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Integrating Remote Sensing and Local Vegetation Information for a High-Resolution Biogenic Emissions Inventory—Application to an Urbanized, Semiarid Region

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ABSTRACT

This paper presents a methodology for the development of a high-resolution (30-m), standardized biogenic volatile organic compound (BVOC) emissions inventory and a subsequent application of the methodology to Tucson, AZ. The region's heterogeneous vegetation cover cannot be modeled accurately with low-resolution (e.g., 1-km) land cover and vegetation information. Instead, local vegetation data are used in conjunction with multispectral satellite data to generate a detailed vegetation-based land-cover database of the region. A high-resolution emissions inventory is assembled by associating the vegetation data with appropriate emissions factors. The inventory reveals a substantial variation in BVOC emissions across the region, resulting from the region's diversity of both native and exotic vegetation.

The importance of BVOC emissions from forest lands, desert lands, and the urban forest changes according to regional, metropolitan, and urban scales. Within the entire Tucson region, the average isoprene, monoterpene, and OVOC fluxes observed were 454, 248, and 91 $\mu g/m^2/hr$, respectively, with forest and desert lands emitting nearly all of the BVOCs. Within the metropolitan area, which does not include the forest lands, the average fluxes were 323, 181, and 70 $\mu g/m^2/hr$, respectively. Within the urban area, the average fluxes were 801, 100, and 100 $\mu g/m^2/hr$, respectively, with exotic trees such as eucalyptus, pine, and palm emitting most of the urban BVOCs. The methods presented in this paper can be modified to create detailed, standardized BVOC emissions inventories for other regions, especially those with spatially complex vegetation patterns.

IMPLICATIONS

Many areas of the United States might acquire ozone nonattainment status in the near future and be forced to perform regulatory modeling using gridded emissions inventories. The current, default biogenic emissions inventories provided by the U.S. Environmental Protection Agency (EPA) might underestimate BVOC emissions substantially, especially in urbanized, semiarid regions. In these regions, the default inventories contain insufficient vegetation information for urban areas as well as for the surrounding desert lands. Local vegetation information and a realistic land-cover classification are needed to accurately quantify BVOC emissions. This paper presents a methodology for the development of a high-resolution (30-m), standardized BVOC emissions inventory. The resulting inventory can be used in photochemical modeling or other analytical applications (e.g., temporalizing the inventory to determine month-to-month variations in BVOC emissions) to quantify the impact of BVOC emissions on ozone production.

INTRODUCTION

For tropospheric (surface) ozone, the two major groups of precursor chemicals are nitrogen oxides (NO_x) and reactive (i.e., nonmethane) volatile organic compounds (VOCs), both of which have anthropogenic as well as biogenic sources. Biogenic VOCs (BVOCs) are important contributors to the formation of regional/local photochemical oxidants, such as ozone. Ozone formation involves the reaction of BVOCs and anthropogenic VOCs (AVOCs) in the presence of NO_x and sunlight.[1] In several air basins, BVOC emissions have proven to be an obstacle to reducing ozone concentrations. For example, in two different urbanized areas, Los Angeles, CA, and Atlanta, GA, the abundance of BVOCs is hampering efforts to reduce AVOCs sufficiently to meet ambient air quality standards for ozone.[2,3]

Besides being potentially abundant, BVOCs are typically more reactive than AVOCs are; thus, they may have a greater ozone-forming potential.[4,5] In addition, BVOC production generally increases with higher temperature and light intensity; therefore, the diurnal timing of maximum BVOC emissions (i.e., early afternoon) also adds to the higher ozone-forming potential of BVOCs. BVOCs represent background VOC concentrations that cannot be realistically removed from the atmosphere by emission control measures. Even if ozone production is constrained by a limited availability of VOCs, VOC reductions may prove futile if a substantial fraction of the VOC emissions are from biogenic sources.[1]

Reliable estimates of BVOC emissions allow more confident predictions of changes in ozone concentrations that would result from proposed changes in anthropogenic emissions. Sillman[6] stated that the choice of biogenic emission inventories is possibly the most important scientific issue associated with NO_x–VOC policy in the United States. From an ozone-control perspective, the development of a complete and accurate standardized biogenic emissions inventory (a spatial database containing VOC emission information for a given modeling domain) is crucial. A standardized inventory contains BVOCs emissions estimates for high temperature (30 °C), high light intensity (1000 μmol/m^2/sec), and maximum leaf biomass conditions. However, time-specific temperature, light intensity, and biomass coefficients can be used to temporalize the inventory.

Overview of Biogenic Emissions Inventories

Many biogenic emissions inventories are created using the biogenic emissions land-cover database (BELD). BELD contains county-level data for nine land-use classes for every county in the contiguous United States. Each land-use class can include many different land-use types.[7] For semiarid areas, such as Tucson, AZ, the major limitation of this database is the mistreatment of urban areas. In BELD, desert cities are assumed to be 11% forested and 89% urban-other.[8] For the urban-other emission factor, 20% grass coverage is assumed. This percentage may be high for a semiarid city, such as Tucson, that has prevalent xerophytic landscaping. In addition, BELD assumes that the composition of the urban forest mimics the composition of the nonurban portion of the county. However, in the southwestern United States, this strategy is unsound because urban vegetation can differ dramatically from the surrounding desert vegetation. Consequently, BELD provides relatively inadequate vegetation data for southwestern urban areas, especially those with significant amounts of exotic vegetation.

An alternative to BELD is the construction of biogenic emissions inventories from local land-use databases. However, land use is not always a good indicator of vegetative cover, especially in residential areas. The United States Geological Survey (USGS) land-use/land-cover database is also a potential alternative, but, as a consequence of its scale (1:250,000), it is not the best option. Optimally, a biogenic emissions inventory should be created from a high-resolution land-cover database.

Purpose

BVOC emissions have proven to be important ozone precursor chemicals in several urbanized areas. Consequently, this paper's aim is to describe novel methods used to create a high-resolution, standardized biogenic emissions inventory for the Tucson region. The inventory can be used to improve the understanding of ozone formation. The methods comprise a conceptual model founded on the linkage of remotely sensed data with local vegetation information, within a geographic information system.

