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Allocating anthropogenic pollutant emissions over space: application to ozone pollution management

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An inventory of volatile organic compound (VOC) and nitrogen oxides (NO_x) emissions is an important tool for the management of ground-level ozone pollution. This paper has two broad aims: it illustrates the potential of a geographic information system (GIS) for enhancing an existing spatially-aggregated, anthropogenic emissions inventory (EI) for Tucson, AZ, and it discusses the ozone-specific management implications of the resulting spatially-disaggregated EI. The main GIS-related methods include calculating emissions for specific features, spatially disaggregating region-wide emissions totals for area sources, and adding emissions from various point sources. In addition, temporal allocation factors enable the addition of a multi-temporal component to the inventory. The resulting inventory reveals that on-road motor vehicles account for approximately 50% of VOC and NO_x emissions annually. On-road motor vehicles and residential wood combustion are the largest VOC sources in the summer and winter months, respectively. On-road motor vehicles are always the largest NO_x sources. The most noticeable weekday vs. weekend VOC emissions differences are triggered by increased residential wood combustion and increased lawn and garden equipment use on weekends. Concerning the EI's uncertainties and errors, on-road mobile, construction equipment, and lawn and garden equipment are identified as sources in the most need of further investigation. Overall, the EIs spatial component increases its utility as a management tool, which might involve visualization-driven analyses and air quality modeling.

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Introduction

Emissions inventories (EIs) are databases of atmospheric pollutant emissions for selected regions. These inventories can be used to assess global scale environmental issues (e.g. global warming) as well as local scale problems (e.g. urban air pollution). Hence, EIs can range in spatial and temporal complexity from annual emissions at the global scale (i.e. a single value for cumulative global emissions) to hourly emissions for thousands to millions of cells within an urban area, which is necessary for rigorous examinations of ambient pollutant concentrations.

Spatial allocation methods and geographic information systems

Spatial allocation is used to infuse EIs with a spatial component (i.e. spatial variation). The spatial allocation of emissions can involve 'top-down' and 'bottom-up' approaches. The 'top-down' approach yields sub-regional emissions estimates by modifying regional estimates typically with indicator variables (e.g. population, land use, etc.). It assumes that the emission pattern is highly correlated with the pattern of a particular indicator variable. Developing EIs with the 'bottom-up' approach requires dividing an emissions area into grid cells or administrative units and creating separate inventories for each sub-unit (Orthofer and Winiwarter, 1998). Sub-unit emissions are estimated

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by summing emissions that have been estimated at an even higher spatial resolution. Thus, successful application of the 'bottom-up' approach hinges on the availability of local data sets. The 'top-down' approach is easier to perform and less expensive with respect to time and resources; however, the 'bottom-up' approach provides a better representation of emissions estimates for a particular area (Lindley *et al.*, 1996). Widespread application of the 'bottom-up' approach should, in turn, translate into an estimated emissions landscape having a spatial complexity approaching that of 'reality.' Variations in data availability lead to many EIs being created with a combination of both methods (Orthofer and Winiwarter, 1998).

A geographic information system (GIS) is a useful, if not essential, tool for developing spatially disaggregated EIs. In fact, GIS is being promoted as a major component of a preferred spatial allocation method in the future (Eastern Research Group, 2001). Defined broadly, a GIS is a computer system for collecting, checking, integrating, and analyzing information related to the surface of the earth (Rhind, 1988). With regard to Els, it can perform the following functions:

(1) Import various types of spatial data, which are then used as indicators/surrogates when performing 'top-down' spatial allocation or as building blocks of the EI when performing the 'bottom-up' method.
(2) Houses emissions databases so that emissions information can be queried, retrieved, and modified.
(3) Perform spatial modeling functions, such as the estimation of indicator surfaces (i.e. creation of a map of source activity so that emissions associated with that source can be spatially disaggregated).
(4) Extract information from an EI and display it with tables, charts, graphs, and maps or allow the user to export data to other applications.

One of the most important aspects of a GIS is its ability to store emissions-related information as attributes in both vector and raster data models, thereby facilitating the distribution of information among entities (i.e. points, lines, polygons, and cells). Consequently, emissions can be estimated efficiently and spatially disaggregated at a relatively high spatial resolution (i.e. tens of meters) before being aggregated as part of the final gridded product.

Characteristics and uses of spatially disaggregated EIs in the context of urban ozone pollution

Spatially disaggregated emissions estimates are important from an air quality management perspective, especially the examination of ground-level ozone. Ozone is a secondary atmospheric pollutant (i.e. not emitted directly by sources) that can be generated in both polluted and unpolluted atmospheres by the oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) and sunlight (Chameides and Lodge, 1992). Ozone's adverse impacts on human health, crops, and forest ecosystems have become a major environmental concern (Sillman, 1999).

An EI employed to examine ozone pollution typically contains gridded estimates of emissions of VOCs, NO_x, and CO. Emissions estimates pertain to area and point sources. Point sources are usually factories, power plants, or other facilities with sufficiently large emissions to warrant individual cataloging. Area sources include sources that are too small, numerous, and dispersed to catalog individually, but that collectively contribute significantly to a region-wide total (Placet *et al.*, 2000). For urban-scale studies (i.e. domains from 100 to 200 km), EIs usually have hourly estimates at spatial resolutions from 2 to 10 km (Scheffe and Morris, 1993), while for regional-scale studies (i.e. domains of approximately 1 000 km), the spatial resolution approaches 20 km (Lamb, 1983). In addition, the VOCs–of which there are thousands of species - are usually condensed into a usable number of groups via the lumped approach and the carbon-bond approach (Scheffe and Morris, 1993).

Accuracy is another important characteristic of EIs, for the estimation of atmospheric emissions using any procedure is associated with a high degree of uncertainty (Lindley and Longhurst, 1998). Several studies note that VOCs tend to be significantly underestimated in inventories, especially those that employ the 'top-down' method (Chang *et al.*, 1992; Harley *et al.*, 1993; Winner *et al.*, 1995). For example, it has been found that actual VOC emissions from on-road mobile sources in Los Angeles are two to three times higher than the on-road mobile VOC emissions estimate present in the official State of California EI (Winner *et al.*, 1995). Measurements of ambient pollutant concentrations in roadway tunnels have been used to quantify the differences between modeled and actual on-road mobile emissions with the differences typically attributed to large emissions from a small number of vehicles (Chang *et al.*, 1992; Harley *et al.*, 1993). In addition to underestimates of mobile VOC emissions, the omission of many small VOC sources also contributes to underestimates of point and area VOC emissions (Chang *et al.*, 1992). Coupled with inaccurate VOC emissions estimates are uncertainties associated with NO_x emissions; nevertheless, estimates of the latter are usually more accurate than those of the former (Sillman, 1999).

EIs can be used to examine ozone pollution in several different ways. Sadler (1998) notes that management uses include the identification of potential air quality 'hot spots,' source apportionment, input into models to predict pollutant concentrations, and the testing of policy scenarios. A common application is to employ numerical models to demonstrate that candidate emissions control strategies will provide desired reductions in ambient pollutant concentrations (Hanna *et al.*, 1998). These models calculate ozone concentrations by simulating the physical and chemical processes in the atmosphere that affect ozone, thus accounting for spatial and temporal variations as well as differences in the reactivity (speciation) of emissions (Scheffe and Morris, 1993). Unfortunately, if the estimated base emissions are erroneous, the simulated response of ozone concentrations to emission controls will also be erroneous (Schere, 1988; Placet *et al.*, 2000). EIs can also be used in less rigorous, more qualitative applications, such as data visualization. For example, when inventories are both spatial and multi-temporal, the dynamic spatio-temporal nature of the emissions landscape can be visualized; consequently, the 'where' and 'when' of emissions can be understood more fully.

Aims and objectives

GIS is commonly used to produce EIs; however, there is a scarcity of published methodologies that discuss the development of spatially-resolved EIs within a GIS for urbanized areas, especially those in the western United States. Therefore, this paper's aims are twofold: to illustrate the potential of a GIS for enhancing an existing spatially-aggregated, anthropogenic EI; and to discuss the ozone-specific management implications of the resulting spatially-disaggregated EI. The associated objectives are (1) to describe the methods needed to produce a relatively high-resolution (500 m grid cells) inventory of anthropogenic emissions of the two main ozone precursors, VOC and NO_x, for typical weekdays and weekends of each month for a period corresponding to the mid- to late 1990s, (2) to determine and explain the spatio-temporal variations in emissions, (3) to discuss the potential errors of the EI, and (4) to discuss several management applications. The above process is demonstrated using the example of Tucson, Arizona, which is a rapidly growing urban area in the southwestern part of the United States.

