g dry leaf wt)$^{-1}$ h^{-1}, and greater than 10 μg total emissions (g dry leaf wt)$^{-1}$ h^{-1}. Based upon these definitions, 115 of the 316 species (36%) were low-emitters, 105 (34%) were moderate-emitters, and 96 (30%) were high-emitters. When these definitions were applied only to the 124 measured species, 39% were low-emitters, 30% were moderate-emitters, and 31% were high-emitters.

Validation of the taxonomic method

Although the use of taxonomic methods (Horie *et al.*, 1990; Sidawi and Horie, 1992; Sudol and Winer, 1992; Tanner *et al.*, 1992) for assigning hydrocarbon emission rates to unmeasured plant species is supported by phytochemical research (Seigler, 1981; Croteau, 1987; Charlwood and Charlwood, 1991), there are alternative schemes for making such assignments. Accordingly, we investigated the statistical robustness of the present taxonomic method (based on genus and family) relative to three other assignment

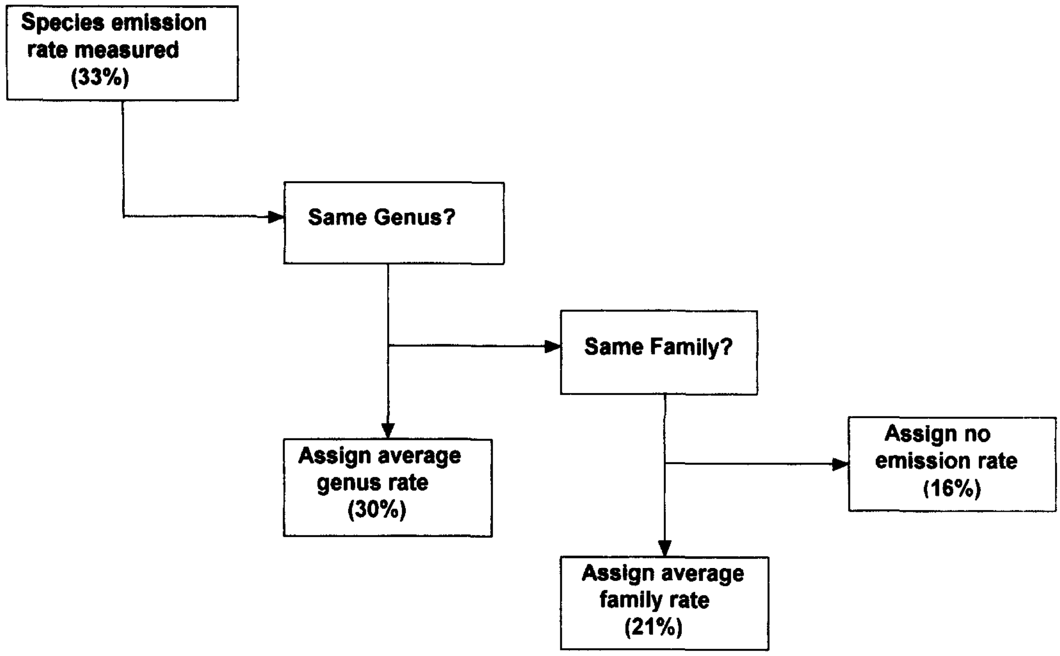

Fig. 1. Flowchart showing taxonomic methodology for the assignment of emission rates to species for which measured emission rates do not exist. The percentages shown represent the fraction of species in the database for which emission rates were assigned at each stage of the taxonomic method.

methods (i.e. vegetation class, preferred sun exposure, and plant growth rate) by calculating the coefficient of variation (COV) for each method. The COV is an estimate of the relative standard deviation of a population and is often used to quantify the variability of different analytical methods (Gilbert, 1987; Skoog and Leary, 1992).

In this comparison, the COVs of the five assignment methods were calculated using the species emission rates reported in Table 2. For each method, the 124 species were assigned to bins depending upon the parameter of interest. For example, in the case of the growth rate method, species were assigned to six growth rate bins (slow, moderately slow, moderate, moderately fast, fast, very fast) based on botanical information (PGE, 1991; Bauml, 1994). In addition to the growth rate bins, species were assigned to 75 genus bins, 37 family bins, six vegetation class bins (conifer, broad-leaf evergreen, broad-leaf deciduous, palms, shrubs, unknown), and three exposure bins (sunny, partly shady, shady). Statistics, including the COV, were then generated for both isoprene and monoterpene emissions for each bin for which there were sufficient emission rates. Based on the individual bin COVs, a mean COV for each method was then calculated, thus permitting quantitative comparison of the variability of the different assignment methods.

The results of this statistical analysis are presented as a plot of the mean COV values, including the 95% confidence interval, for both isoprene and monoterpene emissions for each assignment method (Fig. 3). Of the methods examined, it is apparent that the genus and family assignment methods have the least variability. Of these two methods, the genus method exhibits the lower COVs, suggesting that it is the preferable assignment method. We found that emission rates for most tree species within the same genus differ by less than a factor of ten (e.g. *Acer*, *Schinus*, *Picea*) whereas species within some families (e.g. *Arecaceae*) differ by as much as a factor of 32. Regardless, COVs for all of the methods are relatively high, ranging from approximately 0.7 to 2.0, indicating considerable uncertainty in assigned emission rates. These high COV values reflect the relatively small number of measured species reported in the literature, as well as the inherent error involved in the measurement of highly complex, biological systems.

