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Plant species composition, calculated leaf masses and estimated biogenic emissions of urban landscape types from a field survey in Phoenix, Arizona

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Abstract

Vegetation in the Phoenix, Arizona, metropolitan area was surveyed using a modified stratified random sampling design to identify plant species and to measure foliar volumes for species-specific calculation of leaf mass. We identified the genus and species and measured the crown dimensions of plants located in a park and parking lot, and in three types of urban landscapes: flood-irrigated, mesic and xeric. Species compositions of these landscape types were compared quantitatively using a Sorenson index of similarity and the landscape types were found to be dissimilar. The three landscape types varied in calculated leaf masses and the respective identities of the dominant species, and relatively few plant species accounted for the majority of the leaf mass. Plant species and leaf mass data were used to estimate relative contributions from each landscape type of the biogenic volatile organic compounds isoprene and monoterpenes. Results from this study have implications for future plant surveys taken for biogenic emissions inventory development, and for plant species selection for urban landscapes, especially large-scale tree planting programs. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Leaf mass; Urban landscape; Mesic landscape; Xeriscape; Biogenic emissions; BVOC

1. Introduction

Green plants confer numerous physical and aesthetic benefits in urban environments. Plants sequester carbon dioxide and release oxygen, and surfaces allow deposition of pollutants. Trees provide shade and their transpiration cools air beneath canopies, which can mitigate urban heat islands and lower energy consumption for air conditioning (Akbari et al., 1992; McPherson, 1998; Scott et al., 1998; Simpson, 1998). These effects help reduce air pollution levels in urban areas. However, in addition to the release of oxygen, green plants emit trace (biogenic) gases, including volatile organic compounds (VOC) (Isidorov et al., 1985; Sharkey et al., 1991; Winer et al., 1992). Emitting vegetation has been shown to include plant species from urban landscapes, agricultural crops, and natural plant communities (Winer et al., 1983, 1992; Corchnoy et al., 1992; Arey et al., 1995; Benjamin et al., 1996; BEMA, 1997; Csiky and Seufert, 1999).

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VOC from both natural and anthropogenic sources can react in the lower atmosphere in the presence of oxides of nitrogen (NO*x*) to form ozone and other chemical compounds in photochemical smog (Finlayson-Pitts and Pitts, 2000). Biogenic VOC (BVOC) emissions may be an important or even dominant VOC source in certain airsheds (Chameides et al., 1988), and accurate estimates of the magnitude of BVOC contributions are critical in formulating effective strategies to reduce photochemical air pollution (Milford et al., 1989; NRC, 1991). For example, in the Tucson, AZ metropolitan area, seasonal changes of BVOC emissions may be responsible for switching from a VOC-limited to NO*x*-limited urban atmosphere (Diem, 2000). For an arid environment such as that of Maricopa County, AZ, BVOC contributions of urban plants may be relatively more important than for cities in wetter climates because of the sparse vegetation found in the surrounding desert.

BVOC emissions inventories require data on plant species composition and leaf masses (Geron et al., 1994; Benjamin et al., 1997; Benjamin et al., 1998). The need for such inventories has prompted development of methodologies for obtaining quantitative descriptions of urban plant communities in cities and regions of interest. For natural plant communities, species identities and numerical values for leaf masses may be available from forest inventories or landcover databases (Davis et al., 1995; Guenther, 1997; Kinnee et al., 1997; Karlik and McKay, 1999; Chung and Winer, 1999). However, analogous data are not generally available for urban areas, so a field study characterizing plant species identities and foliar volumes can be a first step toward a quantitative description of an urban landscape.

Two previous studies in the Los Angeles basin included field surveys addressing species composition of urban vegetation in that large region (Miller and Winer, 1984; Horie et al., 1991). However, no similar quantitative data were available to describe plant species identities and corresponding foliar masses for the Phoenix metropolitan area. Therefore, a limited field study was conducted to provide data on species composition and plant crown dimensions. These data were then used to calculate crown volumes and leaf masses, and to estimate relative BVOC contributions from urban landscape types in Maricopa County.