Study region

Tucson (centered at ~32° N latitude and ~111° W longitude) as defined in this study, is a rectangular region in southern Arizona that covers approximately 10 900 square kilometers (100 km E–W by 109 km N–S) that is contained almost entirely within Pima County (Figure 1). The region is situated in the Sonoran Desert and has elevations ranging from 600 m (~2 000 ft) above sea level (a.s.l.) in the northwest to over 2 500 m (over ~8 000 ft) a.s.l. in the Rincon and Santa Catalina Mountains. In concert with the expansion of the metropolitan area, Tucson's population total grew rapidly from approximately 265 000 to over 800 000 people from 1960 to the late 1990s (PAG, 2001).

The combination of its size, geographical setting, and climate makes Tucson conducive to elevated ozone levels. If, in fact, the existing 1-hour National Ambient Air Quality Standard (NAAQS) for ozone is replaced in the next few years with a new 8-hour standard, Tucson might violate the new standard (Keyes *et al.*, 2001). This possibility heightens the importance of reducing VOC and NO_x emissions in the short-term. Spatially-resolved EIs can play a pivotal role in the ozone control decision-making process.

Data

Data used in the inventory development process consisted of both emissions-related and spatial data that pertained primarily to the 1995 to 1998 period. The emissions-related data consisted of either actual estimates or factors. The spatial data were needed not only to spatially allocate existing emissions estimates, but also to calculate some baseline estimates.

Emissions-related data

The emissions-related data were acquired from county, state, and national agencies as well as

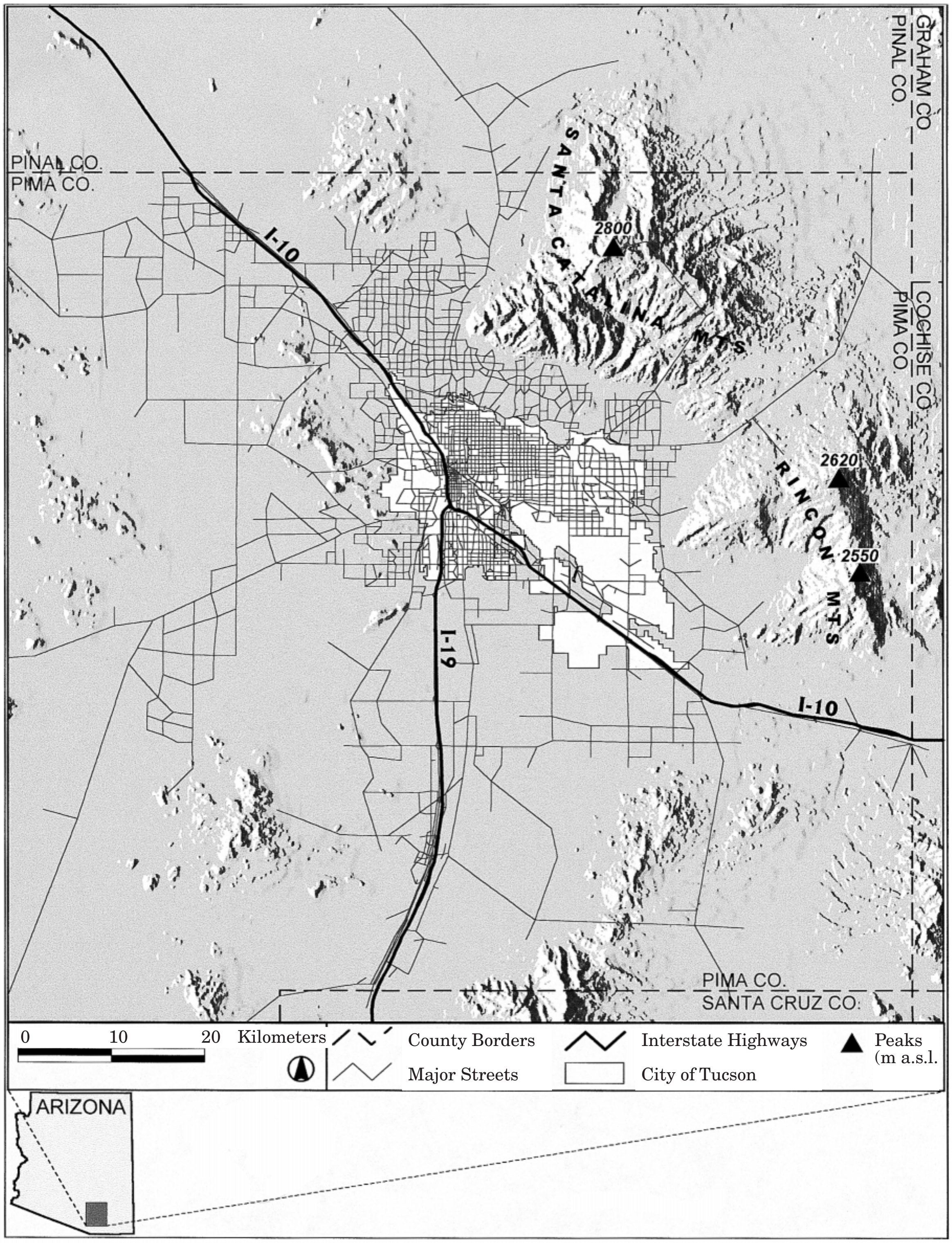

Figure 1. Map of the Tucson region showing the City of Tucson, the metropolitan area, the interstates, and the surrounding mountains.

a university research unit and private consulting firms. The following data were obtained from Pima County Department of Environment Quality (PDEQ): 1995 county-level, anthropogenic pollutant emissions estimates (PDEQ, 1997a); 1995/1996 sector-specific residential wood burning estimates (PDEQ, 1997b); 1995 county-level, railroad and railyard activity emissions estimates (PDEQ, 1995); and 1998 vehicle fleet distribution information. Dwelling unit and population projections for Pima County's traffic analysis zones (TAZs) were provided by Pima Association of Governments (PAG). Daily weekday and weekend traffic counts by month for selected Pima County roads were obtained from Pima County Department of Transportation (PCDOT) while estimates of percentages of heavy-duty diesel vehicles on the Tucson portion of Interstate 10 were provided by the Arizona Department of Transportation (ADOT). Maricopa Association of Governments (MAG) provided county-level anthropogenic pollutant emissions estimates for Maricopa County in 1994. Daily temperature data for Tucson International Airport from 1995 to 1998 were obtained from the National Climatic Data Center (NCDC). Monthly values of new authorized housing units in the Phoenix and Tucson metropolitan areas were provided by the Karl Eller Graduate School of Management at The University of Arizona (KEGSM, 1995a,b, 1997). 1995 emissions estimates for various metropolitan statistical areas (MSAs) in the US were acquired from the United States Environmental Protection Agency's National Emission Trends Database. Finally, 1996 lawn information for Maricopa County and national per-capita solvent use factors were obtained from Sonoma Technology, Inc. and Eastern Research Group, respectively (Chinkin *et al.*, 1996; Eastern Research Group, 1996).

Spatial data

Except for the aerial photographs and topographic maps, all of the data described below were georeferenced (UTM (zone 12) coordinate system with Clarke 1866 Spheroid and NAD27 Datum) and digital. The following data were provided by PCDOT for Pima County: 1990 street network, which was the latest available; 1996 Pima County rail network; 1997 traffic analysis zones (TAZs). A 1998 gridded land-cover database for the Tucson region, a 1998 street network database for Pima County that contains 1998 traffic speed and volume estimates for major streets, and actual traffic data from 1996 to 1998 were obtained from Pima Association of Governments (PAG) for Pima County. 1996 gasoline station and county-permitted point source databases for Pima County were obtained from Pima Department of Environmental Quality (PDEQ). A 1995 land-use database for Pima County was provided by the School of Renewable Natural Resources at The University of Arizona. Finally, 1996/1997 aerial photographs (1:14 400 scale) of Tucson metropolitan area and 7·5 minute topographic quadrangles (1:24 000 scale) for the Tucson region were obtained from Landiscor, Inc. and the United States Geological Survey (USGS), respectively.