CONCLUSIONS AND RECOMMENDATIONS

In many non-attainment urban airsheds, present state and federal air quality regulations call for large reductions in anthropogenic VOCs to meet air quality standards for ozone and PM-10. It has been suggested (Chameides *et al.*, 1988) that in some airsheds, biogenic hydrocarbon emissions could become critical if anthropogenic VOCs are sufficiently reduced. Assuming 5 million new trees were planted in the SoCAB over the next 20 years, on a typical summer day, a mix of high-emitting species would contribute an additional 35 TPD of biogenic VOCs as compared to

Table 3. Trees and shrubs ranked by sum of hourly emission rate of isoprene and monoterpenes

Botanical name	Common name	Isoprene	monoterpenes	Iso. + mono.	Assign
		μg(g dry leaf wt)$^{-1}$ h^{-1}			
Arbutus menziesii	Madrone	0.0	0.0	0.0	3
Arbutus unedo	Strawberry Madrone	0.0	0.0	0.0	3
Arctostaphylos glandulosa	Peninsular Manzanita	0.0	0.0	0.0	1
Arctostaphylos glauca	Bigberry Manzanita	0.0	0.0	0.0	1
Arctostaphylos manzanita	Dr. Hurd Manzanita	0.0	0.0	0.0	2
Carissa macrocarpa	Natal Plum	0.0	0.0	0.0	1
Ceanothus crassifolius	Hoaryleaf Ceanothus	0.0	0.0	0.0	1
Celtis sinensis	Chinese Hackberry	0.0	0.0	0.0	3
Cercocarpus betuloides	Mountain Mahogany	0.0	0.0	0.0	1
Cercocarpus ledifolius	Curly-Leaf Mountain Mahogany	0.0	0.0	0.0	2
Citrus limon 'Meyer'	Meyer Lemon	0.0	0.0	0.0	1
Comarostaphylis diversifolia	Summer Holly	0.0	0.0	0.0	3
Cotoneaster pannosus	Cotoneaster	0.0	0.0	0.0	1
Eriogonum fasciculatum	California Buckwheat	0.0	0.0	0.0	1
Fraxinus caroliniana	Carolina Ash	0.0	0.0	0.0	1
Fraxinus dipetala	Foothill Ash	0.0	0.0	0.0	2
Fraxinus latifolia	Oregon Ash	0.0	0.0	0.0	2
Fraxinus pennsylvanica	Green Ash	0.0	0.0	0.0	2
Fraxinus uhdei	Evergreen Ash	0.0	0.0	0.0	1
Fraxinus velutina	Arizona Ash	0.0	0.0	0.0	2
Fraxinus velutina 'Modesto'	Modesto Ash	0.0	0.0	0.0	2
Fraxinus velutina coriacea	Montebello Ash	0.0	0.0	0.0	2
Hymenosporum flavum	Sweetshade	0.0	0.0	0.0	3
Ilex aquifolium	English Holly	0.0	0.0	0.0	2
Ilex cassine	Dahoon Holly	0.0	0.0	0.0	1
Ilex comuta	Chinese Holly	0.0	0.0	0.0	2
Jacaranda mimosifolia	Jacaranda	0.0	0.0	0.0	1
Lagerstroemia indica	Crape Myrtle	0.0	0.0	0.0	1
Ligustrum lucidum	Glossy Privet	0.0	0.0	0.0	1
Nerium oleander	Oleander	0.0	0.0	0.0	1
Persea americana	Avocado	0.0	0.0	0.0	1
Pittosporum rhombifolium	Queensland Pittosporum	0.0	0.0	0.0	2
Pittosporum tobira	Japanese Pittosporum	0.0	0.0	0.0	1
Pittosporum undulatum	Victorian Box	0.0	0.0	0.0	1
Podarcarpus macrophyllus	Yew Pine	0.0	0.0	0.0	3
Podocarpus gracilior	Fern Pine	0.0	0.0	0.0	1
Pyrus calleryana 'Aristocrat'	Aristocrat Flowering Pear	0.0	0.0	0.0	2
Pyrus calleryana 'Bradford'	Bradford Pear	0.0	0.0	0.0	2
Pyrus kawakamii	Evergreen Pear	0.0	0.0	0.0	1
Pyrus sp.	Pear	0.0	0.0	0.0	2
Rhaphiolepis excelsa	Lady Palm	0.0	0.0	0.0	2
Rhaphiolepis indica	India Hawthorne	0.0	0.0	0.0	1
Rhaphiolepis 'Majestic Beauty'	Majestic Beauty-Indian Hawthorne	0.0	0.0	0.0	2
Rhododendron spp.	Azalea/Rhododendron	0.0	0.0	0.0	3
Rhus glabra	Smooth Sumac	0.0	0.0	0.0	2
Rhus lancea	African Sumac	0.0	0.0	0.0	2
Rhus ovata	Sugarbush	0.0	0.0	0.0	1
Sambucus callicarpa	Red Coastal Elderberry	0.0	0.0	0.0	2
Sambucus glauca	Blue Elderberry	0.0	0.0	0.0	2
Sambucus mexicana	Hairy Blue Elderberry	0.0	0.0	0.0	2
Sambucus simponii	Elderberry	0.0	0.0	0.0	1
Tecomaria capensis	Cape-Honeysuckle	0.0	0.0	0.0	1
Ulmus americana	American Elm	0.0	0.0	0.0	1
Ulmus parvifolia	Chinese Elm	0.0	0.0	0.0	1
Zelkova serrata	Sawleaf Zelkova	0.0	0.0	0.0	3
Prunus dulcis	Nonpareil Almond	0.0	0.0	0.0	1
Cercis canadensis	Redbud	0.0	0.0	0.0	1
Cercis occidentalis	Western Redbud	0.0	0.0	0.0	2
Cinnamomum camphora	Camphor	0.0	0.0	0.0	1
Cinnamomum pedunculatum	Camphor	0.0	0.0	0.0	2
Glycine max		0.0	0.0	0.0	1
Prunus domestica	Santa Rosa Plum	0.0	0.0	0.0	1
Amelanchier alnifolia	Mountain Serviceberry	0.0	0.1	0.1	3
Eriobotrya deflexa	Bronze Loquat	0.0	0.1	0.1	3
Eriobotrya japonica	Loquat	0.0	0.1	0.1	3
Heteromeles arbutifolia	Toyon	0.0	0.1	0.1	3
Lyonothamnus floribundus aspenifolia	Catalina Ironwood	0.0	0.1	0.1	3
Malus sp.	Apple	0.0	0.1	0.1	3
Photinia fraseri	Common Photinia	0.0	0.1	0.1	3
Pyracantha coccinea	Firethorn	0.0	0.1	0.1	3