2. Methods

2.1. Identification of urban areas of homogeneous vegetation

Since the highest ozone concentrations measured in Maricopa County occurred in the northeast section of Phoenix (MAG, 1995), the field study emphasized vegetation in that portion of the County. For the urban area, the approach taken was similar to that of past studies (Winer et al., 1983; Miller and Winer, 1984; Horie et al., 1991), in which areas of relatively homogenous composition of vegetation were identified, followed by field assessments and measurements. In a desert climate, such as that of Phoenix, irrigation is required to sustain an urban landscape, and irrigation methods have varied over time, depending on delivery systems and perceived abundance of water. Plant selection has also been influenced by these factors. Following a consultation with individuals familiar with local urban landscapes (Mikel, 1995; Rademacher, 1995), the urban area was divided into three landscape types based on irrigation regimen: flood-irrigated, mesic and xeric. A park and a parking lot were also surveyed.

The flood-irrigated landscape type represented the oldest residential area in Phoenix, developed in the 1950s and 1960s. Prior to residential development, this area was agricultural, mostly containing citrus orchards, and mature orange trees remained as reminders of the earlier land use. Well-adapted plants from original residential landscapes had survived 30 years or more. Turfgrass was sustained by flood irrigation, requiring low berms around lawn areas extending to the property lines in both the front- and back-yards.

The mesic landscape type was found in neighborhoods developed in the 1970s and early 1980s. Sprinkler irrigation was used to deliver water to landscaped areas which often contained large shade trees. Turfgrass was common in front- and back-yards.

The xeric area represented newer neighborhoods, such as those in the northeast suburbs of Phoenix, which began to be built in the mid-1980s. Urban expansion in the arid Southwest has been accompanied by limited availability of water. Research related to water use within landscape components and plant consumptive water use rates has resulted in formulation of xeriscape landscape design principles emphasizing water conservation (O'Brien, 1989), which include incorporation of adapted plant species and effective use of turf. Shrubs and trees found in this landscape type included native species which could survive with limited quantities of irrigation water. Areas of turfgrass were limited, and lawns were usually confined to backyards where they were likely to be used as recreational surfaces in addition to providing aesthetic benefit.

2.2. Field procedures

After gaining permission to survey the home grounds within neighborhoods of the requisite irrigation type, plant identities were recorded and foliar dimensions measured. Tree heights less than 5.5 m were measured with a steel tape while tree heights greater than 5.5 m were measured with a clinometer. Canopy radius, taken as the distance from the trunk to the dripline, was measured with a steel tape for most trees except the largest, for which a measuring wheel was used. For shrubs, the height, width and length of plants were measured to the nearest 0.1 m with a steel tape. Plants with contiguous foliage, such as hedges, were recorded as a unit without attempting to count the number of rooted stems. Consequently, frequency data for shrubs indicate the number of plant groups where more than one stem may be represented. Trees were always measured individually so the number of plantings was equivalent to the number of individual trees.

Plant volumes were approximated by assigning simple geometric solids, such as cylinders, cones and rectangular prisms, to foliar masses (Winer et al., 1983; Horie et al., 1991; Karlik and Winer, 1999). The volume of oriental arborvitae (*Platycladus orientalis)* was calculated based on green foliage only. Other plants were found generally to be uniform in live foliage and the entire volume was used in subsequent calculations.

2.3. Assignment of leaf mass constants and calculation of leaf mass per hectare

Foliar masses for each plant species were calculated by multiplying foliar volume by a leaf mass constant, with units of grams dry leaf mass per cubic meter of crown volume (Miller and Winer, 1984; Horie et al., 1991; Karlik and Winer, 1999). Whenever possible, experimentally determined values for leaf mass constants were assigned (Winer et al., 1983; Miller and Winer, 1984). Where leaf mass constants based on experimental data were not available, a value for a related species or structural class was used (Horie et al., 1991). For each landscape type, leaf mass per species was calculated by summing the volumes for each species within the sampled areas, multiplying the sum by the leaf mass constant, and then normalizing to one hectare by considering the total area sampled.