The Study Region: Tucson, AZ

The Tucson region (centered at 32.25° N latitude and –111° W longitude) as defined in this study is a rectangular area that covers ~10,900 km^2 (100 km E-W by 109 km N-S) (Figure 1). Elevation ranges from 600 to over 2500 m above sea level (a.s.l.), with peaks in the Santa Catalina, Rincon, and Santa Rita Mountains to the north, east, and south of the city, respectively. This extreme relief results in a wide variety of native species within the region. The gradient of vegetation extends from subalpine fir forests near the mountain peaks through montane fir forest and pine forest, pine-oak forest, pine-oak woodland, pygmy conifer-oak scrub, open oak woodland, and desert grassland to spiny and partially woody Sonoran semidesert vegetation on the mountain slopes. On the desert plain below the mountains, the vegetation assemblages include paloverde-bursage and, at the lowest elevations, creosote-bush.[9]

In contrast to most cities in the eastern United States, Tucson's urban vegetation is considerably different from that of the surrounding areas. The city has a substantial urban forest, even though it is located in a semiarid environment. Attitudes toward urban vegetation in Tucson have changed over time (as evidenced by tree planting campaigns during the early 1900s to create shade and reduce dust levels and adoption of desert landscaping during the 1970s), leading to a mixture of xerophytic vegetation (e.g., mesquite, paloverde, and an assortment of cacti), large shade trees (e.g., eucalyptus and pine), and other exotic trees (e.g., palms, citrus, olives, and cypress) across the city.[10] The region's diverse natural vegetation, combined with the complex array of exotic and native species in the urban area, complicates the development of a biogenic emissions inventory.

The assignment of BVOC emission rates to Tucson's vegetation represents the major obstacle to the development of a biogenic emissions inventory. Measured emissions data is available for only a relatively small number of plant species in most regions, and only a small percentage of those measured species are found in the Tucson region. For example, isoprene and monoterpene emission rates have been measured experimentally for only ~30% of tree and shrub species in California's South Coast Air Basin (SoCAB) (i.e., the Los Angeles area),[11] an intensively studied basin with a vegetation composition that has limited similarities to that of the Tucson region.

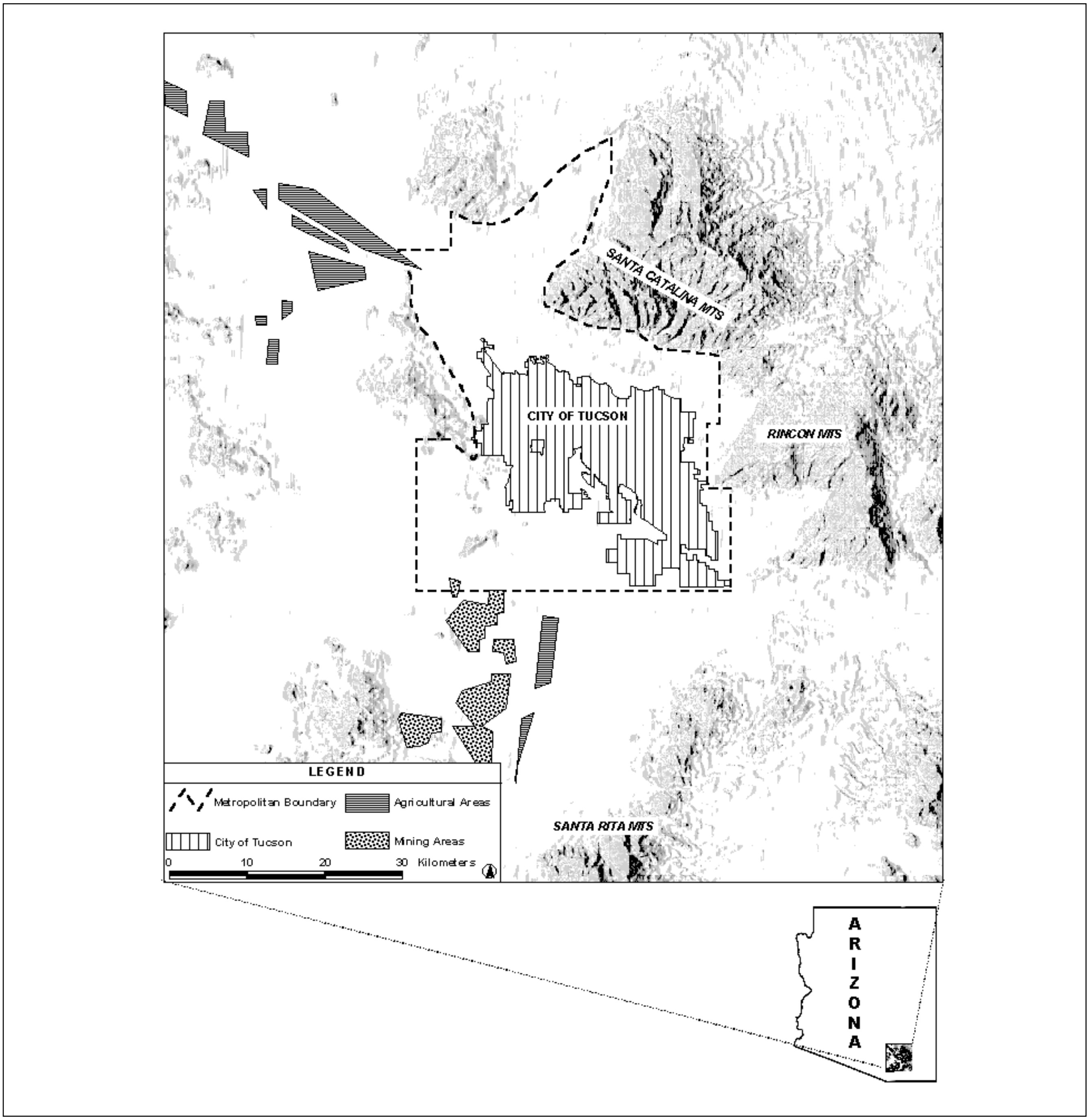

Figure 1. Map of the Tucson region showing the city, the metropolitan area, and the topography. The Santa Catalina, Rincon, and Santa Rita Mountains contain most of the forest land, while most of the area outside of the city of Tucson, the agricultural areas, and the mining areas is desert land.