Methods

Emissions estimates were either generated specifically for the gridded EI, derived from annual emissions estimates in the 1995 Pima County EI (PDEQ, 1997a), which has only total county-wide estimates, or were modified from another region's inventory. Standard methodologies were used by county personnel to calculate emissions estimates for various sources (e.g. fuel combustion, petroleum transfer and storage, etc.) in the above inventories. A summary of all emissions sources and associated data sources are listed in Table 1. These sources are similar to those presented in the 1995 EI with various sources aggregated and disaggregated when appropriate. Emissions were associated with points, line segments, polygons, and grid cells before being aggregated up to the 500 m grid cell level. Finally, multi-temporal emissions were generated by time-specific model runs, the application of temporal allocation factors (TAFs), or both.

The key GIS-related methods used to develop the spatial component of the EIs included the following:

(1) Calculating emissions for specific features.
(2) Spatially disaggregating region-wide emissions totals.
(3) Adding emissions from various point sources to the emissions surfaces.

The following sections provide an overview of the above methods.

Calculating emissions for specific features

The calculation of emissions for specific features, which is an example of the 'bottom-up' method, was only performed for on-road mobile emissions on major road segments due to data availability. This procedure is known as the link method (Brandmeyer and Karimi, 2000). On-road mobile sources have been recognized as the largest emissions source in the Tucson region (PDEQ, 1997a) and entire papers have been devoted to describing

Table 1. List of emissions sources and associated data sources

Symbol	Emissions source	Emissions data source	Spatial data source	Feature type	Date	Resolution	Provider
AC	Aircraft	PDEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
AGE	Agricultural Equipment	MAG	Digital land-cover map	Grid	1998	30 m	SMOGMAP
AGPW	Agricultural Pesticides and Waste Burning	PDEQ	Digital land-cover map	Grid	1998	30 m	SMOGMAP
AIRDEF	Aircraft Manufacturing and Defense	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
AC	Aircraft	PDEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
ASARCO	ASARCO Mine	PDEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
AZPORT	Arizona-Portland Cement Plant	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
AZPUB	Arizona Public Service Electric Power Plant	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
BIO2	Biosphere2 Center	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
C	Commercial Land-Use Fuel Combustion	PDEQ	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
CBA	Cutback Asphalt	PDEQ	Digital street network (all streets)	Line	1990	1:12 000	PCDOT
CE	Commercial Land-Use Equipment	MAG	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
CSTE	Construction Equipment	MAG, PDEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
CYP	Cyprus Sierrita Mine	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
DM	Davis-Monthan AFB (non-aircraft)	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
F	Forest Management	PDEQ	Digital land-cover classification	Grid	1998	30 m	SMOGMAP
GAS	Gasoline Stations	PDEQ	Point coverage	Point	1996	1:24 000	PDEQ
I	Industrial Land-Use Fuel Combustion	PDEQ	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
IE	Industrial Land-Use Equipment	MAG	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
LG	Lawn and Garden Equipment	MAG	Digital land-cover map	Grid	1998	30 m	SMOGMAP
MHA	Municipal/Hospitals/Airports	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
			Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
MISC	Miscellaneous	PDEQ	Digital land use map	Polygon	1995	1:3 000	U of A (RNR)
ORGSOLV	Consumer Organic Solvent Use	ERG	Traffic analysis zones	Polygon	1997	1:100 000	PAG, PCDOT

ORMV	On-Road Motor Vehicles	EPA, PAG, PDEQ	Digital street network (all streets)	Line	1990	1:12 000	PCDOT
			Digital street network (major streets)	Line	1998	1:12 000	PAG
PET	Petroleum Storage and Transfer	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
RESNG	Residential Natural Combustion	PDEQ	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
RESWD	Residential Wood Combustion	PDEQ	Digital land-use map	Polygon	1995	1:3 000	U of A (RNR)
RL	Rail Lines	PDEQ	Digital rail line network	Line	1992	1:24 000	PCDOT
RY	Railyard	PDEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
SMSMELT	BHP Copper Mine (San Manuel)	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
TEP	TEP Irvington Electric Power Plant	ADEQ	Aerial photographs	NA	1996	1:14 400	Landiscor Inc.
TUCNEWS	Tucson Newspapers Facility	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
UNCLASS	PDEQ Industrial/Commercial Permits	PDEQ	Point coverage of county-permitted facilities	Point	1996	1:24 000	PDEQ
URBPEST	Urban Pesticide Use	ERG	Traffic analysis zones	Polygon	1997	1:100 000	PAG, PCDOT
WF	Wildfires	PDEQ	Digital land-cover map	Grid	1998	30 m	SMOGMAP

NA=not applicable.

the spatial disaggregation of traffic volume in other regions (Brandmeyer and Karimi, 2000). Calculating on-road mobile emissions for major road segments involved the integration of output from TRANPLAN, a transportation planning model (Urban Analysis Group, 1998), and Mobile 5a, a mobile emissions model (US EPA, 1994) within a GIS. The TRANPLAN database contained calculated and predicted traffic volume and speeds for major road segments (i.e. interstate highways and primary arteries). The TRANPLAN modeling was executed by PAG, and the modeling error in the metropolitan area was approximately 15% (C. Hodges, Pima Association of Governments, personal communication, 2001). This information was only representative of a typical day; therefore, it was neither month- nor season-specific. Mobile 5a was used to calculate daily VOC and NO_x emission factors (g/mi) for each segment based on vehicle speed, vehicle mix (i.e. proportion of vehicles in each vehicle class), and daily vehicle miles traveled (VMT).

VOC and NO_x emission factors for 1996 were calculated for each major road segment based on typical monthly temperatures (average daily, daily minimum, and daily maximum), vehicle speed, estimated Reid vapor pressures (average of high and low altitude Reid vapor pressures), vehicle fleet distribution, and fuel type. Therefore, month-specific, and vehicle class-specific emission factors for speeds from 5 to 60 mph ($\sim$8 to 96 km h^{-1}) at 5 mph ($\sim$8 km h^{-1}) increments were calculated within Mobile5a. The eight vehicle classes and their relative proportions of the total vehicle population are listed in Table 2 while month-specific temperature values are listed in Table 3. The month-specific emission factors were influenced by the use of oxygenated fuels during the winter months (October through March) and the use of non-oxygenated fuels during the summer months (April through September). Oxygenated fuel is gasoline that is blended with additives that contain oxygen, and the additional oxygen promotes more efficient combustion and thus reduces emissions of carbon monoxide. Segment-specific daily emissions estimates were calculated by multiplying VMT by the appropriate composite emission factor (i.e. weighted average of the factors for the eight vehicle classes) to yield the daily emissions total. The equation is as follows:

$$\mathrm{TME_S} = \mathrm{VMT_D} * [(\mathrm{P_{HDDV}} * \mathrm{EF_{HDDV}}) * (\mathrm{P_{HDGV}} * \mathrm{EF_{HDGV}}) * \ldots (\mathrm{P_{MC}} * \mathrm{EF_{MC}})], \quad (1)$$

where $\mathrm{TME_S}$ is the TRANPLAN, segment-specific mobile emissions, $\mathrm{VMT_D}$ is the TRANPLAN, segment-specific total daily vehicle miles traveled,

Table 2. The eight vehicle classes and their proportions of the total vehicle population on non-highway and highway roads in the Tucson region

Vehicle class	Description	Non-highway	Highway
HDDV	Heavy-duty diesel vehicles	0·060	0·300
HDGV	Heavy-duty gasoline vehicles	0·036	0·027
LDDT	Light-duty diesel trucks	0·001	0·001
LDDV	Light-duty diesel vehicles	0·003	0·002
LDGT1	Light-duty gasoline trucks (0 to 6000 lb. gross vehicle weight)	0·173	0·130
LDGT2	Light-duty gasoline trucks (6001 to 8500 lb. gross vehicle weight)	0·085	0·063
LDGV	Light-duty gasoline vehicles	0·638	0·474
MC	Motorcycles	0·004	0·003

Table 3. Month-specific temperatures and traffic volume factors

Month	Daily maximum temperature (°C)	Daily minimum temperature (°C)	Average daily temperature (°C)	Residential VOC emission factor (g mi)	Residential NO_x emission factor (g mi)	Traffic volume factor
January	19·0	4·3	11·6	3·46	3·10	0·991
February	20·3	6·3	13·3	3·49	3·09	1·037
March	24·2	8·2	16·2	3·59	3·03	1·070
April	26·9	9·9	18·8	3·13	2·92	1·048
May	32·8	15·7	24·9	3·22	2·80	1·010
June	37·8	19·8	29·3	3·58	2·78	0·982
July	38·2	23·9	31·1	3·68	2·77	0·948
August	36·9	23·6	29·8	3·54	2·78	0·966
September	33·3	20·7	27·6	3·33	2·79	0·961
October	29·6	13·3	20·4	3·85	2·94	0·992
November	24·3	8·6	16·4	3·60	3·02	0·986
December	18·6	3·8	11·2	3·45	3·14	1·012

and the P and EF variables are the proportion of the various types of vehicle classes on non-highway roads and the month- and speed-specific emission factors for each vehicle class, respectively.