2.4. Assignment of BVOC emission rates and calculation of emissions per hectare under standard environmental conditions

The emissions per species per hectare for each landscape type were calculated by multiplying the normalized leaf mass per hectare of each species by its isoprene or monoterpene emission rate under standard conditions of photosynthetically active radiation (PAR) flux of 1000 μmol m^{-2} s^{-1}, and of temperature of 30°C (Guenther et al., 1993). Plant species emission rates were assigned using a tabulation of measured emission rates (Horie et al., 1991; Benjamin et al., 1996), or, where no published rates were available, using a taxonomic approach (Benjamin et al., 1996; Benjamin et al., 1997). For each urban landscape type, emissions for all plant species normalized to an area of one hectare were summed to provide a comparison of estimated emissions for each landscape type under standard conditions.

3. Results

3.1. Urban plant species identified

Surveyed areas from the three landscape types contained vegetation, but did not include areas of streets, swimming pools, or hardscapes. The areas surveyed were unequal, mostly due to access. Additional effort was focused on the xeric landscape type because it represented ongoing development in the Phoenix area.

Genera of trees and shrubs common in urban landscapes throughout the west were found in the three landscape types, as seen in Tables 1–3, including

Table 1
Tree and shrub species identified in 3450 m^2 of vegetated area in the flood-irrigated landscape type

Scientific name	Common name	Plantings (No.)[a]
Albizia julibrissin	Mimosa	1
Bougainvillea sp.	Bougainvillea	5
Camellia japonica	Camellia	1
Carya illinoensis	Pecan	1
Citrus sinensis	Orange	25
Citrus paradisi	Grapefruit	5
Euonymus fortunei	Euonymus	5
Euryops pectinatus	Euryops daisy	4
Fraxinus velutina	Arizona ash	3
Gardenia jasminoides	Gardenia	1
Geijera parviflora	Australian willow	1
Hibiscus rosa-sinensis	Hibiscus	1
Jasminium sp.	Jasmine	2
Juniperus chinensis 'pfitzer'	Pfitzer juniper	4
Justicia spigera	Firecracker plant	1
Laurus nobilis	European bay	1
Leucophyllum frutescens	Texas ranger	1
Myrtis communis	Myrtle	2
Nerium oleander	Oleander	3
Pinus eldarica	Mondell pine	2
Pinus halepensis	Aleppo pine	1
Pistachia chinensis	Chinese pistache	2
Pittosporum tobira	Pittosporum	1
Pittosporum tobira variegata	Variegated pittosporum	2
Platanus racemosa wrightii	Arizona sycamore	1
Platycladus orientalis	Oriental arborvitae	4
Podocarpos macrophylla	Fern pine	1
Prunus domestica	Plum	2
Pyracantha sp.	Pyracantha	7
Rhus lancea	African sumac	2
Robinia pseudoacacia	Black locust	1
Rosa hybrida	Rose	14
Rosmarinus officinalis	Rosemary	2
Rosmarinus officinalis 'prostrata'	Prostrate rosemary	1
Tecomaria capensis	Cape honeysuckle	2
Trachelospermum jasminoides	Star jasmine	1
Vitis vinifera	Grape	1
Washingtonia robusta	Mexican fan palm	1

[a] Plants in hedges and groups were not counted separately. However, trees were always counted as individuals.

Fraxinus (ash), *Juniperus* (junipers), and *Euonymus* (euonymus). The landscapes of the Phoenix metropolitan area also contained plants found in surrounding natural areas, such as *Cercidium* sp. (palo verde), and subtropical plants suited for the warm low-desert climate, such as *Bougainvillea*. *Citrus sinensis* (orange) trees, *Bougainvillea*, and *Rosa hybrida* (roses) were the plants found most frequently within the three landscape types. Although, citrus trees were found in all three landscape types, those in the flood-irrigated landscapes were oldest and most numerous, apparently remnants of commercial groves. The flood-irrigated landscape, which was the oldest landscape-type, contained many genera noted for their durability, for example, *Pittosporum* (mockorange) and *Nerium* (oleander).