DATA

Data consisted of satellite imagery, aerial photographs, urban vegetation surveys, project-specific vegetation surveys, a digital elevation model (DEM), leaf biomass constants, foliar density values, and BVOC emission factors. The satellite image was a geo-rectified Landsat thematic mapper (TM) image (~30-m spatial resolution) acquired on June 30, 1993, available from Arizona Regional Image Archive (ARIA) at The University of Arizona. Since this is not a multi-temporal study and the image is cloud-free, the image was not atmospherically corrected. The aerial photographs were taken on September 21, 1996, and have a scale of 1:14,400. Vegetation survey data from a wildlife habitat study conducted in 1993 and a pollen study conducted in the early 1980s were used to determine the vegetation composition of some urban areas. The wildlife habitat study and pollen study, respectively, were performed by the School of Renewable Natural Resources at The University of Arizona and Mary Kay O'Rourke of The University of Arizona.

To supplement the aforementioned vegetation surveys, we collected vegetation data from a project-specific field survey across the Tucson modeling domain. Species composition, specimen height, crown width, basal diameter, and live/green crown ratio were recorded at 123 plots (314-m^2 circle) and 56 front yards. The DEM (30 m spatial resolution) covers the entire Tucson region and is available from ARIA. Finally, leaf biomass constants, foliar density values, and BVOC emission factors were collected from various papers, reports, and personal communications with other researchers in the biogenic emissions field.[11-13]

METHODS

The general methods involved in creating the biogenic emissions inventory are presented in Figure 2. The following subsections provide detailed information about each method.

Creating a Land-Cover Database

The Tucson region's vegetation-based land-cover database relies on information from the 1993 Landsat TM image. Standard remote sensing techniques were used to perform an unsupervised classification of the image. Using values from the three visible (i.e., blue, green, and red), two near infrared, and two computed bands [a "greenness" band (the second band of the Kauth-Thomas transformation) and a normalized difference vegetation index (NDVI) texture band], the image's pixels were placed into clusters, using a clustering algorithm based on minimal spectral distances. The NDVI texture band highlights local variations in aboveground green biomass across the entire region. Relatively homogeneous forested areas have low NDVI texture values, while heterogeneous urban areas have high texture values. The Kauth-Thomas greenness band is a green vegetation index with values that are related strongly to the amount of green vegetation in the scene.[14]

Creation of Classified Image. Prior to classification, the region was divided into two areas based on degree of urbanization. The urbanized center of the region (an area roughly approximating the legal boundaries of the city of Tucson) was classified separately from the rest of the image. This procedure provided better discrimination of land cover, and it has been used in other biogenics-related land-cover studies.[15] The peripheral area was classified into eight categories, sufficient to capture a majority of the region's natural vegetation communities. Even though the size of the urbanized center was substantially smaller than that

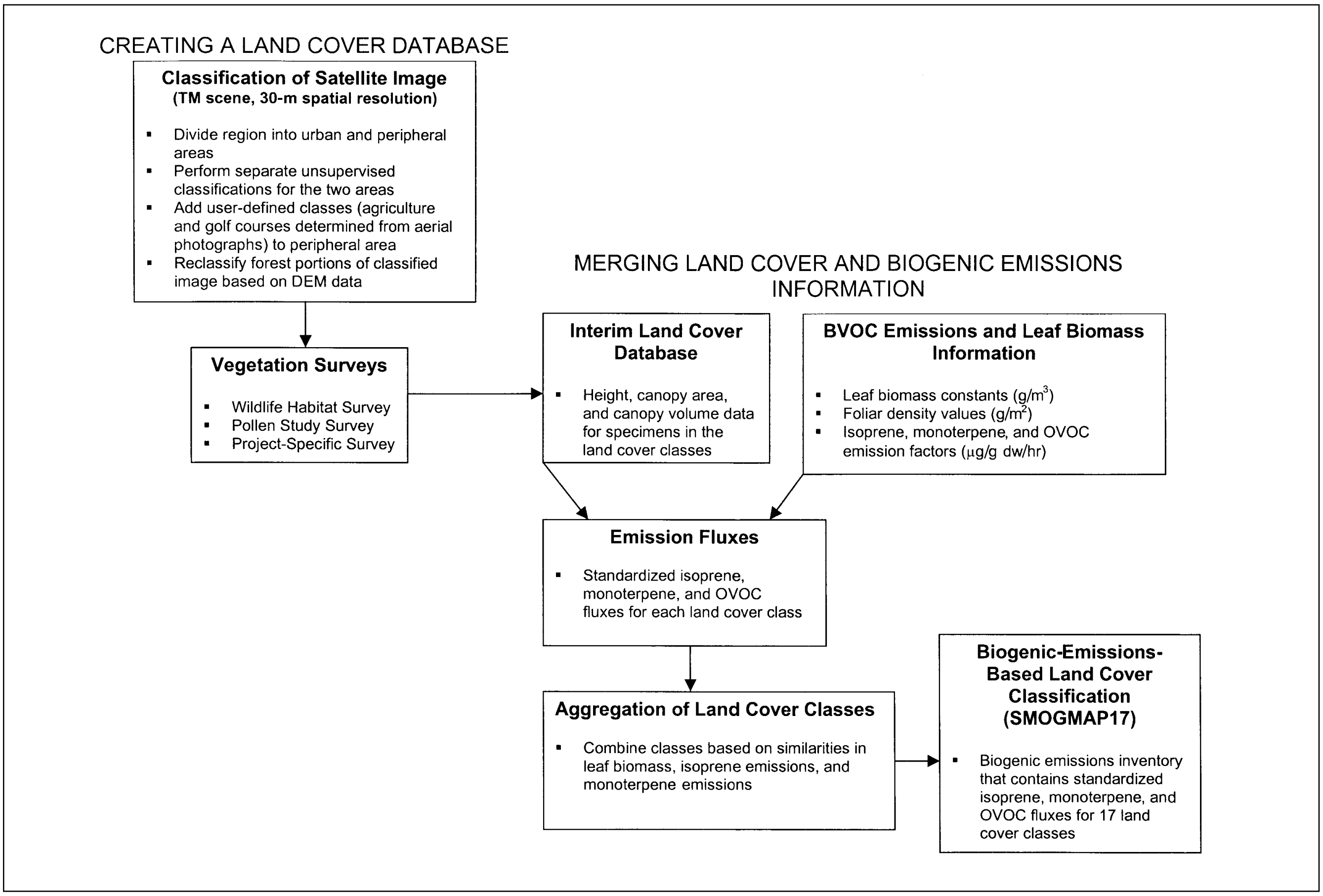

Figure 2. Flow chart of the methods used to develop the SMOGMAP17 biogenic emissions inventory for the Tucson region.

of the peripheral region, the urbanized pixels were placed into seven categories. More land-cover detail is desirable for the urbanized area, since urban vegetation usually has considerably more spatial heterogeneity than do natural vegetation communities.