Table 3. (*Continued*)

Botanical name	Common name	Isoprene	monoterpenes	Iso. + mono.	Assign
		μg(g dry leaf wt)$^{-1}$ h^{-1}			
Rosa sp.	Rose	0.0	0.1	0.1	3
Jasminum sp.	Jasmine	0.0	0.1	0.1	3
Osmanthus fragrans	Sweet Olive	0.0	0.1	0.1	3
Prunus caroliniana	Carolina Laurel Cherry	0.0	0.1	0.1	2
Prunus cerasifera	Cherry Plum	0.0	0.1	0.1	2
Prunus ilicifolia	Hollyleaf Cherry	0.0	0.1	0.1	2
Prunus lusitanica	Portugal Laurel	0.0	0.1	0.1	2
Prunus lyonii	Catalina Cherry	0.0	0.1	0.1	2
Prunus serotina	Black Cherry	0.0	0.1	0.1	2
Prunus subcordata	Sierra Plum	0.0	0.1	0.1	2
Prunus virginiana	Choke Cherry	0.0	0.1	0.1	2
Prunus avium	Bing Cherry	0.0	0.1	0.1	1
Cupressus sempervirens	Italian Cypress	0.0	0.1	0.1	1
Abelia grandiflora	Glossy Abelia	0.0	0.1	0.1	3
Adenostoma fasciculatum	Chamise	0.0	0.1	0.1	1
Prunus armeniaca	Blenheim Apricot	0.0	0.1	0.1	1
Prunus persica	Halford Peach	0.0	0.1	0.1	1
Prunus persica	Halford Peach	0.0	0.1	0.1	1
Pinus densiflora	Red Pine	0.0	0.2	0.2	1
Viburnum rufidulum	Viburnum	0.0	0.2	0.2	1
Pisum pinea	Italian Stone Pine	0.0	0.2	0.2	1
Olea europaea	Olive	0.0	0.3	0.3	1
Pinus halepensis	Aleppo Pine	0.0	0.3	0.3	1
Laurus nobilis	Grecian Laurel	0.0	0.4	0.4	3
Sassafras albidum	Sassafras	0.0	0.4	0.4	3
Cedrus atlantica	Atlas Cedar	0.0	0.6	0.6	2
Cedrus deodara	Deodar Cedar	0.0	0.6	0.6	1
Juniperus californica	California Juniper	0.0	0.6	0.6	2
Juniperus chinensis	Chinese Juniper	0.0	0.6	0.6	1
Juniperus occidentalis	Western Juniper	0.0	0.6	0.6	2
Pinus sabiniana	Foothill Pine	0.0	0.6	0.6	1
Carya aquatica	Water Hickory	0.0	0.7	0.7	1
Carya sp.	Red Hickory	0.0	0.7	0.7	2
Calocedrus decurrens	Incense Cedar	0.0	0.8	0.8	3
Chamaecyparis lawsoniana	Port Orford Cedar	0.0	0.8	0.8	3
Chamaecyparis nootkatensis	Nootka Cypress	0.0	0.8	0.8	3
Cupressocyparis leylandii	Leylandi Cypress	0.0	0.8	0.8	3
Cycas revoluta	Sago Palm	0.0	0.8	0.8	3
Platycladus orientalis	Oriental Arborvitae	0.0	0.8	0.8	3
Thuja plicata	Western Red Cedar	0.0	0.8	0.8	3
Pinus radiata	Monterey Pine	0.0	0.8	0.8	1
Cupressus glabra	Smooth Arizona Cypress	0.0	0.9	0.9	2
Cupressus macnabrana	Macnab Cypress	0.0	0.9	0.9	2
Cupressus macrocarpo	Monterey Cypress	0.0	0.9	0.9	2
Citrus sinensis 'Valencia'	Valencia Orange	0.0	0.9	0.9	1
Myrtica cerifera	Wax Myrtle	0.0	1.1	1.1	1
Pseudotsuga macrocarpa	Bigcone Douglas Fir	0.0	1.1	1.1	1
Persea borbonia	Red Bay	0.0	1.2	1.2	1
Calodendrum capense	Cape Chestnut	0.0	1.5	1.5	3
Casimiroa edulis	White Sapote	0.0	1.5	1.5	3
Citrus limonia burm.	Meyer Lemon	0.0	1.5	1.5	2
Citrus orangoma	Orange	0.0	1.5	1.5	2
Citrus paradisi	Grapefruit	0.0	1.5	1.5	2
Geijera parvifolia	Australian Willow	0.0	1.5	1.5	3
Morus alba 'Fruitless'	Fruitless Mulberry	0.0	1.6	1.6	2
Morus rubra	Red Mulberry	0.0	1.6	1.6	1
Cupressus forbesii	Tecate Cypress	0.0	1.7	1.7	1
Juglans californica	California Walnut	0.0	1.8	1.8	2
Juglans hindsii	California Black Walnut	0.0	1.8	1.8	2
Juglans nigra	Black Walnut	0.0	1.8	1.8	2
Juglans regia	English Walnut	0.0	1.8	1.8	1
Citrus sinensis	Navel Orange	0.0	1.8	1.8	1
Citrus sinensis	Valencia Orange	0.0	1.8	1.8	1
Ceanothus spinosus	Greenbark	0.0	1.8	1.8	1
Schinus molle	California Pepper	0.0	1.9	1.9	1
Acer floridanum	Silver Maple	0.0	2.0	2.0	1
Pinus canariensis	Canary Island Pine	0.0	2.1	2.1	1
Ceanothus thyrsiflorus	Blue Blossom	0.0	2.4	2.4	2
Acer circinatum	Vine Maple	0.0	2.8	2.8	2
Acer glabrum	Rocky Mountain Maple	0.0	2.8	2.8	2
Acer macrophyllum	Bigleaf Maple	0.0	2.8	2.8	2