Turfgrass or groundcovers were present in vegetated areas not occupied by shrubs in almost all the

Table 2
Tree and shrub species identified in a vegetated area of 1720 m^2 in the mesic landscape type

Scientific name	Common name	Plantings (No.)[a]
Acacia sp.	Acacia	1
Asparagus sprengeri	Asparagus fern	1
Bougainvillea sp.	Bougainvillea	3
Buddleia davidii	Butterflybush	2
Caesalpinia pulcherrima	Mexican bird-of-paradise	2
Carissa grandiflora	Natal plum	1
Citrus limon	Lemon	1
Citrus paradisi	Grapefruit	1
Citrus sinensis	Orange	3
Citrus paradisi × C. reticulata	Tangelo	1
Cupressus sempirvirens	Italian cypress	2
Cyperus alternifolius	Umbrella plant	2
Ficus edulis	Edible fig	1
Fraxinus velutina	Arizona ash	2
Jasminium sp.	Jasmine	1
Juniperus chinensis ‘pfitzer’	Pfitzer juniper	2
Juniperus chinensis	Chinese juniper	2
Lantana camara	Lantana	2
Ligustrum sp.	Privet	1
Morus alba	Mulberry	1
Myrtis communis	Myrtle	1
Nerium oleander	Oleander	3
Pittosporum tobira	Pittosporum	1
Pittosporum tobira ‘variegata’	Variegated pittosporum	1
Platycladus orientalis	Oriental arborvitae	4
Prunus persica	Peach	1
Rhus lancea	African sumac	1
Rosa hybrida	Rose	2
Syagrus romanzoffiana	Queen palm	1
Thevetia peruviana	Yellow oleander	1
Washingtona filifera	California fan palm	4
Washingtonia robusta	Mexican fan palm	2
Xylosma congestum	Xylosma	1
Yucca sp.	Yucca	1

[a] Plants in hedges and groups were not counted separately. However, trees were always counted as individuals.

flood-irrigated and mesic landscapes. In contrast, turf and groundcovers occupied only about 20% of the xeric vegetated area. *Cynodon dactylon* (bermudagrass) was the groundcover most often observed in all three landscape types and occupied the largest area.

The xeric landscape type was of particular interest in species composition. The legume family was especially well represented. Most desert natives observed, such as *Cercidium* species, were not found in the other landscape types. However, the xeric landscape type contained many plants also found in the mesic or flood-irrigated landscape types, such as *Pyracantha*. Certain plants found in the xeric landscape type, e.g. the *Caesalpinia* species (desert bird-of-paradise), have been used extensively in the Phoenix area along freeways and in other non-residential settings.

In an urban landscape, a relationship describing the number of species identified per size of sampled area may give an indication of the appropriate area to be sampled in future studies. In a natural system, the cumulative number of plant species generally increases in proportion to the log of the area sampled (Primack, 1993). To explore this relationship for the three landscape types, the cumulative number of plant species identified was plotted against the log of area sampled (Fig. 1), and the coefficients of determination

Table 3
Tree and shrub species identified in vegetated area of 7780 m^2 in the xeric landscape type