Addition of User-Defined Classes. Several user-defined classes, which represent pixels in the peripheral area that are commonly incorrectly classified as forested areas during the unsupervised classification procedure, were added to the land-cover classification. Using aerial photographs, areas corresponding to row crops, pecan orchards, and golf courses were identified on the classified satellite image and then reclassified.

Reclassification of Classified Image. Since the forest lands are major BVOC sources and only 1 out of 18 classes in the land-cover classification represented these forest lands, the original forest class was divided into more detailed classes in order to differentiate between oak-dominated, potentially high isoprene-emitting zones and conifer-dominated, potentially high monoterpenes-emitting zones. Using the classified image as well as a DEM, two new land-cover classes were created. These classes corresponded to two distinct elevation zones. All pixels between 1500 and 2000 m a.s.l. were placed into a lower-elevation forest class, and all pixels above 2000 m a.s.l. were placed into a higher-elevation forest class. These elevation zones correspond to the southwestern United States' Madrean evergreen woodland and Madrean montane conifer forest vegetation categories, respectively.[16] All remaining original forest pixels were placed into the lower-elevation forest class. The two forest classes were again re-divided into two classes each to separate the pixels based on vegetation cover. The aforementioned eight spectral bands and the clustering method were used to create the four new classes. After the initial classification and subsequent reclassifications, the domain was represented by 21 land cover classes (7 in the urban area and 14 in the peripheral area).

Use of Vegetation Survey Information. Three vegetation surveys, including two pre-existing surveys (i.e., wildlife habitat survey and pollen study survey) and a project-specific survey, were used to assign vegetation information to the various land-cover classes. The wildlife habitat survey data were used to determine the vegetation composition of two land-cover classes, residential/parks and golf courses. Frequency, height, and width information for various species were included in the survey database. This database contained ~10 sampled hectares for each class, which is a relatively large proportion of vegetation information for parks and golf courses. The pollen study contains vegetation data for hundreds of front yards in Tucson. These data were used to determine the vegetation composition of a residential land-cover class. Average height, width, and green crown ratio were calculated for relevant species from the wildlife habitat and project-specific data. These average values were then applied to the pollen study database.

For the vegetation survey that was conducted for this study, a stratified random sampling scheme was employed to select sample pixels from most of the remaining land-cover classes. Nonresidential land-cover classes were sampled with 123 10-m (~314 m^2) radius plots, while sampling of a residential class consisted of surveying 56 residential front yards. Most of the nonresidential sampling sites were located at the following locations: Tucson Mountain Park (west of Tucson), Catalina State Park (north of Tucson), Sabino Canyon Recreation Area (northeast of Tucson), Tanque Verde Falls area (east of Tucson), and several sites adjacent to Mt. Lemmon Highway (north of Tucson at higher elevations). These sites were intentionally chosen because they have different terrain characteristics and, hence, slightly different vegetation assemblages from one another, thereby maximizing the representation of within-group variance for each land-cover class. Collected data consisted of (1) plant species, (2) frequency of species, (3) height of each specimen, (4) green crown ratio of each specimen, and (5) crown width of each specimen. A clinometer was used to measure tree heights >3 m.

Merging of Land Cover and BVOC Emissions Information

Leaf Biomass and Emissions Information. Using several reports and papers as primary guides,[11-13] leaf biomass constants (g/m^3), foliar density values (g/m^2), isoprene emission factors (μg/g dry weight (dw)/hr), monoterpenes emission factors (μg/g dw/hr), and, when necessary, OVOC (other VOCs) emission factors (μg/g dw/hr) were assigned to each species in the vegetation database. Additional estimates of isoprene and monoterpene emission factors for prevalent species in the Tucson region were also used.[17] At the present time, no BVOC emission measurements have been made in the Tucson region. The above BVOC classification is used because Biogenic Emissions Inventory System, Version 2 (BEIS2), which is the current biogenic emissions modeling system, only requires input data for those three types of BVOCs to estimate hourly BVOC emissions for a gridded modeling domain.[13,18]

Since many of the species documented in the Tucson study are either exotic or are found exclusively in the Sonoran Desert, species-specific biomass values and emission factors do not usually exist. Benjamin et al.[11] noted that "within broad qualitative ranges, taxonomic relationships between plant species at the lowest possible level (i.e., genus, family) can be used to assign measured emission factors to other species within that level for which no measurements exist." Using the taxonomic method, one assigns an emission factor to an unmeasured species based initially on the average factor for measured species within the same genus as the unmeasured species. If no data are available for the genus, the average factor for the family is used. Assigning emission factors to unmeasured species involves considerable uncertainty, with factors varying by as much as 4 orders of magnitude depending on the plant species.[11] In addition to employing the taxonomic method in the Tucson study, species are disregarded if they have negligible canopy volumes. The region's most important species (with respect to leaf biomass) and their respective BVOC emission factors are listed in Table 1.

Calculation of Emission Fluxes. The standardized emission fluxes (μg/m^2/hr) of isoprene, monoterpenes, and OVOCs were calculated for each land-cover class. The emission flux is simply the sum of the biomass-modified factors (μg/hr) from each plant divided by the total area sampled (m^2). The biomass-modified factors for each plant are the product of the plant's biomass (g) multiplied by its emission factor (μg/g dw/hr). For all specimens in the nonforest land-cover categories, the leaf biomass was calculated by multiplying the canopy volume (m^3) by the leaf biomass constant (g/m^3). Depending on the type of plant, the specimens' canopies were calculated based on different geometric shapes (i.e., cone, upper-half spheroid, ellipsoid). For all specimens in the forest category, the biomass value equals the area of canopy coverage (m^2) multiplied by the foliar density value (g/m^2).