Table 3. (*Continued*)

Botanical name	Common name	Isoprene $\mu g(g\ dry\ leaf\ wt)^{-1}\ h^{-1}$	monoterpenes	Iso. + mono.	Assign
Acer negundo	Box Elder	0.0	2.8	2.8	2
Acer palmatum	Japanese Maple	0.0	2.8	2.8	2
Acer saccharinum	Silver Maple	0.0	2.8	2.8	1
Ginkgo biloba	Ginkgo	0.0	3.0	3.0	1
Citrus limon	Lisbon Lemon	0.0	3.2	3.2	1
Quercus lobata	Valley Oak	3.4	0.0	3.4	1
Acer rubrum	Red Maple	0.0	3.5	3.5	1
Pinus albicaulis	Whitebark Pine	0.0	3.4	3.5	2
Pinus aristata	Bristlecone Pine	0.0	3.5	3.5	2
Pinus attenuata	Knobcone Pine	0.0	3.5	3.5	2
Pinus balfouriana	Foxtail Pine	0.0	3.5	3.5	2
Pinus contorta	Beach Pine	0.0	3.5	3.5	2
Pinus coulteri	Coulter Pine	0.0	3.5	3.5	2
Pinus edulis	Pinyon Pine	0.0	3.5	3.5	2
Pinus flexilis	Limbar Pine	0.0	3.5	3.5	2
Pinus jeffreyri	Jeffery Pine	0.0	3.5	3.5	2
Pinus lambertiana	Sugar Pine	0.0	3.5	3.5	2
Pinus monophylla	Singleleaf Pinyon Pine	0.0	3.5	3.5	2
Pinus monticola	Western White Pine	0.0	3.5	3.5	2
Pinus muricata	Bishop Pine	0.0	3.5	3.5	2
Pinus pinaster	Cluster Pine	0.0	3.5	3.5	2
Pinus ponderosa	Ponderosa Pine	0.0	3.5	3.5	2
Pinus quadrifolia	Four Needle Pinyon Pine	0.0	3.5	3.5	2
Pinus thunbergiana	Japanese Black Pine	0.0	3.5	3.5	2
Pinus torreyana	Torrey Pine	0.0	3.5	3.5	2
Harpephyllum caffrum	Kaffir Plum	0.0	4.2	4.2	3
Mangifera indica	Mango	0.0	4.2	4.2	3
Abies bracteata	Santa Lucia Fir	1.4	2.9	4.3	3
Abies concolor	White Fir	1.4	2.9	4.3	3
Abies grandis	Lowland Fir	1.4	2.9	4.3	3
Abies magnifica	Red Fir	1.4	2.9	4.3	3
Abies procera	Noble Fir	1.4	2.9	4.3	3
Pseudotsuga menziesii	Douglas Fir	1.4	2.9	4.3	3
Tsuga heterophylla	Western Hemlock	1.4	2.9	4.3	3
Tsuga mertensiana	Mountain Hemlock	1.4	2.9	4.3	3
Acacia baileyana	Bailey Acacia	0.0	4.7	4.7	2
Acacia farnesiana	Sweet Acacia	0.0	4.7	4.7	1
Acacia melanoxylon	Blackwood Acacia	0.0	4.7	4.7	2
Acacia subporosa	River Wattle	0.0	4.7	4.7	2
Sabel palmetto	Sabel Palmetto	4.7	0.4	5.1	1
Pinus taeda	Loblolly Pine	0.0	5.1	5.1	2
Picea sitchensis	Sitka Spruce	4.0	1.1	5.1	1
Pinus ellotii	Slash Pine	0.0	5.3	5.3	1
Ceanothus leucodermis	Chaparral Whitehorn	0.0	5.4	5.4	1
Albizia julibrissin	Silk Tree	4.3	1.4	5.7	3
Bauhinia variegata	Purple Orchid Tree	4.3	1.4	5.7	3
Calliandra haematocephela	Pink Powder Puff	4.3	1.4	5.7	3
Ceratonia siliqua	Carob	4.3	1.4	5.7	3
Cercidium floridum	Blue Palo Verde	4.3	1.4	5.7	3
Cercidium microphyllum	Foothills Palo Verde	4.3	1.4	5.7	3
Dalea spinosa	Smoke Tree	4.3	1.4	5.7	3
Erythrina caffra	Kaffirboom Coral Tree	4.3	1.4	5.7	3
Olneya tesota	Desert Ironwood	4.3	1.4	5.7	3
Parkinsonia aculeata	Jerusalem Thorn	4.3	1.4	5.7	3
Sophora japonica	Japanese Pagoda Tree	4.3	1.4	5.7	3
Tipuana tipu	Tipu Tree	4.3	1.4	5.7	3
Umbellularia californica	California Laurel	4.3	1.4	5.7	3
Schinus terebinthifolius	Brazilian Pepper	0.0	5.9	5.9	1
Chilopsis linearis	Desert Willow	0.0	5.9	5.9	3
Tabebuia chrysotricha	Golden Trumpet Tree	0.0	5.9	5.9	3
Pinus palustris	Longleaf Pine	0.0	5.9	5.9	1
Magnolia grandiflora	Magnolia	0.0	5.9	5.9	1
Magnolia soulangiana	Saucer Magnolia	0.0	5.9	5.9	2
Pinus sylvestris	Scots Pine	0.0	6.4	6.4	1
Xylosma congestum	Shiny Xylosma	6.8	0.0	6.8	1
Hevea brasiliensis	Rubber Tree	7.5	0.5	8.0	1
Quercus prinus	Chestnut Oak	6.5	1.5	8.0	1
Eucalyptus viminalis	Ribbon Gum	8.0	0.0	8.0	1
Salvia mellifera	Black Sage	0.0	8.3	8.3	1
Sequoia sempervirens	Coast Redwood	0.0	8.5	8.5	3
Sequoiadendron giganteum	Giant Sequoia	0.0	8.5	8.5	3