Scientific name	Common name	Plantings (No.)[a]
Acacia saliciana	Acacia	1
Bougainvillea sp.	Bougainvillea	30
Brachychiton populneus	Bottle tree	2
Butia capitata	Pindo palm	4
Caesalpinia gilliesii	Desert bird-of-paradise	1
Caesalpinia mexicana	Mexican bird-of-paradise	1
Caesalpinia pulcherrima	Mexican bird-of-paradise	8
Callistemon citrinus	Bottlebrush	7
Carissa grandiflora	Natal plum	4
Cassia artemisiodes	Feathery cassia	18
Cercidium floridum	Blue palo verde	1
Cercidium microphyllum	Littleleaf palo verde	1
Cercidium praecox	Palo brea	1
Chaemerops humilis	Mediterranean fan palm	8
Citrus paradisi	Grapefruit	3
Citrus sinensis	Orange	10
Cupressus sempirvirens	Italian cypress	2
Cycas revoluta	Sago palm	2
Cyperus alternifolius	Umbrella plant	2
Dalbergia sissoo	Dalbergia	1
Dodonea viscosa	Hopseedbush	1
Eucalyptus sp.	Eucalyptus	14
Euonymus fortunei	Euonymus	1
Euryops pectinatus	Euryops daisy	1
Ficus sp.	Fig	1
Fraxinus velutina	Arizona ash	1
Gardenia jasminoides	Gardenia	1
Hibiscus rosa-sinensis	Hibiscus	2
Jacaranda acutifolia	Jacaranda	1
Jasminium sp.	Jasmine	1
Juniperus chinensis	Chinese juniper	25
Juniperus horizontalis	Horizontal juniper	2
Laegerstroemia indica	Crape myrtle	1
Lantana camara	Bush lantana	4
Leucophyllum frutescens	Texas ranger	8
Ligustrum sp.	Privet	5
Myrtis communis	Myrtle	2
Nandina domestica	Nandina	1
Nandina domestica ‘compacta’	Nandina dwarf	2
Nerium oleander	Oleander	10
Nerium oleander ‘petite’	Oleander dwarf	13
Olea europaea	Olive	8
Pennisetum setaceum	Fountain grass	1
Pennisetum setaceum purpurea	Purple fountain grass	6
Phoenix dactylifera	Date palm	3
Photinia fraseri	Photinia	1
Pinus halepensis	Aleppo pine	5
Pithecellobium flexicaule	Texas ebony	1
Pittosporum tobira ‘variegata’	Variegated pittosporum	1
P. tobira ‘Wheeler’s dwarf’	Dwarf pittosporum	3
Platycladus orientalis	Oriental arborvitae	4
Prosopis chilensis	Mesquite	7
Prunus cerasifera ‘krauter vesuvius’	Purpleleaf plum	1

Table 3 (*Continued*)

Scientific name	Common name	Plantings (No.)[a]
Pyracantha sp.	Pyracantha	24
Raphiolepis indica	Raphiolepis	2
Rhus lancea	African sumac	4
Rosa hybrida	Rose	16
Rosemarinus officinalis 'prostrata'	Prostrate rosemary	1
Rosmarinus officinalis	Rosemary	3
Ruellia peninsularia	Blue ruellia	6
Santolina chamaecyparissus	Gray santolina	1
Sophora secundiflora	Mescal bean	3
Syagrus romanzoffiana	Queen palm	21
Tecomaria capensis	Cape honeysuckle	2
Thevetia peruviana	Yellow oleander	5
Ulmus parvifolia	Chinese elm	1
Washingtonia robusta	Mexican fan palm	25
Xylosma congestum	Xylosma	2
Yucca sp.	Yucca	3
Unknown		4

[a] Plants in hedges and groups were not counted separately. However, trees were always counted as individuals.

for a linear regression were greater than 0.87 for each landscape type. The slope of the regression line was greatest for the xeric landscape type, perhaps reflecting the number of native and exotic species available for water-conserving landscapes and the efforts of landscape architects to make xeriscape design varied and attractive.

3.2. Leaf mass of predominant species in surveyed landscapes

A small number of species, and in some cases a few specimens, within each landscape type accounted disproportionately for calculated volumes (Table 4) and leaf masses (Table 5) within the sampled areas.