The least amount of emissions information exists for OVOCs; thus, compared with isoprene and monoterpenes, OVOC emission factors used in this inventory are the most uncertain. Standardized emission fluxes of OVOCs are only calculated for the four forest classes. All species present in the four classes were assigned a default OVOC emission factor of 1.5 mg/g dw/hr according to procedures used by Geron et al.[13] EPA default values were assigned to desert land-cover classes. For the urban classes, the monoterpene flux was also a proxy for the OVOC flux, based on the fact that the species responsible for most of the monoterpene emissions have been assigned nearly equal monoterpene and OVOC emission fluxes in BEIS2.[12]

Fluxes for two of the 21 classes were calculated without the use of any vegetation survey information. The typical crop composition of row crop areas in the Tucson modeling domain comprises ~65% cotton and 35% alfalfa during the summer growing season.[19] Therefore, a hybrid emission flux (i.e., alfalfa-cotton) was created by proportionately combining the BEIS alfalfa and cotton emission fluxes.[20] For the pecan orchard land-cover class, the density of pecan trees was determined by examining aerial photos of pecan orchards near the Santa Cruz River and Green Valley, AZ. This information, along with size, leaf biomass, and emission factor data, facilitated the estimation of an emissions flux for the pecan orchard class.

Aggregation of Land-Cover Classes. As a means of refining the land-cover classification, statistical tests were performed to determine whether various classes could be combined. Mann-Whitney U tests were performed for leaf biomass, isoprene, and monoterpene emission values for each sampled plot. These tests evaluated differences among the classes for all three variables. Results led to the aggregation of seven classes into three classes (i.e., a reduction from 21 to 17 classes).

Biogenic Emission-Based Land-Cover Classification. The result of the various class eliminations and aggregations was a land-cover classification with 17 different classes, including an unvegetated urban class. The classification is sufficiently accurate, since the class-specific sample plots have similar vegetation compositions and leaf biomass totals. No anomalous plots were encountered during the sampling. As a quantitative measure, an analysis of variance test of differences in leaf biomass totals between the land-cover classes revealed significantly more variation ($\alpha = 0.05$) between the classes than within them (based on plot-specific values). The classification, known as SMOGMAP17, is in effect a detailed extension of the USGS land use and land cover classification system, for it has an additional (i.e., further stratified) level of land-cover information.[21,22] For descriptive purposes, the 17 land-cover classes were placed into five broad (Level I) land-cover categories (urban/built-up, agriculture, desert, forest, and barren) (Table 2). Most of the classes are in the urban/built-up, desert, and forest categories. The desert classes are collectively described as Sonoran desert scrub.

The names of the 17 land-cover classes reflect the dominant species, based on frequency and contribution to total leaf biomass. Frequently occurring desert species were triangle-leaf bursage and creosote-bush, while the major leaf biomass contributors were larger shrubs such as mesquite and paloverde. The urban/built-up vegetation landscape was characterized by exotic trees such as eucalyptus, pine, Italian cypress, juniper, olive, and palm. The forest classes contained native trees such as oak, juniper, pine, and Douglas fir. Table 3 lists the 17 classes and their associated projected areas, BVOC fluxes, and leaf biomass totals.

RESULTS

Emissions within the Tucson Region

Projected areas from the land-cover classification revealed that ~80% of the Tucson study region is desert land, 10% is

Table 1. The Tucson region's dominant trees and shrubs according to total leaf biomass. Leaf biomass factors, emission factors and fluxes, and sources are included.

DESERT **Tree/Shrub**	**Genus/Species**	**Leaf Biomass Constant (µg/m^3)**	**Biomass Sources**	**Isoprene Emission Factor (µg/g dw/hr)**	**Monoterpene Emission Factor (µg/g dw/hr)**	**Emission Factor Sources**
Mesquite	*Prosopis spp.*	150	A	0	0	E
Creosote-bush	*Larrea tridentata*	460	A	0	3	A
Paloverde	*Cercidium spp.*	150	A	4.3	1.4	A
Ironwood	*Olneya tesota*	150	A	4.3	1.4	B
Triangle-leaf bursage	*Ambrosia deltoidea*	230	A	0	28.3	A
Acacia	*Acacia spp.*	150	A	0	3	E

URBAN/BUILT-UP **Tree/Shrub**	**Genus/Species**	**Leaf Biomass Constant (µg/m^3)**	**Other Biomass Measure**	**Biomass Sources**	**Isoprene Emission Factor (µg/g dw/hr)**	**Monoterpene Emission Factor (µg/g dw/hr)**	**Emission Factor Sources**
Eucalyptus	*Eucalyptus spp.*	305		A	60	3	E
Pine	*Pinus spp.*	390		A	0	3	E
Juniper	*Juniperus spp.*	3700		D	0	0.6	B
Italian cypress	*Cupressus semipirvirens*	5100		A	0	0.1	E
Palm	*Washingtonia spp.*		520 g/frond	A	36	0	E
Olive	*Olea europaea*	500		A	0	0	E

FOREST **Tree/Shrub**	**Genus/Species**	**Foliar Density (g/m^2)**	**Biomass Sources**	**Isoprene Emission Factor (µg/g dw/hr)**	**Monoterpene Emission Factor (µg/g dw/hr)**	**OVOC Emission Factor (µg/g dw/hr)**	**Emission Factor Sources**
Pine	*Pinus spp.*	700	C	0	3	1.5	C, E
Douglas fir	*Pseudotsuga menziesii*	1500	C	0	1.5	1.5	C, E
Oak	*Quercus spp.*	375	C, D	100	0.2	1.5	C, E
Alligator juniper	*Juniperus deppeana*	700	C, D	0	0.65	1.5	C, E

AGRICULTURE **Tree/Shrub**	**Genus/Species**	**Leaf Biomass Constant (g/m^3)**	**Biomass Sources**	**Isoprene Emission Flux (µg/m^2/hr)**	**Monoterpene Emission Flux (µg/m^2/hr)**	**OVOC Emission Flux (µg/m^2/hr)**	**Isoprene Emission Factor (µg/g dw/hr)**	**Monoterpene Emission Factor (µg/g dw/hr)**	**Emission Factor/Flux Sources**
Cotton	*Gossypium spp.*	NA	NA	7.6	19	11.4	NA	NA	BEIS
Alfalfa	*Medicago sativa*	NA	NA	19	7.6	11.4	NA	NA	BEIS
Pecan	*Carya illinoensis*	168	A	NA	NA	NA	0	0.7	A

Notes: A = Chinkin et al.;[12] B = Benjamin et al.;[11] C = Geron et al.;[13] D = Benjamin et al.;[24] E = Guenther;[17] BEIS = Biogenic Emissions Inventory System;[16] NA = not applicable.