Interstate highway emission totals were adjusted by using different vehicle proportions (i.e. larger proportion of heavy-duty diesel vehicles (HDDVs) for highway segments. According to ADOT, 30% of the vehicles on Tucson's interstate highways are HDDVs. The remaining 70% is the same vehicle mix as the rest of the region. Using the adjusted fleet distribution, the same procedures used to yield VOC and NO_x emissions estimate for non-highway segments were used for the highway segments. Emissions within each grid cell were calculated by summing all segment-specific emissions within each cell.

Spatially disaggregating region-wide emissions totals

The spatial disaggregation of emissions employed the 'top-down' method and thus distributed emissions among cells based on those cells' values of a particular indicator variable. Unlike on-road mobile emissions for major road segments, emission sources that require the 'top-down' method cannot have emissions calculated feasibly for specific entities. For the purposes of this paper, these sources were considered area sources even though some might be more appropriately categorized as mobile or point sources. One might argue that mobile sources are actually area sources, since it is impractical to directly estimate emissions for mobile sources (e.g. estimating emissions separately for every on-road motor vehicle).

Area sources included agricultural pesticides and waste burning, commercial land-use fuel combustion, consumer organic solvent use, cut-back asphalt, forest fires, gasoline stations, industrial land-use fuel combustion, miscellaneous fires, non-road mobile sources (i.e. agricultural equipment, aircraft and airport equipment, commercial land-use equipment, construction equipment, industrial land-use equipment, lawn and garden equipment, rail lines, and railyard), residential natural gas combustion, residential on-road motor vehicles, residential wood combustion, urban pesticide use, and wildfires. These sources were associated with spatially varying indicators that were proxies for the source's actual activity levels. Using an indicator surface (i.e. map of an indicator's values), emissions were allocated among the grid cells based on the proportion of the cell's indicator value to the cumulative indicator value. Thus, a form of weighted spatial allocation was used. The area sources and associated indicators are listed in Table 4.

It was recognized that the 1995 Pima County EI had inadequate emissions estimates for residential on-road mobile and some non-road mobile sources. Residential on-road mobile pertained to motor vehicles on minor streets while the targeted non-road mobile sources included agricultural equipment, commercial land-use equipment, construction equipment, industrial land-use equipment, and lawn and garden equipment. Therefore, new estimates were incorporated directly into the spatially disaggregated EI.

Residential on-road mobile

Residential on-road mobile emissions were based on several assumptions. First, it was assumed that residential on-road VMT was 15% of the TRANPLAN-derived total daily VMT estimate (i.e. total VMT on major streets), which was approximately 29·3 million kilometers (~18·2 million miles). Therefore, the total VMT on residential streets was approximately 4·4 million kilometers (~2·7 million miles). Second, the average motor vehicle speed on residential streets was assumed to be $15\,\mathrm{mi\,hr^{-1}}$ ($\sim 24\,\mathrm{km\,hr^{-1}}$). The total residential on-road mobile emissions value was calculated by multiplying the residential VMT estimate by the month-specific emissions factors that were based on a typical vehicle fleet distribution traveling at $15\,\mathrm{mi\,hr^{-1}}$ ($\sim 24\,\mathrm{km\,hr^{-1}}$). The equation is as follows:

$$\mathrm{RME_T} = \mathrm{RVMT} * \mathrm{EF_M}, \qquad (2)$$

where $\mathrm{RME_T}$ is the total residential on-road mobile emissions, RVMT is the total residential VMT, and $\mathrm{EF_M}$ is the month-specific emissions factor. The estimates of total residential on-road mobile emissions were refined by adjusting the month-specific emissions with the month-specific average daily traffic volume data (refer to Table 3). Emissions estimates were spatially allocated to the cells based on each cell's proportion of the region's total road length (i.e. cumulative length of all roads).

Non-road mobile

Non-road mobile emissions estimates were based on estimates used for the Phoenix area (MAG,

Table 4. Area emission sources, the source or derivation of the region-wide emissions estimate, indicator variables, major problems associated with the indicator variables, and the relative spatial correlation between the emissions source and the indicator variable

Emissions source	Source/ derivation	Indicator variable	Problems	Relative spatial correlation
Aircraft	PDEQ, 1997a	Runway length	b	Low
Agricultural equipment	Multiply Phoenix estimate (MAG, 1997) by 0·12, the Tucson/Phoenix row crop area ratio	Row crop land cover class	a	High
Agricultural pesticides and waste burning	PDEQ, 1997a	Row crop land cover class	a	High
Commercial land-use equipment	Multiply Phoenix estimate (MAG, 1997) by 0·31, the Tucson/Phoenix population ratio	Commercial land use	c	Medium
Commercial land-use fuel combustion	PDEQ, 1997a	Commercial land use class	c	Medium
Construction equipment	Multiply Phoenix estimate (MAG, 1997) by 0·17, the Tucson/Phoenix activity ratio	Construction activity	d	Low
Consumer organic solvent use	Multiply population total by per capita use value 3·34 kg yr^{-1} (ERG, 1996)	Population	e	Medium
Cutback asphalt	PDEQ, 1997a	Road length	f	Low
Forest management	PDEQ, 1997a	Forest land-cover classes	f	Low
Gasoline stations	PDEQ, 1997a	Gas station frequency	g	Medium
Industrial land-use equipment	Multiply Phoenix estimate (MAG, 1997) by 0·31, the Tucson/Phoenix population ratio	Industrial land use class	c	Medium
Industrial land-use fuel combustion	PDEQ, 1997a	Industrial land use class	c	Medium
Lawn and garden equipment	Multiply Phoenix estimate (MAG, 1997) by 0·18, the Tucson/Phoenix use ratio	Dwelling units with lawns	h	Medium
Miscellaneous fires	PDEQ, 1997a	Built-up land	f	Low
On-road motor vehicles (residential)	This paper	Road length	i	Medium
Rail lines	PDEQ, 1995	Rail length	a	High
Railyard	PDEQ, 1995	Railyard area	a	High
Residential natural gas combustion	PDEQ, 1997a	Dwelling units	e	Medium
Residential wood combustion	PDEQ, 1997b	Dwelling units in various sectors	e	Medium
Urban pesticide use	Multiply population total by per capita use value 0·22 kg yr^{-1} (ERG, 1996)	Population	j	Medium
Wildfires	PDEQ, 1997a	Desertscrub land cover classes	f	Low

Key:
a: Negligible.
b: Does not account for flight lines.
c: Much spatial variation and much variation in emissions levels within a source.
d: Much spatial variation and assumes that there is strong spatial autocorrelation among construction activity.
e: Does not account for socioeconomic factors.
f: Activity is spatially sporadic.
g: Does not account for differences in activity levels between stations.
h: Much uncertainty associated with determination of cells that might contain lawns.
i: Assumes that every residential street has the same amount of motor vehicle traffic.
j: Does not account for socioeconomic and environmental factors.

1997). It was considered reasonable to treat Tucson and Phoenix as similar since the two cities are separated by less than 200 km (~120 miles) and they have similar climates and settlement patterns. The two cities do differ substantially in size, however, for the Phoenix area's population total (~2·4 million) is three times that of the Tucson area (~800 000). Tucson's emissions totals from commercial land-use equipment and industrial land-use equipment were estimated by multiplying Phoenix's total by 0·31, which was the Tucson/Phoenix population ratio. Thus, emissions were assumed to be proportional to total population. Concerning emissions from agricultural equipment, Chinkin *et al.* (1996) estimated that agricultural equipment traverses approximately 1 005 km^2 (~400 mi^2) of the Phoenix area. Using a land-cover database, it was determined that 123 km^2 (~50 mi^2) in the Tucson region was affected by agricultural equipment. Phoenix's agricultural equipment emissions were multiplied by 0·12, which was the Tucson/Phoenix row-crop area ratio, to yield Tucson's estimate. Tucson's emissions total from construction equipment was estimated by multiplying Phoenix's total by 0·17, which was the Tucson/Phoenix construction activity ratio. This ratio was based on monthly totals of authorized new housing units in Tucson and Phoenix (KEGSM, 1995a,b, 1997).