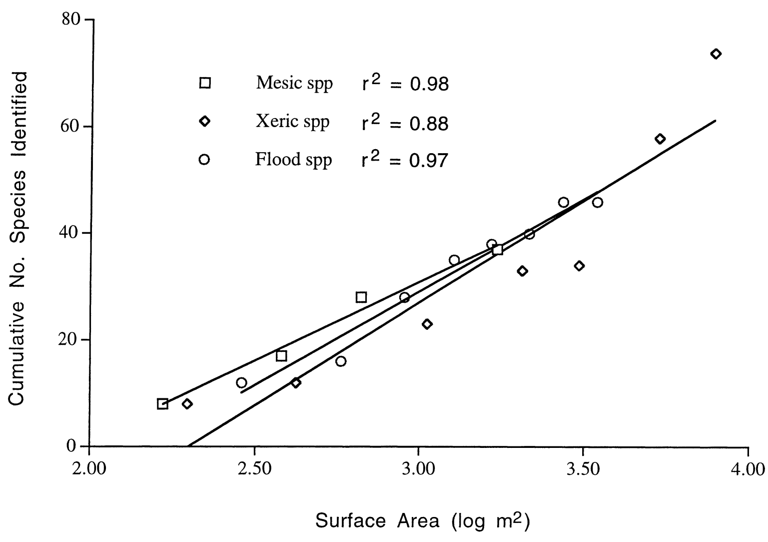

Fig. 1. Number of species identified in three Phoenix landscape types plotted against the log of the surface area surveyed.

Table 4
Predominant species found in urban landscapes in Phoenix, Arizona, ranked by calculated volume per hectare

Plant		Plantings (No.)	Volume (m^3 ha^{-1})
Scientific name	Common name		
Flood-irrigated landscape			
Citrus sinensis	Orange	25	1360
Rhus lancea	African sumac	2	810
Pinus halepensis	Aleppo pine	1	670
Citrus paradisi	Grapefruit	5	560
Albizzia julibrissin	Mimosa	1	440
Mesic landscape			
Morus alba	Mulberry	1	390
Rhus lancea	African sumac	1	360
Citrus reticulata × paradisi	Tangelo	1	340
Citrus sinensis	Orange	3	240
Ficus edulis	Edible fig	1	230
Xeric landscape			
Eucalyptus sp.	Eucalyptus	14	4400
Prosopis chilensis	Chilean mesquite	7	1700
Olea europaea	Olive	8	700
Pinus halepensis	Aleppo pine	5	580
Cercidium floridum	Blue palo verde	1	24

Table 5
Predominant species found in urban landscapes in Phoenix, Arizona ranked in order of calculated leaf mass per hectare

Plant		Plantings (No.)	Leaf mass (kg ha^{-1})
Scientific name	Common name		
Flood-irrigated			
Citrus sinensis	Orange	25	1110
Platycladus orientalis	Oriental arborvitae	4	870
Pinus halepensis	Aleppo pine	1	760
Rhus lancea	African sumac	2	470
Citrus paradisi	Grapefruit	5	450
Mesic			
Platycladus orientalis	Oriental arborvitae	4	4210
Juniperus chinensis	Pfitzer juniper	2	680
Citrus reticulata × paradisi	Tangelo	1	550
Rhus lancea	African sumac	1	420
Citrus sinensis	Orange	3	390
Xeric			
Eucalyptus sp.	Eucalyptus	14	1540
Olea europaea	Olive	8	400
Washington robusta	Mexican fan palm	25	380
Prosopis chilensis	Chilean mesquite	7	290
Pinus halepensis	Aleppo pine	5	260

For example, the five predominant species listed for each landscape type (Table 4) accounted for more than 60% of the foliar volume for the flood-irrigated and mesic landscape types, respectively, and more than 80% of the foliar volume for the xeric landscape type. As expected, plant species with high volumes, such as certain shade tree species, tended to have large calculated leaf masses. For example, the five predominant species listed for each landscape type (Table 5) accounted for more than 65% of calculated leaf mass for each type. The high leaf mass constants for oriental arborvitae and junipers, made these species important in terms of leaf mass per hectare despite relatively smaller crown volumes.