forest land, 7% is barren land, 3% is urban/built-up land, and only 1% is agricultural land (see Table 3). The average region-wide isoprene, monoterpene, and OVOC emission fluxes for the entire Tucson region were 454, 248, and 91 µg/m^2/hr, respectively. Over 95% of the BVOCs were emitted from forest (classes 12 through 15) and desert (classes 1 through 4) lands, with the remainder of the BVOCs emitted primarily from the urban forest (classes 6, 8, and 10). Using multi-temporal coefficients presented in Guenther et al.[23] for a global model of biogenic emissions, the average region-wide isoprene and monoterpene fluxes for a typical summer day (in August) were 1.4 and 3.7 kg/km^2/day, respectively. The Tucson region's combined (i.e., isoprene plus monoterpenes) flux was approximately equal to that of the SoCAB, but only about one-tenth of the Atlanta region's flux.[24,25] Thus, Tucson's BVOC emissions are similar to those from an urbanized area with a Mediterranean climate (i.e., mid-latitude and summer-dry), but much less than those from an urbanized area with a moist, subtropical climate. During the arid foresummer (May and June), important drought-deciduous plants in the Tucson region's desert lands, such as paloverde, triangle-leaf bursage, whitethorn acacia, creosote-bush, brittlebush, and even some sclerophyllic oaks at middle elevations in the Santa

Table 2. SMOGMAP17's land cover categories (Level I) and classes (Level II) and associated major trees and shrubs.

Level I	Level II	Major Trees/Shrubs (% of Total Leaf Biomass)
Desert	Paloverde-cacti-mixed scrub series	Mesquite (62%), Paloverde (16%), Ironwood (9%)
	Creosote-bursage series (A)	Creosote-bush (33%), Paloverde (29%)
	Creosote-bursage series (B)	Mesquite (39%), Paloverde (33%), Creosote-bush (15%)
	Creosote-bursage series (C)	Mesquite (27%), Paloverde (22%), Creosote-bush (19%), Triangle-leaf bursage (13%), Acacia (10%)
Barren	Barren	NA[a]
Urban/Built-up	Highly vegetated residential/Urban parks	Eucalyptus (18%), Olive (16%), Pine (15%)
	Unvegetated	NA
	Moderately vegetated residential	Cypress/Juniper (15%), Palm (14%), Eucalyptus (13%)
	Highly developed	NA[a]
	Sparsely vegetated residential	Cypress/Juniper (30%), Palm (16%), Citrus (14%)
	Golf courses	Pine (40%), Eucalyptus (18%), Mesquite (9%)
Forest	Oak/Pine/Juniper	Pine (57%), Alligator juniper (23%), Oak (20%)
	Oak/Juniper	Oak (53%), Alligator juniper (22%)
	Pine/Douglas fir	Douglas fir (52%), Pine (48%)
	Rock/Oak/Pine/Douglas fir	Douglas fir (59%), Pine (34%)
Agriculture	Pecan orchards	Pecan (100%)
	Row crops	Cotton (65%), Alfalfa (35%)

[a]Emissions are primarily from burrobrush (*Hymonclea salsola*).

Table 3. Standardized BVOC fluxes for SMOGMAP17's classes. Fluxes are standardized to 30 °C and 1000 μmol/m^2/sec.

Class	Land Cover	Area (ha)	Percent of Total Area	Isoprene Flux (μg/m^2/hr)	Monoterpene Flux (μg/m^2/hr)	OVOC Flux (μg/m^2/hr)	Maximum Leaf Biomass (kg/ha)
1	Paloverde-cacti-mixed scrub series	80,603	7.4	633	129	57[a]	1588
2	Creosote-bursage series (A)	306,960	28.1	118	243	57[a]	64
3	Creosote-bursage series (B)	141,483	13.0	254	348	57[a]	1563
4	Creosote-bursage series (C)	336,054	30.8	45	235	57[a]	406
5	Barren	71,845	6.6	0	18	57[a]	10
6	Highly vegetated residential and urban parks	2522	0.2	2849	355	355[b]	2433
7	Unvegetated urban	6991	0.6	0	0	0[b]	0
8	Moderately vegetated residential	7603	0.7	1868	178	178[b]	1790
9	Highly developed urban	6700	0.6	0	54	54[b]	23
10	Sparsely vegetated residential	5395	0.5	306	42	42[b]	1029
11	Golf courses	756	0.1	2566	449	449[b]	2047
12	Oak/Pine/Juniper	39,668	3.6	4191	428	374	2390
13	Oak/Juniper	49,186	4.5	3256	46	81	541
14	Pine/Douglas fir	12,951	1.2	0	2328	1677	11,177
15	Rock/Oak/Pine/Douglas fir	7734	0.7	752	228	176	1177
16	Pecan orchards	2037	0.2	0	611	611[b]	5400
17	Row crops	12,305	1.1	15	12	11	NA

[a]OVOC fluxes are EPA default values from BEIS;[17] [b]Monoterpene fluxes are used as proxies for OVOC fluxes.

Catalina, Rincon, and Santa Rita Mountains, lose some to most of their leaves.[26,27] Therefore, the Tucson region's BVOC flux is either much smaller than or equal to SoCAB's flux, depending on the season.

Spatial Variations of BVOC Emissions within the Tucson Region

Within the entire Tucson study region, the derived isoprene and monoterpene emission fluxes varied considerably among the land-cover classes (Figures 3 and 4). Spatial variations in OVOC fluxes are not presented here, due to the aforementioned uncertainty of the OVOC emission rates. The region's forest lands (classes 12 through 15) were major sources of isoprene and monoterpenes. More specifically, conifers (classes 14 and 15) were responsible for the large monoterpene flux at the highest elevations. The Madrean evergreen woodland (classes 12 and 13), located at middle elevations, had the highest isoprene flux estimates (3315–4191 $\mu g/m^2/hr$) and is thus an important isoprene emission area. Nevertheless, the impact of BVOC emissions from forest lands on ozone concentrations in populated areas depends on complex mountain-valley wind patterns. The sheer amount of desert scrub in the region, along with modest monoterpene emissions from prevalent species, such as paloverde, creosote-bush, and triangle-leaf bursage, accounted for a majority of the monoterpenes being emitted from desert lands (classes 1 through 4). The urban forest, which exists entirely within the city of