Producing a dependable estimate of emissions from lawn and garden equipment proved to be substantially more difficult than producing estimates for the other non-road mobile sources. Chinkin *et al.* (1996) estimated that 70% of Phoenix's residences might be subjected to regular land and garden equipment use. Using a land-cover database, it was estimated that approximately 50% of Tucson's residential land-use area was covered with either moderately- or highly-vegetated residences. It was hypothesized that 80% of these residences had lawns; consequently, 40% of Tucson's residences were considered to have lawns. The Tucson/Phoenix population and lawn percentage proportions, 0·31 and 0·57 (i.e. 40% divided by 70%), respectively, were employed to estimate Tucson's lawn and garden emissions as follows:

$$LG_{TUC} = P_{TUC} * (L_{TUC} * LG_{PHX}), \qquad (3)$$

where LG_{TUC} is Tucson's lawn and garden equipment emissions estimate, P_{TUC} is 0·31, L_{TUC} is 0·57, and LG_{PHX} is Phoenix's lawn and garden equipment emissions. Consequently, Tucson's lawn and garden equipment emissions were estimated to be 18% of Phoenix's emissions.

Spatially allocating emissions from agricultural equipment, commercial land-use equipment, industrial land-use equipment, and lawn and garden equipment was relatively straightforward (Table 4) while allocating the construction equipment emissions was more challenging. Construction sites in the Tucson region were identified on aerial photographs from 1996, and construction activity levels were estimated based on the number of hectares of disturbed soil within each site. These activity levels were represented by 33 points, 17 of which were located in a cluster northwest of the city. The network of construction site points was supplemented with nearly 700 points having zero activity levels. These points were placed throughout the remainder of the region at a spacing of 4 km, which was the average spacing of construction sites in the northwestern cluster, and at a distance greater than or equal to 4 km from the nearest construction point. A simple spatial interpolation technique, inverse distance weighting (IDW), was used to create a construction activity surface. IDW requires the presence of spatial autocorrelation (i.e. values at nearby points are more similar than are values at distant points) to produce meaningful results. Using Moran's I tests (Cliff and Ord, 1973), it was verified that significant spatial autocorrelation existed among the construction activity points. The resulting IDW-derived surface of construction activity enabled temporal variations in construction activity to be accounted for since it assigned many grid cells non-zero activity values while also placing the highest values in northwestern Tucson, the region's construction 'hot spot'. Thus, even though the surface was created with data from 1996, the surface ultimately represented potential construction areas for the mid- to late 1990s. Emissions were spatially allocated to the cells based on each cell's proportion of the region-wide total construction activity.

Point source emissions

The Tucson region's point source emissions represented those emissions from county- and state-permitted facilities. Some facilities were kept as distinct sources (i.e. an attribute in the GIS database) if they had a relatively large amount of annual emissions; otherwise, similar facilities were lumped into a single source category based on similarities in facility type or operating schedules. Emissions and spatial data sources are listed in Table 1. These emissions were linked to the exact locations of the facilities, thereby enabling the transfer, within a GIS, of a facility's emissions to the grid cell within which the facility was located.

Temporal allocation of annual emissions

Annual emissions were converted to monthly emissions and daily emissions with the aid of temporal allocation factors (TAFs). TAFs were expressed as the proportion of annual emissions occurring in each month as well as the proportion of weekly emissions occurring on each day of the week. TAFs are listed in Tables 5, 6, and 7 and were specific to the Phoenix area and southern Arizona when the national TAFs were deemed inappropriate for the Tucson region (MAG, 1997). For sources with only annual emissions estimates, monthly emissions were calculated by multiplying the annual emissions estimate by a monthly factor. Monthly emissions were divided by 30·42 (the average number of days per month) to yield month-specific average daily emissions. In addition, weekday- and weekend-specific factors were applied to average daily values to calculate average daily weekday and average daily weekend emissions estimates. The equation used to calculate daily emissions is as follows:

$$E_D = (E_A * F_M)/30.42 * F_D, \qquad (4)$$

where E_D is the total daily emissions, E_A is the total annual emissions, F_M is month-specific emissions factor, and F_D is the day-specific emissions factor.

Results and discussion

By employing spatial allocation methods and temporal allocation factors within a GIS, spatio-temporal databases of VOC and NO_x emissions were produced for the Tucson region. These databases are essentially tables with the region's 43 600 cells (200 × 218 cells at 500 m resolution) as the rows (i.e. records) and the various emission sources as the columns (i.e. attributes). The information system has enabled primarily geographic examinations of emissions. The results of these examinations with respect to the determination and explanation of spatio-temporal variations in emissions are presented below.

Annual emissions

Anthropogenic sources emit 39 596 and 40 505 metric tons of VOCs and NO_x, respectively, in the Tucson region annually (Table 8). On-road motor vehicles are the dominant source accounting for approximately 50% of both pollutants' emissions. Residential wood combustion and a large cement-producing facility emit approximately 20% and 10% of the VOCs and NO_x, respectively. Non-road mobile is also a major VOC and NO_x source,

Table 5. Month-specific temporal allocation factors for the various emissions sources

Code	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0·083	0·083	0·083	0·083	0·083	0·083	0·083	0·083	0·083	0·083	0·083	0·083
2	0·013	0·027	0·040	0·067	0·133	0·133	0·133	0·133	0·133	0·107	0·067	0·013
3	0·067	0·067	0·086	0·086	0·095	0·095	0·095	0·095	0·095	0·086	0·086	0·067
4	0·183	0·183	0·147	0·110	0·037	0·037	0·037	0·006	0·037	0·037	0·037	0·147
5	0·283	0·156	0·047	0·001	0·001	0·001	0·001	0·001	0·001	0·055	0·151	0·303
6	0·183	0·183	0·147	0·110	0·037	0·037	0·037	0·006	0·037	0·037	0·037	0·147
7	0·000	0·000	0·015	0·074	0·147	0·147	0·147	0·147	0·147	0·147	0·029	0·000
8	0·082	0·086	0·089	0·087	0·084	0·083	0·080	0·081	0·080	0·083	0·082	0·083
9	0·051	0·055	0·074	0·075	0·083	0·118	0·116	0·105	0·085	0·114	0·074	0·051
10	0·083	0·086	0·089	0·087	0·084	0·082	0·079	0·081	0·080	0·083	0·082	0·084
11	0·012	0·004	0·095	0·047	0·073	0·123	0·197	0·198	0·157	0·052	0·040	0·002

Code	Sources
1	AC, AIRDEF, ASARCO, AZPORT, AZPUB, BIO2, CBA, CE, CSTE, CYP, DM, I, IE, MHA MISC, ORGSOLV, RL, RY, SMSMELT, TUCNEWS, UNCLASS, URBPEST
2	AGE, AGPW
3	LG
4	C
5	RESWD
6	RESNG
7	F, WF
8	GAS
9	PET
10	ORMV
11	TEP

Table 6. Day-specific temporal allocation factors for the various emission sources

Code	Mon	Tues	Weds	Thurs	Fri	Sat	Sun
1	0·143	0·143	0·143	0·143	0·143	0·143	0·143
2	0·111	0·111	0·111	0·111	0·111	0·222	0·222
3	0·164	0·164	0·164	0·164	0·164	0·115	0·065
4	0·167	0·167	0·167	0·167	0·167	0·167	0·000
5	0·129	0·128	0·129	0·129	0·156	0·169	0·160

Code	Sources
1	AC, AGE, AGPW, ASARCO, AZPORT, AZPUB, CBA, CYP, F, GAS, MHA, MISC, ORGSOLV, PET, RL, RY, SMSMELT, TEP, TUCNEWS, URBPEST, WF
2	LG, RESNG
3	BIO2, C, CE, CSTE
4	AIRDEF, DM, I, IE, UNCLASS
5	RESWD

Table 7. Weekday- and weekend-specific temporal allocation factors for the various emissions sources

Code	Weekday	Weekend
1	1·000	1·000
2	0·778	1·556
3	1·147	0·633
4	1·167	0·583
5	0·939	1·151
6	1·000	0·770

Code	Sources
1	AC, AGE, AGPW, ASARCO, AZPORT, AZPUB, CBA, CYP, F, GAS, MHA, MISC ORGSOLV, PET, RL, RY, SMSMELT, TEP, TUCNEWS, URBPEST, WF
2	LG, RESNG
3	BIO2, C, CE, CSTE
4	AIRDEF, DM, I, IE, UNCLASS
5	RESWD
6	ORMV