Table 3. (*Continued*)

Botanical name	Common name	Isoprene $\mu g(g\ dry\ leaf\ wt)^{-1}\ h^{-1}$	monoterpenes	Iso. + mono.	Assign
Taxodium sp.	Cypress	0.0	8.5	8.5	1
Quercus douglasii	Blue Oak	8.7	0.0	8.7	1
Serenoa repens	Saw Palmetto	8.9	0.0	8.9	1
Pistacia chinensis	Chinese Pistache	0.0	9.0	9.0	2
Pistacia vera	Kerman Pistachio	0.0	9.0	9.0	1
Quercus alba	White Oak	7.8	1.5	9.3	1
Pueraria lobata		9.6	0.0	9.6	1
Washingtonia filifera	California Fan Palm	9.9	0.0	9.9	1
Washingtonia robusta	Mexico Fan Palm	9.9	0.0	9.9	2
Liriodendron tulipifera	Tulip Tree	4.1	5.9	10.0	3
Quercus laurifolia	Diamond Leaf Oak	10.4	0.2	10.6	1
Platanus racemosa	Western Sycamore	10.9	0.0	10.9	1
Picea abies	Norwegian Spruce	10.1	1.2	11.4	2
Pinus clausa	Sand Pine	0.0	11.5	11.5	1
Picea breweriana	Brewer's Weeping Spruce	10.1	1.9	12.1	2
Quercus wislizenii	Interior Live Oak	12.5	0.0	12.5	1
Salix caroliniana	Coast Plain Willow	12.5	0.0	12.5	1
Eugenia grandis	Eugenia	12.1	2.1	14.1	3
Robinia pseudoacacia	Black Locust	11.8	2.3	14.1	1
Quercus myrtifolia	Myrtle Oak	15.2	0.2	15.4	1
Phoenix canariensis	Canary Island Date Palm	15.8	0.0	15.8	2
Phoenix dactlifera	Date Palm	15.8	0.0	15.8	1
Phoenix recliinata	Senegal Date Palm	15.8	0.0	15.8	2
Callistemon citrinus	Bottlebrush	16.0	0.0	16.0	1
Callistemon viminalis	Weeping Bottlebrush	16.0	0.0	16.0	2
Quercus rubra	Northern Red Oak	14.8	1.8	16.7	1
Trichostema lanatum	Woolly Blue Curls	0.0	17.7	17.7	1
Platanus acerifolia	London Plane Tree	19.2	0.0	19.2	2
Picea engelmannii	Engelmann Spruce	16.3	3.4	19.7	1
Quercus velutina	Black Oak	18.9	1.0	19.9	1
Quercus virginiana	Virginia Live Oak	20.2	0.3	20.5	1
Agonis flexuosa	Willow Myrtle	21.2	2.1	23.2	3
Feijoa sellowiana	Pineapple Guava	21.2	2.1	23.2	3
Melaleuca ericifolia	Heath Melaleuca	21.2	2.1	23.2	3
Melaleuca linariifolia	Flaxleaf Paperbark	21.2	2.1	23.2	3
Melaleuca quinquenervia	Cajeput Tree	21.2	2.1	23.2	3
Metrosideros excelsus	New Zealand Christmas Tree	21.2	2.1	23.2	3
Myrica californica	Pacific Wax-Myrtle	21.2	2.1	23.2	3
Psidium guajava	Guava	21.2	2.1	23.2	3
Syzygium paniculatum	Brush Cherry	21.2	2.1	23.2	3
Tristania conferta	Brisbane Box	21.2	2.1	23.2	3
Quercus coccinea	Scarlet Oak	20.1	3.2	23.3	1
Thelypteris decursive-pinnata		24.5	0.0	24.5	1
Quercus nigra	Water Oak	24.6	0.0	24.6	1
Quercus laevis	Scrub Oak	24.3	0.8	25.1	1
Nandina domestica	Heavenly Bamboo	25.1	0.0	25.1	1
Salix nigra	Black Willow	25.2	0.0	25.2	1
Fagus sp.	Beech	24.8	0.6	25.4	3
Quercus chrysolepis	Canyon Live Oak	24.8	0.6	25.4	2
Quercus durata	Leather Oak	24.8	0.6	25.4	2
Quercus engelmanii	Mesa Oak	24.8	0.6	25.4	2
Quercus falcata	Southern Red Oak	24.8	0.6	25.4	2
Quercus ilex	Holly Oak	24.8	0.6	25.4	2
Quercus kelloggii	California Black Oak	24.8	0.6	25.4	2
Quercus suber	Cork Oak	24.8	0.6	25.4	2
Ficus benjamina	Weeping Chinese Banyan	27.0	0.2	27.1	2
Ficus carica	Edible Fig	27.0	0.2	27.1	2
Ficus elastica	Rubber Plant	27.0	0.2	27.1	2
Ficus fistulosa	Fig	27.0	0.2	27.1	1
Ficus lyrata	Fiddleleaf Fig	27.0	0.2	27.1	2
Ficus macrocarpa	Indian Laurel Fig	27.0	0.2	27.1	2
Ficus macrophylla	Moreton Bay Fig	27.0	0.2	27.1	2
Ficus rubiginosa	Rustyleaf Fig	27.0	0.2	27.1	2
Mallotus paniculatis	Mallotus	26.4	0.8	27.2	3
Platanus occidentalis	American Sycamore	27.5	0.0	27.5	1
Artemisia californica	California Sagebrush	0.0	28.3	28.3	1
Baccharis pilularis	Coyote Brush	0.0	28.3	28.3	3
Euryops pectinatus	Euryops Daisy	0.0	28.3	28.3	3
Rhamnus californica	Coffeeberry	29.3	0.0	29.3	1
Quercus dumosa	California Scrub Oak	29.8	0.0	29.8	1
Quercus borealis	Red Oak	30.1	0.0	30.1	1