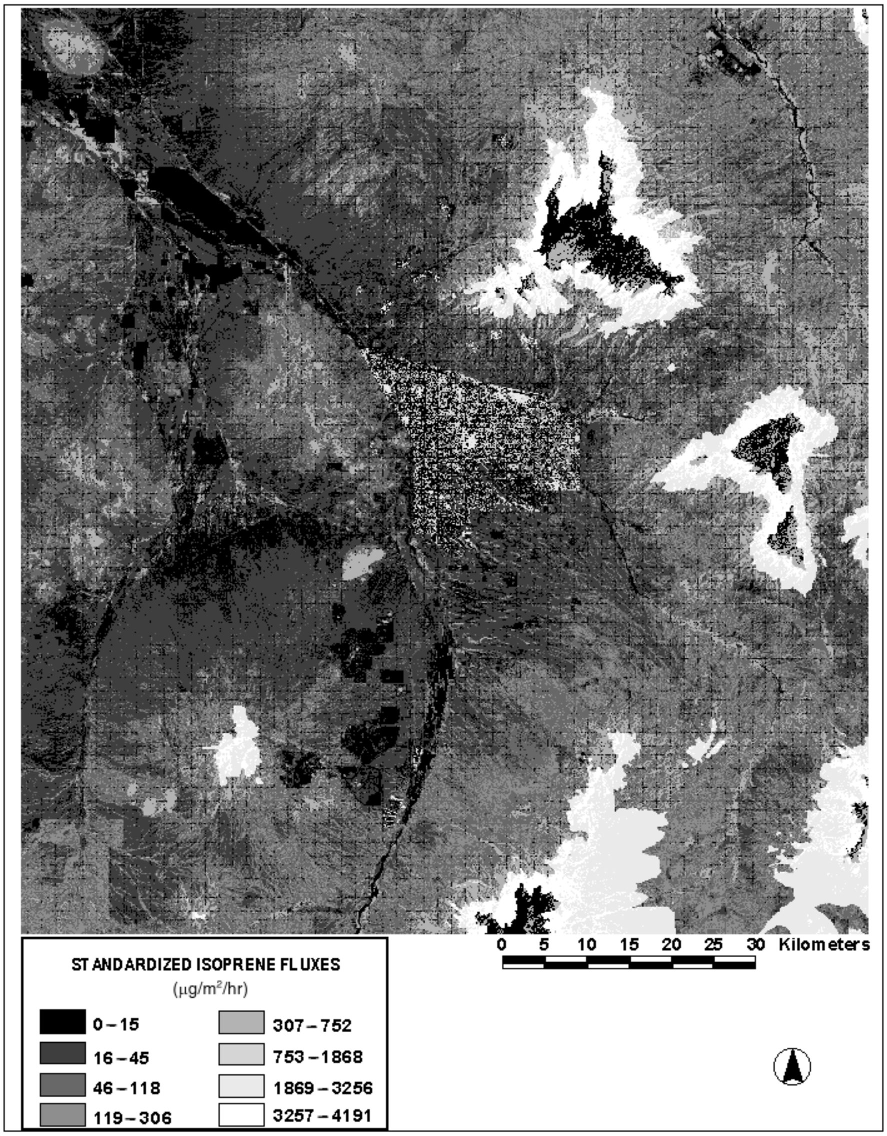

Figure 3. Map of standardized isoprene fluxes ($\mu g/m^2/hr$) within the Tucson region. Heavy emissions areas are the Madrean evergreen woodland, which is represented by light-colored areas at middle elevations in the mountain ranges, and some moderately to heavily vegetated portions of the city.

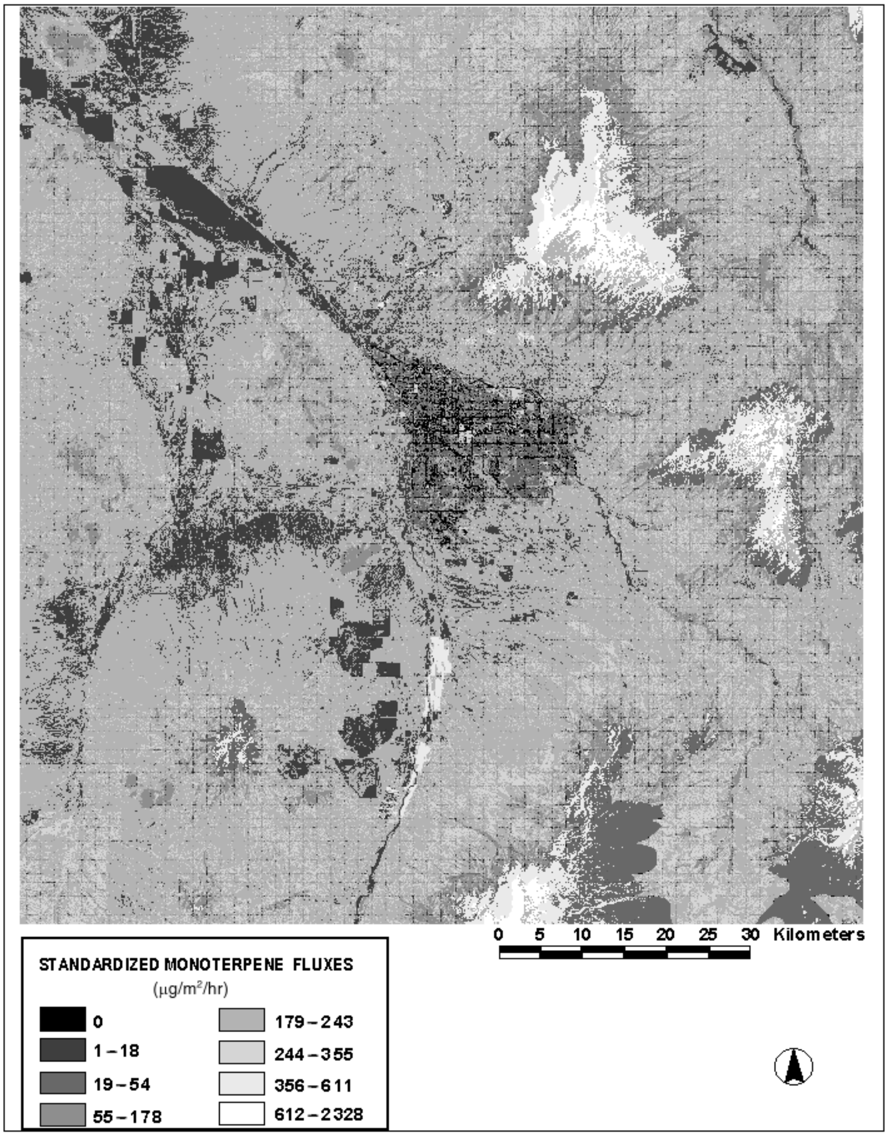

Figure 4. Map of standardized monoterpene fluxes (µg/m²/hr) within the Tucson region. Forest lands in the mountain ranges have heavy emissions, the prevalent desert lands have moderate emissions, and the city has low emissions.