Table 8. Annual VOC and NO_x emissions in the Tucson region. Refer to Table 1 for descriptions of the sources

Source	VOCs (kg)	VOCs (%)	NO_x (kg)	NO_x(%)
AC	234597	0·59	705831	1·74
AGE	10772	0·02	61813	0·15
AGPW	9522	0·02	0	0·00
AIRDEF	97526	0·25	0	0·00
ASARCO	1089	0·00	24494	0·06
AZPORT	4291	0·01	5052530	12·47
AZPUB	1715	0·00	185057	0·46
BIO2	8071	0·02	138938	0·34
C	8422	0·02	160597	0·40
CBA	384644	0·97	0	0·00
CE	385098	0·97	73904	0·18
CSTE	551802	1·39	3166284	7·82
CYP	37140	0·09	145875	0·36
DM	71278	0·18	0	0·00
F	33631	0·08	7086	0·02
GAS	2673459	6·75	0	0·00
I	69944	0·18	1632303	4·03
IE	2173105	5·49	417040	1·03
LG	1082311	2·73	64439	0·16
MHA	105156	0·27	381378	0·94
MISC	18865	0·05	181	0·00
ORGSOLV	2660548	6·72	0	0·00
ORMV	18905533	47·75	22757451	56·18
PET	179325	0·45	0	0·00
RESNG	25891	0·07	334958	0·83
RESWD	8251704	20·84	94346	0·23
RL	75468	0·19	1369089	3·38
RY	22288	0·02	456218	1·13
SMSMELT	9564	0·02	379609	0·94
TEP	15141	0·04	2112614	5·22
TUCNEWS	193108	0·49	0	0·00
UNCLASS	334119	0·84	479898	1·18
URBPEST	172744	0·44	0	0·00
WF	787759	1·99	303519	0·75
SUM	39595630	100	40505229	100

for it is responsible for approximately 10% and 15% of the VOC and NO_x emissions, respectively. Lawn and garden equipment emit approximately half of those VOCs while construction equipment accounts for approximately half of those NO_x emissions.

The Tucson region is similar to most other large MSAs in the western US with respect to major VOC and NO_x sources (Table 9). On-road mobile and non-road mobile sources are a more important source of VOCs and NO_x in western cities relative to the national average. Tucson, however, differs from several western cities in three major ways: (1) solvent utilization, which is responsible for less than 10% of VOC emissions, is a relatively unimportant VOC source, (2) non-road mobile is a less important VOC source; and (3) residential wood combustion is a major VOC source. The large contribution from residential wood combustion reduces the relative importance of common, large VOC sources, such as non-road mobile and solvent utilization. Even though it suspected that VOC emissions from solvent utilization, especially surface coating activities, have been underestimated for Tucson, the relative contribution probably does not equal that in most of the other western cities. Concerning emissions from lawn and garden equipment, Tucson's low emissions are associated with reduced lawn and garden equipment activity resulting from a prevalence of xerophytic landscaping. Finally, Tucson's relatively large contribution of VOC emissions from residential wood burning stems in part from approximately 20% of Tucson's households burning wood with greater than 8% of the households burning more than one cord ($\sim$3·6 m^3) of wood per year (PDEQ, 1997b).

Table 9. Major ozone precursor sources and daily VMT per capita in the Tucson region and other western USA Metropolitan Statistical Areas (MSAs)

MSA/region	Largest VOC source (% of total)	Second largest VOC source (% of total)	Largest NO_x source (% of total)	Second largest NO_x source (% of total)
Albuquerque, NM	On-road mobile (49)	Solvent utilization (30)	On-road mobile (57)	Industrial fuel combustion (22)
Denver-Boulder-Greeley, CO	Solvent utilization (37)	On-road mobile (26)	On-road mobile (30)	Non-road mobile (26)
Las Vegas, NV-AZ	On-road mobile (36)	Solvent utilization (27)	Electric utilities (45)	Non-road mobile (29)
Los Angeles-Riverside-Orange, CA	On-road mobile (47)	Solvent utilization (22)	On-road mobile (47)	Non-road mobile (38)
Phoenix-Mesa, AZ	Solvent utilization (37)	On-road mobile (32)	On-road mobile (40)	Non-road mobile (45)
Sacramento-Yolo, CA	On-road mobile (43)	Solvent utilization (22)	On-road mobile (61)	Non-road mobile (30)
Salt Lake City-Ogden, UT	On-road mobile (33)	Solvent utilization (32)	On-road mobile (37)	Non-road mobile (31)
San Antonio, TX	On-road mobile (40)	Solvent utilization (32)	On-road mobile (44)	Electric utilities (23)
San Diego, CA	On-road mobile (46)	Non-road mobile (23)	On-road mobile (49)	Non-road mobile (40)
San Francisco-Oakland-San Jose, CA	On-road mobile (44)	Non-road mobile (23)	On-road mobile (50)	Non-road mobile (33)
Tucson, AZ region	On-road mobile (48)	Residential wood combustion (21)	On-road mobile (56)	Non-road mobile (16)
USA	Solvent utilization (30)	On-road mobile (29)	On-road mobile (31)	Electric utilities (25)

Note: Data for the MSAs were obtained from the US. EPA's 1996 National Emission Trends Database (Version 3) (http://www.epa.gov/ttn/rto/areas/net.htm), data for the entire USA was obtained from the US. EPA's National Air Pollutant Emission Trends: 1900–1998 (March 2000) EPA 454/R-00-002 (http://www.epa.gov/ttn/chief/trends/trends98), and data for the Tucson region is provided in this paper.

Thematic maps of VOC and NO_x emissions (Figures 2 and 3) reveal substantial spatial variations in emissions across the Tucson region. In particular, a NO_x map (Figure 3) shows a gridiron pattern of high-emitting cells which reveals the importance of on-road motor vehicle emissions. The emissions landscape (Figure 4) is also shaped by several large point sources including a cement plant, an electric power plant, a newspaper printing facility, petroleum storage tanks, and a sewage treatment plant. Rapid decreases in both VOC and NO_x emissions are noticeable as one moves into the Santa Catalina Mountains and other mostly uninhabited areas (Figures 2, 3, and 4). In fact, sources within the City of Tucson emit approximately 50% and 36% of the region's VOCs and NO_x. The city's on-road motor vehicles are responsible for over 25% of the region's VOC and NO_x emissions.

Monthly emissions

Average daily VOC and NO_x emissions have substantially different month-to-month variations, especially during the warm to cool season transition and vice-versa (Figure 5). There is little variation in NO_x emissions throughout the year. Subtle increases are associated with the combustion of oxygenated fuels during March, which is the peak traffic month, and increased electrical generation associated with increased air conditioner use in August. VOC emissions have a considerable wintertime peak due to heavy residential wood combustion during December and January, which have average daily minimum temperatures below 4°C (~39° F) (Table 3). Consequently, residential wood combustion is responsible for nearly 50% of the region's VOC emissions during the winter months.

As can be discerned to a certain extent from above, some of the major emissions sources change from month-to-month (e.g. residential wood combustion is an important winter source of VOCs but it is a negligible summer source). Each season has a different assortment of major pollutant emitters (Figure 6). Adding to this situation are dramatic changes in BVOC emissions during a single season with emissions in August being potentially over 20 times greater than those in June (Diem, 2000; Diem and Comrie, 2001a). This characteristic emphasizes the importance of developing multi-temporal inventories when trying to assess the relative importance of various pollution sources. On-road mobile and residential wood combustion are the largest VOC sources in the summer and winter months, respectively.