3.3. Similarity of vegetation of landscape types

Landscape types were compared using a Sorenson index of similarity (Miller and Winer, 1984). The Sorenson index is equal to $2c/(a+b)$, where c is the number of species in common to both landscapes, and a and b are the total numbers of species in each landscape. A value approaching 1.0 indicates high similarity in species present in the two landscapes. Landscape types found in Phoenix had relatively lower indices of similarity, 0.33–0.44, among them than those of landscapes previously surveyed in the Los Angeles basin, in which 45 of the 70 landscape comparisons had indices of similarity between 0.44 and 0.63 (Miller and Winer, 1984). The low indices of similarity among landscape types found in Phoenix supported our separation based on irrigation regimen.

3.4. Park and parking lot

Common bermudagrass was established throughout the vegetated area of the park. *Eucalyptus* was the most common genus of trees, and had a calculated leaf mass more than twice that of all other trees and shrubs combined. The most common parking lot tree genus was *Fraxinus*. Calculated leaf mass for the parking lot was small, as would be expected.

4. Discussion

4.1. Comparison of results with previous studies

In the present study, data for urban vegetation are reported in units of grams dry leaf mass per hectare of vegetated area rather than total area. As seen in Table 6, leaf mass per hectare for different land uses has been reported (Horie et al., 1991; Tanner et al., 1992). To compare the results of the present study to these data, a coefficient must be introduced corresponding to the fraction of total area which was vegetated for each of the urban landscape types in Maricopa County. The vegetated area in Los Angeles was found to vary from 9 to 58% of total area among the polygons in the urban Los Angeles area, (Brown and Winer, 1986) and an intermediate value of 35% may be a rough approximation for adjusting vegetated area to total area in Phoenix. Although, the values for leaf mass per hectare from the present study appear to be higher than those of previous work, adjustment for

Table 6
Comparison of results of the present study to previously published work[a]

Previous study	Area description	Leaf mass (kg ha^{-1})	Area basis
Horie et al. (1991)	Open-set houses	1250	Total area
Horie et al. (1991)	Close-set houses	990	Total area
Sidawi and Horie (1992)[b]	Urban residential	1050	Total area
Sidawi and Horie (1992)[b]	Commercial/industrial	220	Total area
Sidawi and Horie (1992)[b]	Rural residential	740	Total area
Present study	Flood-irrigated residential	4990	Vegetated area
Present study	Mesic residential	9370	Vegetated area
Present study	Xeric residential	4480	Vegetated area
Present study	Park	1930	Total area
Present study	Parking lot	430	Total area

[a] The study area of Horie et al. (1991) was the Los Angeles basin. The study area reported by Sidawi and Horie (1992) was the San Joaquin Valley of California.
[b] The same data set was used in a report for the Central Valley of California, Tanner et al. (1992).

vegetated area compared to total area by a factor of 0.35 yields closer agreement.

Leaf mass data for the park from this study are presented on the basis of total area sampled because almost all of the park was vegetated. The park included a limited area of gravel on a baseball diamond, hardscape including sidewalks and playground equipment over sand. Data for the parking lot are also given on the basis of total ground area sampled (Table 6).

4.2. Plant species and BVOC emissions

Emissions per plant species depend upon the species-specific emission rate and upon leaf mass, which in turn is affected by plant size. Large tree species with high BVOC emissions rates may account for a majority of BVOC emissions within a landscape, and have the highest ozone-forming potential (Benjamin and Winer, 1998).

We found that a small number of plant species in each landscape type were responsible for disproportionate amounts of estimated isoprene and monoterpene emissions. For example, in the xeric areas, *Eucalyptus* species contributed 80% of calculated isoprene and monoterpene emissions. Although, trees, notably *Eucalyptus* and *Citrus*, dominated the lists of highest-emitting plants, some shrubs, such as *Xylosma congestum* (shiny xylosma), *Leucophyllum frutescens*, (Texas sage) and *Juniperus chinensis* (Chinese juniper) also appeared despite their smaller volumes. Thus, high isoprene or monoterpene emission rates can cause a species to be important despite a low frequency of occurrence. In this study, *Eucalyptus* and *Washingtonia* palms had the largest estimated isoprene emissions, and *Eucalyptus* and *Citrus* had the greatest estimated monoterpene emissions overall in the landscaped areas sampled in Phoenix.