Table 3. (*Continued*)

		Isoprene	monoterpenes		
Botanical name	Common name	μg(g dry leaf wt)$^{-1}$ h^{-1}		Iso. + mono.	Assign
Quercus phellos	Willow Oak	32.2	0.0	32.2	1
Myrtus communis	Common Myrtle	34.0	0.0	34.0	1
Quercus agrifolia	Coast Live Oak	35.3	0.0	35.3	1
Populus deltoides	Eastern Cottonwood	37.0	0.0	37.0	1
Eucalyptus camaldulensis	Red Gum	32.5	4.6	37.1	2
Eucalyptus citriodora	Lemon-Scented Gum	32.5	4.6	37.1	2
Eucalyptus erythrocorys	Red-Cap Gum	32.5	4.6	37.1	2
Eucalyptus gunnii	Cider Gum	32.5	4.6	37.1	2
Eucalyptus maculata	Spotted Eucalyptus	32.5	4.6	37.1	2
Eucalyptus polyanthemos	Silver Dollar Gum	32.5	4.6	37.1	2
Eucalyptus rudis	Flooded Gum	32.5	4.6	37.1	2
Eucalyptus sideroxylon	Red Ironbark	32.5	4.6	37.1	2
Liquidambar formosana	Chinese Sweet Gum	18.9	19.1	38.0	2
Liquidambar styraciflua	Liquidambar	18.9	19.1	38.0	1
Rhamnus crocea ilicifolia	Hollyleaf Redberry	41.9	0.0	41.9	2
Populus angustifolia	Narrowleaf Cottonwood	43.6	0.0	43.6	2
Populus fremontii	Fremont Cottonwood	43.6	0.0	43.6	2
Populus trichocarpa	Black Cottonwood	43.6	0.0	43.6	2
Quercus incana	Bluejack Oak	45.6	0.2	45.8	1
Macaraunga triloba	Macauranga	45.3	0.7	46.0	1
Populus termuloides	Quaking Aspen	50.2	0.0	50.2	1
Salix lasiandra	Western Black Willow	50.9	0.0	50.9	2
Salix lasiolepis	Arroyo Willow	50.9	0.0	50.9	2
Salix scouleriana	Scouler Willow	50.9	0.0	50.9	2
Cupaniopsis anacardioides	Carrotwood	50.9	0.0	50.9	1
Koelreuteria bipinnata	Chinese Flametree	50.9	0.0	50.9	3
Koelreuteria paniculata	Goldenrain Tree	50.9	0.0	50.9	3
Rhamnus crocea	Redberry	54.4	0.0	54.4	1
Quercus garryana	Oregon White Oak	59.2	0.6	59.8	2
Eucalyptus globulus	Blue Gum Eucalyptus	57.0	9.2	66.2	1
Quercus robur	European Oak	76.6	0.6	77.2	2
Salix babylonica	Weeping Willow	115.0	0.0	115	1
Elaeis guinensis	Palm Oil Tree	172.9	0.1	173	3
Aesculus californica	California Buckeye	***	***	***	4
Ailanthus altissima	Tree-of-Heaven	***	***	***	4
Alnus cordata	Italian Alder	***	***	***	4
Alnus oregona	Red Alder	***	***	***	4
Alnus rhombifolia	White Alder	***	***	***	4
Alnus tenuifolia	Mountain Alder	***	***	***	4
Araucaria bidwilli	Bunya-Bunya	***	***	***	4
Araucaria spp.	Araucaria	***	***	***	4
Archontophoenix cunninghamiana	King Palm	***	***	***	4
Arecastrum romanzoffianum	Queen Palm	***	***	***	4
Betula lenta	Sweet Birch	***	***	***	4
Betula nigra	River Birch	***	***	***	4
Betula occidentalis	Streamside Birch	***	***	***	4
Betula pendula	European White Birch	***	***	***	4
Bougainvillea spp.	Bougainvillea	***	***	***	4
Brachychiton acerifolius	Flame Tree	***	***	***	4
Brachychiton populneus	Bottle Tree	***	***	***	4
Brahea edulis	Guadalupe Palm	***	***	***	4
Brahea spp.	Brahea Palm	***	***	***	4
Camellia japonica	Common Camellia	***	***	***	4
Carica papaya	Papaya	***	***	***	4
Cedrella fissilis	Cedrella	***	***	***	4
Cephalanthus occidentalis	Buttonbush	***	***	***	4
Chamaerops humilis	Mediterranean Palm	***	***	***	4
Chorisia speciosa	Silk-Floss Tree	***	***	***	4
Coprosma repens	Mirror Plant	***	***	***	4
Cordyline australis	Bronze Dracaena	***	***	***	4
Cornus nutalli	Pacific Dogwood	***	***	***	4
Cornus sp.	Dogwood	***	***	***	4
Cornus stolonifera	Redstem Dogwood	***	***	***	4
Crassula argentea	Jade Plant	***	***	***	4
Davidia involucrata	Dove Tree	***	***	***	4
Dendromecon harfordii	Island Bushpoppy	***	***	***	4
Diospyros virginiana	American Persimmon	***	***	***	4
Escallonia exoniensis	Escallonia	***	***	***	4
Euonymus japonica	Evergreen Euonymus	***	***	***	4
Fremontodendron californicum	Common Flannel Bush	***	***	***	4