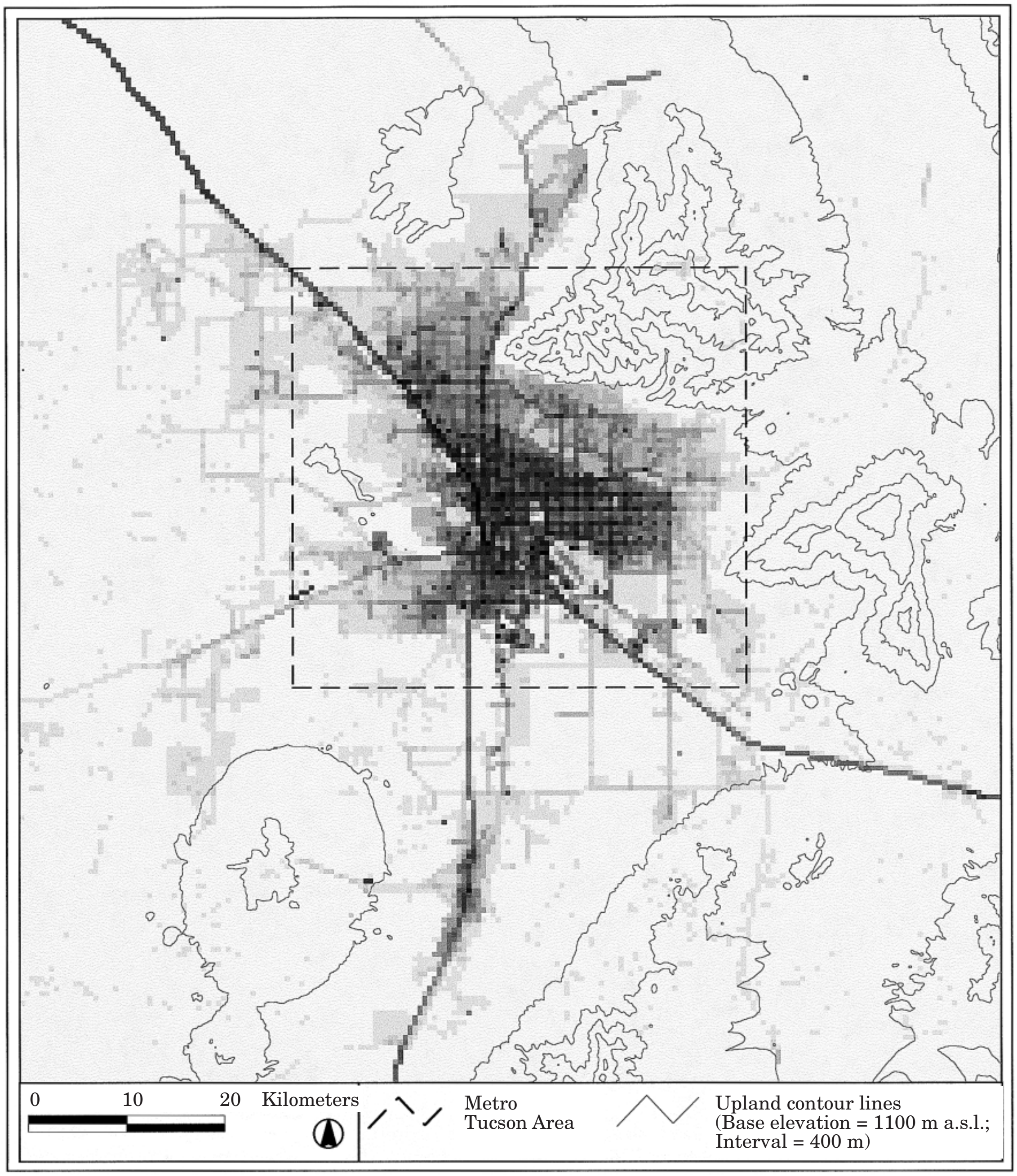

Figure 2. Annual anthropogenic VOC emissions in the Tucson region. Lightest cells have the smallest emissions (minimum of 0 kg) and darkest cells have the largest emissions (maximum of 215 896 kg).

In fact, on-road mobile is an important source during all months while residential wood combustion is a negligible source during non-winter months. Overall, on-road mobile is always the largest NO_x source while the cement plant and construction activities are also consistently large emitters. The TEP power plant is an important NO_x source only during the summer months as a result of increased electricity demand for air conditioning use.

Weekday vs. weekend emissions

The common assumption that more pollutant emissions occur on weekdays than on weekends is not always valid in the Tucson region. NO_x emissions are always lower on weekends than on weekdays while VOC emissions can sometimes be higher on weekends (Figure 7). In general, NO_x emissions are considerably more reduced on weekends than are VOC emissions. This situation is not unique

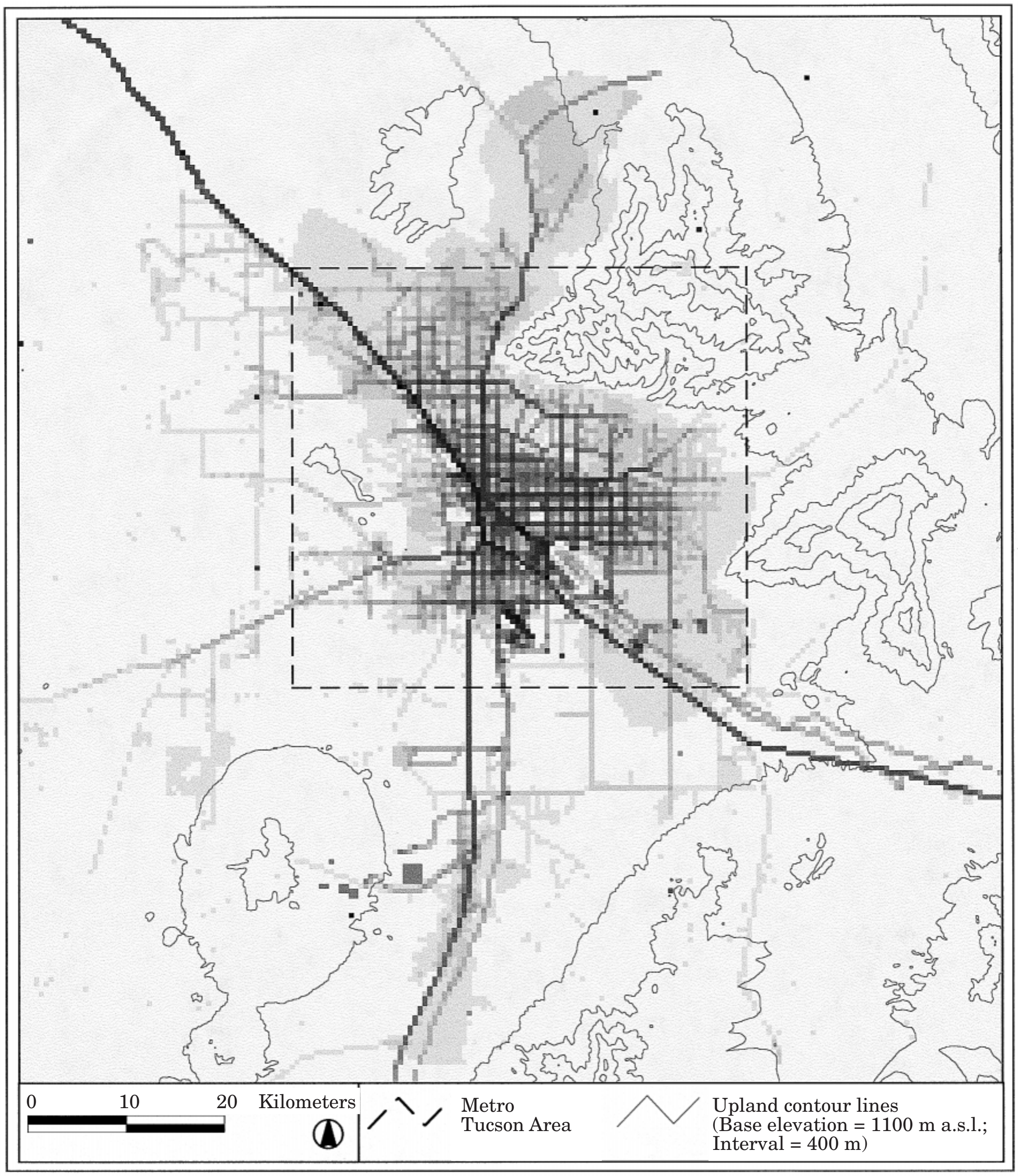

Figure 3. Annual anthropogenic NO_x emissions in the Tucson region. Lightest cells have the smallest emissions (minimum of 0 kg) and darkest cells have the largest emissions (maximum of 5 071 365 kg).

to Tucson, for it has also been noticed in other regions such as southern and northern California (Altshuler, 1995). Based on the temporalization of the Tucson region's anthropogenic EI, the most noticeable weekday vs. weekend VOC emissions differences are triggered by increased residential wood combustion and increased lawn and garden equipment use on weekends. Since residential wood combustion is a major VOC source during the winter months, weekends in December and January actually have higher daily VOC emissions than do weekdays in those months.