Tucson, is an isoprene "hot spot"; however, as mentioned, it contributes little (i.e., <5%) to the total amount of BVOCs emitted at the regional scale. Low BVOC emission areas include row crop areas and barren lands, especially the mining areas southwest of Tucson.

Emissions within the Tucson Metropolitan Area

Within the Tucson metropolitan area (see Figure 1), which consists of urban and surrounding suburban desert areas (i.e., areas between the city and the mountains), the average metropolitan-wide isoprene, monoterpene, and OVOC fluxes were 323, 181, and 70 µg/m²/hr, respectively. The urban forest, which covers ~15% of the area, contributed heavily to isoprene emissions, while the desert scrub, which covers ~70% of the area, is responsible primarily for monoterpene emissions (see Figures 3 and 4).

Emissions within the City of Tucson

Within the city of Tucson, most of the BVOCs were emitted from exotic tree species. The average city-wide isoprene, monoterpene, and OVOC fluxes were 801, 100, and 100 µg/m²/hr, respectively. Over 90% of the isoprene was emitted from eucalyptus (~73%) and palm trees (~20%), which have relatively high isoprene emission factors and biomass values (see Table 1). Over half of the monoterpenes were emitted from eucalyptus (~29%) and pine trees (~27%). The planting of exotic species has changed the city from monoterpene-biased to isoprene-dominated.

DISCUSSION AND CONCLUSIONS

Based on comparisons with results from BVOC studies in the Los Angeles and Atlanta areas, the Tucson region's BVOC emissions are not as low as one might expect for a semiarid area. Tucson's relatively high BVOC emissions are explained by (1) a consistent cover of high-biomass, moderate-emitting trees (i.e., oak, juniper, pine, and Douglas fir) at higher elevations; (2) the prevalence of high-monoterpene-emitting species (i.e., bursage and creosote-bush) at lower elevations; (3) the substantial coverage of moderate-emitting species such as paloverde and acacia throughout the region; and (4) the occasional presence of high-biomass, high-emitting species (e.g., eucalyptus) in the urban areas.

The importance of certain vegetation types with respect to BVOC emissions depends on the spatial scale of analysis. These scales are important from an air quality management perspective, since the potential for in situ ozone production increases as the geographic scale of analysis changes from regional to urban. Within the entire region, forest and desert lands were the major emission areas. However, when attention was placed on the metropolitan and urban areas, the urban forest emerged as a major BVOC source. Since exotic species, such as eucalyptus, palm, and pine, were shown to emit most of the urban forest's BVOCs, these species' emissions might significantly affect ambient ozone concentrations in the urbanized area.

This study has revealed the great utility of satellite imagery for deriving land-cover classes and for ultimately mapping biogenic emissions. The methodology presented in this paper consists of combining satellite mapping methods with local vegetation information and leaf biomass and BVOC emission factors from other sources to produce a detailed biogenic emissions inventory for an area with previously unknown BVOC emissions estimates. Since no BVOC measurements have been made in the Tucson region, leaf biomass and emission factors were taken from other regions and were applied according to the species' genus or family when necessary. The relatively high spatial resolution (~30 m) and spectral resolution (6 bands) of Landsat TM imagery allows for sufficient land-cover classification of urban and rural areas in the Tucson region. This classification is a valuable tool, for even though emission fluxes are derived from measurements made in other regions, the classification can be used as a planning instrument to decide which species to measure in the future.

This study has shown that an initial yet useful biogenic emissions inventory can be produced for the Tucson region despite a substantial amount of uncertainty concerning leaf biomass and emissions factors. In the Tucson region, SMOGMAP17's regionwide isoprene and monoterpene fluxes were ~4 and 2 times greater, respectively, than those calculated with BELD/BEIS information. More dramatically, SMOGMAP17's urban isoprene flux was nearly 70 times greater than the BELD/BEIS flux. BELD/BEIS considers the urban forest to be similar to that of the surrounding desert areas. In reality, Tucson's urban forest is comprised of many exotic trees (e.g., eucalyptus, palm, and pine) that are also major BVOC emitters. With respect to ozone formation, it is important to capture the magnitude of ozone precursor chemical emissions, especially in source-intensive areas. Therefore, SMOGMAP17's more realistic urban BVOC fluxes alone make it an improvement over BELD/BEIS. Without actual ambient BVOC measurements, though, it is difficult to quantitatively determine the accuracy of SMOGMAP17. Nevertheless, temporal variations in ambient ozone concentrations in the Tucson metropolitan area suggest that BVOC emissions probably play an important role in ozone formation.[28]

Future uses of the standardized inventory might include temporalizing the inventory. The inventory can be used as input data for BEIS2 as well as its updated versions to model emissions. Model output can then be incorporated into photochemical models, such as the urban airshed model (UAM).[29] UAM simulations can be used to determine the impact of BVOC emissions on ozone production. Tucson's biogenic emissions inventory is useful not only for ozone modeling purposes, but also for other investigative research. For example, local air quality planners in the Tucson region can comprehend more fully the region's ozone situation by estimating month-specific BVOC emissions using the standardized inventory along with month-specific temperature, light intensity, and leaf biomass data.

This inventory marks the first attempt at quantifying BVOC emissions in the Tucson region and is a suitable starting point for the development of more accurate biogenic emissions inventories. Enhanced inventories could be developed by (1) improving the land-cover classification with current, multitemporal (e.g., spring and summer), extremely high-resolution (e.g., 1 m for the urban areas) satellite imagery; (2) performing a field survey that contains several hundred plots and covers the entire region; and, most importantly, (3) using actual measured multitemporal leaf biomass and BVOC emission factors for dominant species in both the urban and peripheral areas. Multitemporal imagery would lead to a better distinction between deciduous and evergreen vegetation, and thus to a better classification. A comprehensive field survey would eliminate problems associated with using surveys that were guided by different goals. The acquisition of multitemporal emissions and leaf biomass information is extremely important. Emissions from some species might be affected by changes in relative humidity, while several of the dominant desert species are drought-deciduous.

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