4.3. Estimated BVOC emissions from trees and shrubs for each landscape type

Leaf masses and estimated emissions of isoprene and monoterpenes for each tree and shrub species under standard conditions of light and temperature were calculated and summed for the three landscape types [diurnal profiles of temperature and light intensity (Benjamin et al., 1997) would be used in more detailed modeling]. Less leaf mass was present per hectare in the xeric landscape type, but the relative BVOC emissions per hectare of vegetation calculated for the xeric landscape type were greater than for other landscape types. Specifically, calculated isoprene emissions were 70 g ha^{-1} h^{-1} for the xeric landscape type, 3.5 times greater than those of the mesic landscape type and 35 times greater than from the flood-irrigated landscape type. Calculated monoterpene emissions were 10 g ha^{-1} h^{-1} for the xeric landscape type as compared to 6 and 4 g ha^{-1} h^{-1} for the mesic and flood-irrigated landscape types, respectively. The high emissions for the vegetated areas of the xeric landscape type were plausible given the plant species selection and plant density within this landscape type.

Appropriate plant selection, a tenet of xeriscape design, includes use of native plants and others adapted to dry conditions (e.g. species from Australia and southern Africa), but does not require cacti or desert succulents. Genera of plants adapted to dry climates may contain plants with high BVOC emission rates and large mature size, such as *Eucalyptus* (Evans et al., 1982; Benjamin et al., 1996; Benjamin and Winer, 1998; He et al., 2000). *Eucalyptus* trees were frequently found in some neighborhoods of the xeric landscape type, although generally not in the newest areas of Scottsdale, and more than 80% of estimated isoprene and monoterpene emissions were attributed to this genus. Addition of hardscape or other non-vegetative elements may reduce the fraction of vegetated area compared to total area for the xeric landscape, decreasing BVOC emissions as expressed on a total area basis for this landscape type.

The flood-irrigated landscape type had a mixture of durable plant species and most of the surface area was occupied by turfgrass. Most plants were either of moderate size, such as the citrus trees, or had relatively low BVOC emission rates.

The mesic landscapes had the greatest leaf mass per hectare of any of the landscape types. Large shade trees may potentially be high-emitting plants because of their large crown volumes and leaf mass. However, the trees present in the mesic landscape type included only a few tree species with isoprene emission rates greater than 1.0 μg g^{-1} h^{-1}, such as *Washingtonia filifera* (California fan palm) and *Ficus carica* (edible fig) and did not include *Eucalyptus* species.

The park also contained large trees, including nine *Eucalyptus* and seven *Pinus halepensis* (Aleppo pines), and both genera are BVOC emitters (Benjamin et al., 1996). The trees were distributed over an area of 2.0 ha which suggests lower estimated BVOC emissions per hectare than would have occurred with denser planting of these species.

5. Conclusion

This field-based study extended previous work (Winer et al., 1983; Miller and Winer, 1984; Horie et al., 1991) in which landscape elements were described quantitatively for use in compiling BVOC emissions inventories. Plant species and their dimensions were listed for sample sites within three urban landscape types found in the Phoenix metropolitan area. A few plant species accounted for disproportionate shares of foliar volume and calculated leaf mass. The number of plant species identified increased in proportion to the log of the area sampled. The present results can be compared with field surveys for landscapes in other geographical areas, and provide information for the landscape design process. Certain plant species used in xeriscape design, e.g. the legumes, may be low or non-emitters of BVOC. In contrast, *Eucalyptus* may contribute a majority of BVOC emissions in landscapes where it is common.

In areas of high air pollution potential, such as Maricopa County, data on emissions of BVOC from plant species (Benjamin and Winer, 1998) can guide landscape and horticultural practices toward establishment of low- or non-emitting species of trees and shrubs, which can provide shade and aesthetic benefits without adding substantial BVOC to the atmosphere. This becomes particularly important for mega-scale tree planting programs undertaken for aesthetics, to mitigate urban heat islands, and/or to sequester carbon dioxide.

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