Table 3. (*Continued*)

Botanical name	Common name	Isoprene μg(g dry leaf wt)$^{-1}$ h^{-1}	monoterpenes	Iso. + mono.	Assign
Fremontodendron mexicanum	Southern Flannel Bush	***	***	***	4
Garrya elliptica	Coast Silktassel	***	***	***	4
Grevillea robusta	Silk Oak	***	***	***	4
Grevillea rosmarinifolia	Rosemary Grevillea	***	***	***	4
Hebe buxifolia	Boxleaf Hebe	***	***	***	4
Hibiscus rosa-sinensis	Chinese Hibiscus	***	***	***	4
Justicia brandegeana	Shrimp Plant	***	***	***	4
Maytenus boaria	Mayten Tree	***	***	***	4
Melia azedarach	Chinaberry	***	***	***	4
Musa paradisiaca	Banana	***	***	***	4
Myoporum laetum	Myoporum	***	***	***	4
Nicotiana glauca	Tree Tobacco	***	***	***	4
Nyssa sylvatica	Black Gum	***	***	***	4
Plumbago auriculata	Cape Plumbago	***	***	***	4
Punica granatum	Pomegranate	***	***	***	4
Sapium sebiferum	Chinese Tallow Tree	***	***	***	4
Schefflera actinophylla	Octopus Tree	***	***	***	4
Stenocarpus sinuatus	Firewheel Tree	***	***	***	4
Strelitzia nicolai	Giant Bird of Paradise	***	***	***	4
Taxus brevifolia	Western/Oregon Yew	***	***	***	4
Torreya californica	California Nutmeg	***	***	***	4
Trachycarpus fortunei	Windmill Palm	***	***	***	4
Yucca brevifolia	Joshua Tree	***	***	***	4
Yucca elephantipes	Giant Yucca	***	***	***	4

Emission rate, expressed as μg(g dry leaf wt)$^{-1}$ h^{-1}, corrected to an ambient temperature of 30°C. "Assign" column indicates the method for assigning emission rates to each species: 1 = direct measurement; 2 = assigned based on genus average; 3 = assigned based on family average; 4 = no emission rate assigned.

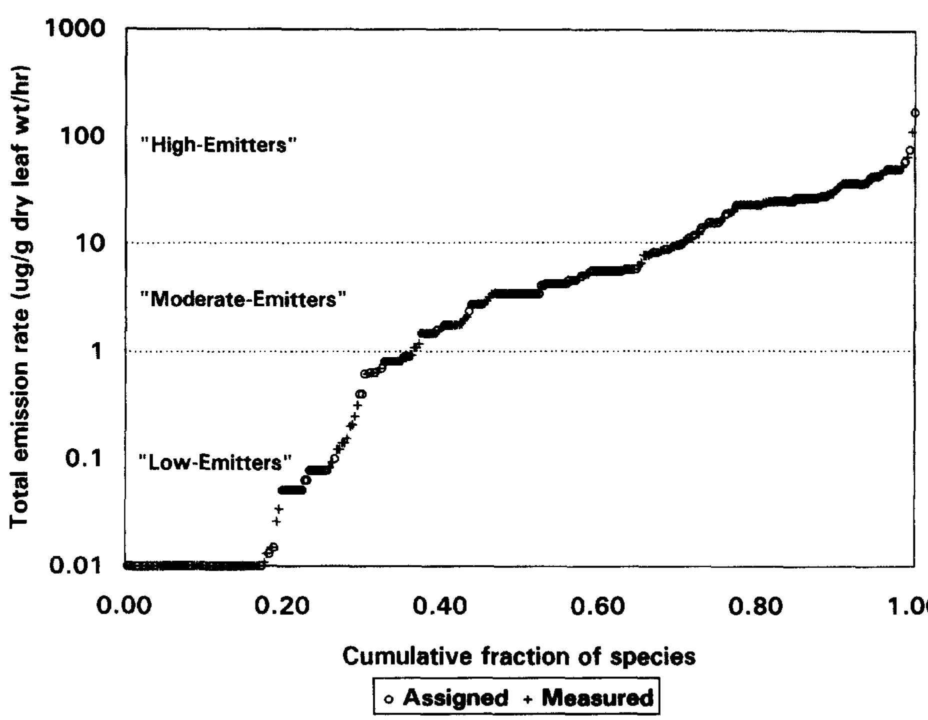

Fig. 2. Total (isoprene and monoterpenes) emission rate vs cumulative fraction of the 316 species for which emission rates were measured or assigned. Species for which zero emission rates were assigned or measured are shown as having emission rates of 0.01 μg(g dry leaf wt)$^{-1}$ h^{-1}.

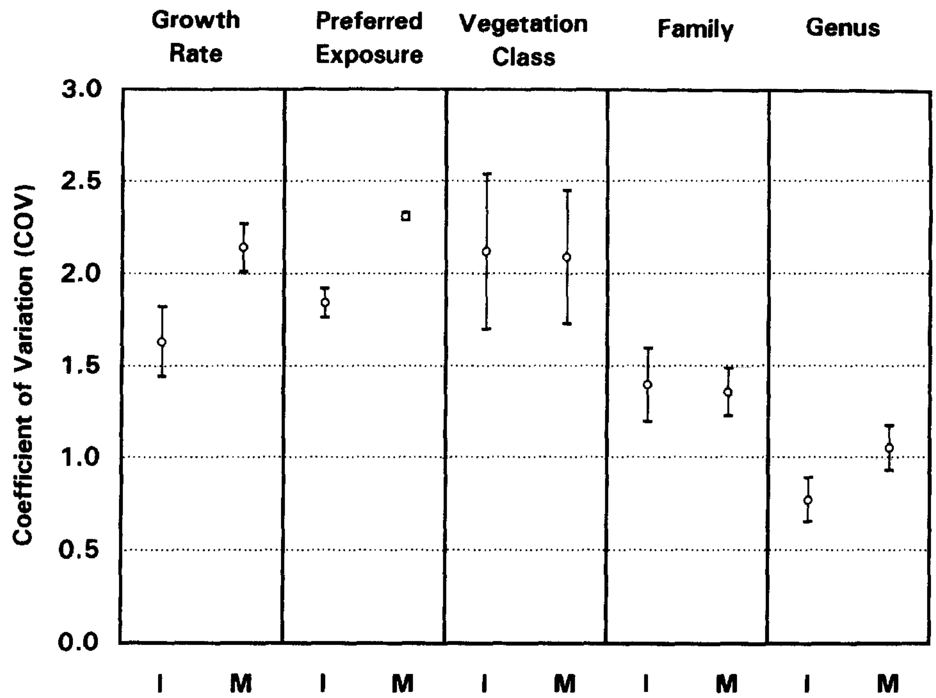

Fig. 3. Comparison of the mean and 95% confidence intervals of the coefficient of variation (COV) of different methods for assigning isoprene and monoterpene emission rates. COVs for each method were calculated using only those 124 species for which emission rates have been measured.

0 TPD for a similar number of low-emitting tree species. Although negligible when compared on a mass basis to the present anthropogenic VOC inventory of approximately 1500 TPD, the relative contribution of these additional biogenic VOCs to ozone formation in the SoCAB is significantly enhanced when their higher reactivities are taken into account (Benjamin and Winer, 1996) and given that anthropogenic VOCs in the SoCAB are to be reduced to only about 300 TPD by 2010 (AQMP, 1994). Hence, the selection of low-emitting tree species can be critical in urban airsheds where large-scale tree planting programs are being implemented for energy conservation, heat island mitigation, and air pollution abatement. Unfortunately, however, biogenic emission rates have been measured for only a fraction of relevant plant species because of the high cost and substantial effort involved in making such measurements.

Using reported biogenic hydrocarbon emission rates, algorithms normalizing for temperature and light intensity, and appropriate taxonomic relationships, we have ranked most of 377 tree and shrub species found in the California SoCAB according to the sum of their hourly emission rates of isoprene and monoterpenes. This ranking allows us to identify low-emitting species for consideration for massive tree planting programs. Of the 316 species for which emission rates were measured or assigned, approximately 36% have emission rates lower than the 1 μg (g dry leaf wt)$^{-1}$ h^{-1} emissions threshold we defined as "low-emitters".

Compared to the other assignment schemes examined in this paper, the phylogenetic method is phytochemically and statistically the most robust means of assigning emission rates. Although the differences between reported emission rates within the genus and family levels can be large, when compared with the four orders of magnitude difference between the lowest and highest emitters, the taxonomic approach appears to provide an adequate first-order approximation of hydrocarbon emission rates for the many trees for which experimental measurements have not been made.

However, research determining species-specific emission rates is needed to provide a more complete coverage of biogenic emissions from tree species planted within the SoCAB and other major airsheds, and to validate the taxonomic relationship methodology. Conversely, the use of taxonomic relationships provides a cost- and time-effective basis for focusing future experimental emission rate measurements on the most important data gaps. Specifically, future efforts should concentrate on those tree species nominally predicted to be low emitters of biogenic hydrocarbons but for which no data exist, and on those tree species which will provide the most rigorous testing and validation of the taxonomic approach. By extension, this should improve the reliability of biogenic emissions inventories and allow positive identification of low-emitting tree species. However, better methods for standardization of emission rate measurements, taking into account all of the important variables, are also needed in future experimental studies. We emphasize that although biogenic hydrocarbon emission rates are an important factor to consider when deciding on which trees and shrubs should be planted, a wide range of horticultural and landscape factors, both biological and physical, must also be critically analyzed. Such factors include water requirements, fire hazard, disease and pollution resistance, aesthetics, growth rate, health of the plant, organic debris production, and allergin potential.

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