This EI does not account for weekday vs. weekend differences in HDDV traffic and vehicle refueling levels. It is believed that increased gasoline evaporation on weekends is associated with increased vehicle refueling. Therefore, it is possible that VOC emissions on weekends might be underestimated. In contrast, weekend NO_x emissions in the Tucson region might be overestimated,

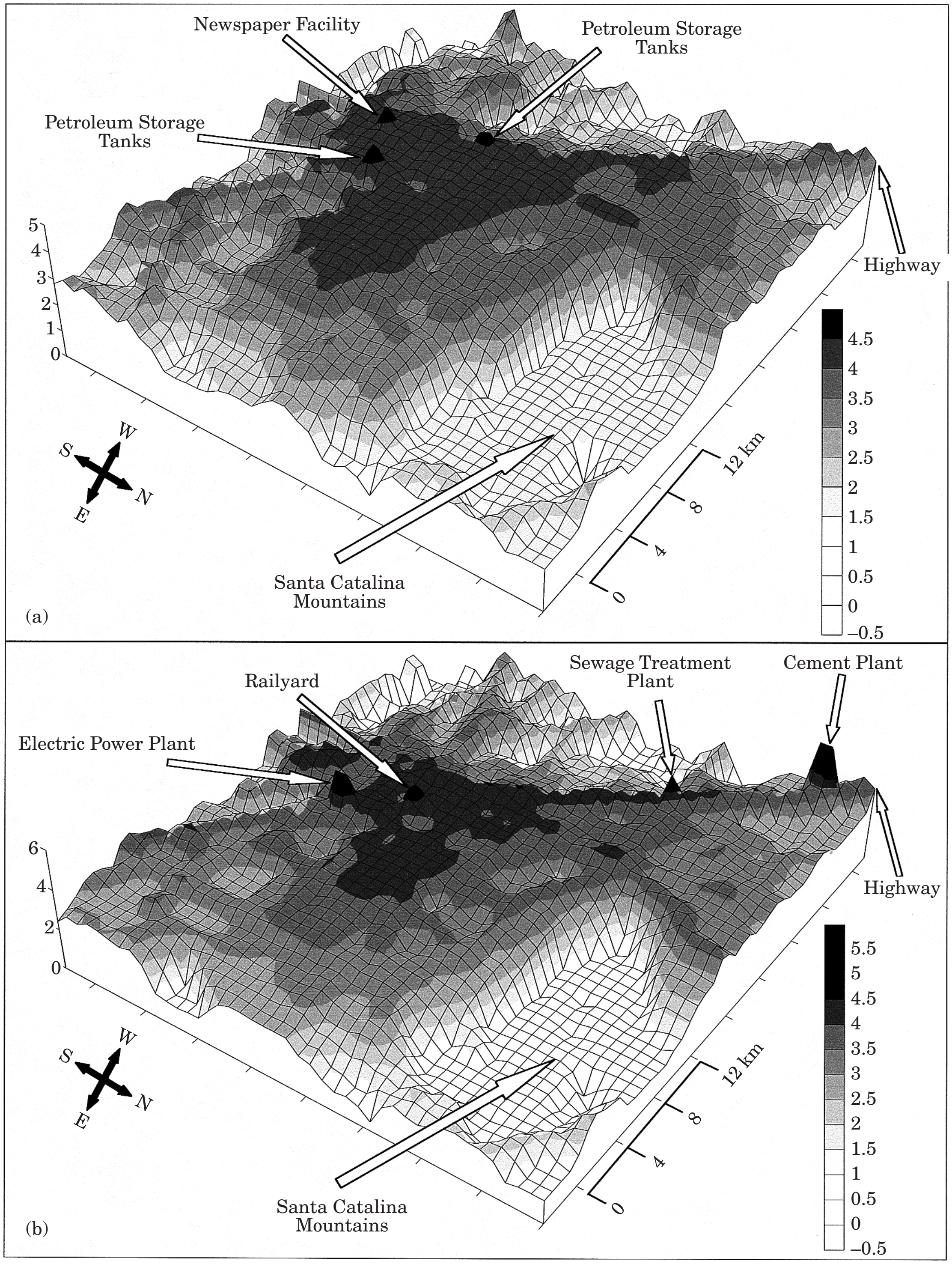

Figure 4. Annual emissions landscape within the metro Tucson area of (a) anthropogenic VOCs and (b) anthropogenic NO_x. A 3×3 mean filter was used to reduce the peaks of the highest emitting cells before the cells were resampled to 1 km resolution. Emissions values are shown as logarithmic transformations of total emissions per 25 hectares.

for NO_x emissions from diesel-powered trucks and buses presumably decrease substantially on weekends (Altshuler, 1995). This is important, for when combined with multi-temporal biogenic VOC (BVOC) emissions estimates, weekday vs. weekend VOC/NO_x emissions ratios can be used to assess the impacts of emissions modifications on ambient ozone concentrations, especially summertime

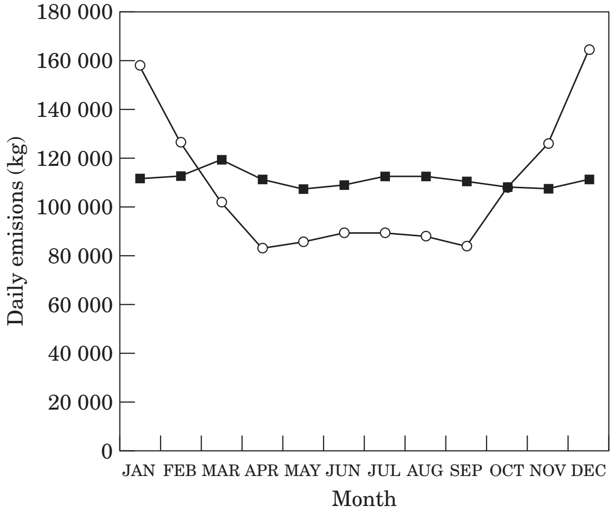

Figure 5. Month-to-month changes in daily VOC (○) and NO_x (■) emissions in the Tucson region.

concentrations (Diem, 2000). Such 'natural experiments' can be useful when formulating optimal ozone reduction strategies.

Errors and uncertainties

As with any data product, especially those created with compiled data, a variety of potential errors exist in the Tucson region's anthropogenic EI. Errors stem from the collection, aggregation, and manipulation of input data. Prevalent errors resulted from the use of modeled values (e.g. TRANPLAN-derived traffic speed and volume data) and generalized factors as well as the presence of assumptions associated with the region-wide EIs. Resulting primarily from the abundance of small, unpermitted sources of VOCs, there is considerably more qualitative confidence in the estimates of NO_x emissions. Regarding dominant emissions sources, the above statement coupled with the possibility of vegetation being a major source of VOCs during the summer months (Diem, 2000; Diem and Comrie, 2000) suggests a much stronger certainty that on-road mobile is the largest emitter of total NO_x as opposed to total VOCs, especially during the summer months.

A major space-based error source involves the use of indicator variables for spatially disaggregating area source emissions. The error increases with a decrease in the relative spatial correlation between the emissions source and the indicator variable. In this EI, construction equipment, cut-back asphalt, forest management, miscellaneous fires, and wildfires have the lowest relative spatial correlations of all the sources (Table 4). Poor correlations result from the presence of excessive and occasionally sporadic spatial variations in emissions (e.g. miscellaneous fires), a wide variety of emissions levels within a source category (e.g. commercial land-use fuel combustion), and not accounting for socioeconomic factors and/or environmental factors (e.g. urban pesticide use).

Other space-based errors can result from positional errors, coarse-to-fine resampling, and the dissolution of spatial variation through the use of polygons (Elston *et al.*, 1997). Most pollutants in the Tucson region are emitted from on-road mobile and point sources, which have the least resolution-based error. Positional accuracy is not a major concern overall since the final products are comprised of 500 m grid cells, rather than a fine-scale vector product. Most data were recorded at a higher spatial resolution than that of the cells; therefore, coarse-to-fine resampling is not a prevalent error source. The only coarse-to-fine resampling occurred during the spatial allocation of area source emissions associated with either land-use, population-based, or dwelling-based polygons. Some of these polygons were larger than 500 m. In addition, the spatial disaggregation of emissions using indicator variables represented by polygons caused the dissolution of some spatial variation in emissions from most area sources, for there is no spatial variation within a polygon.

Management applications

The spatial component of Tucson's EI makes it especially conducive to various management applications. Among its many potential uses, the EI can (1) serve as a public outreach tool, (2) be used as input in air quality models, (3) assist in the identification of sources requiring further investigation, and (4) assist during the selection of emissions reduction measures.

Public outreach

Maps convey a tremendous amount of information. Providing the general public with access to emissions maps and related visuals via the internet, public meetings, and television might influence

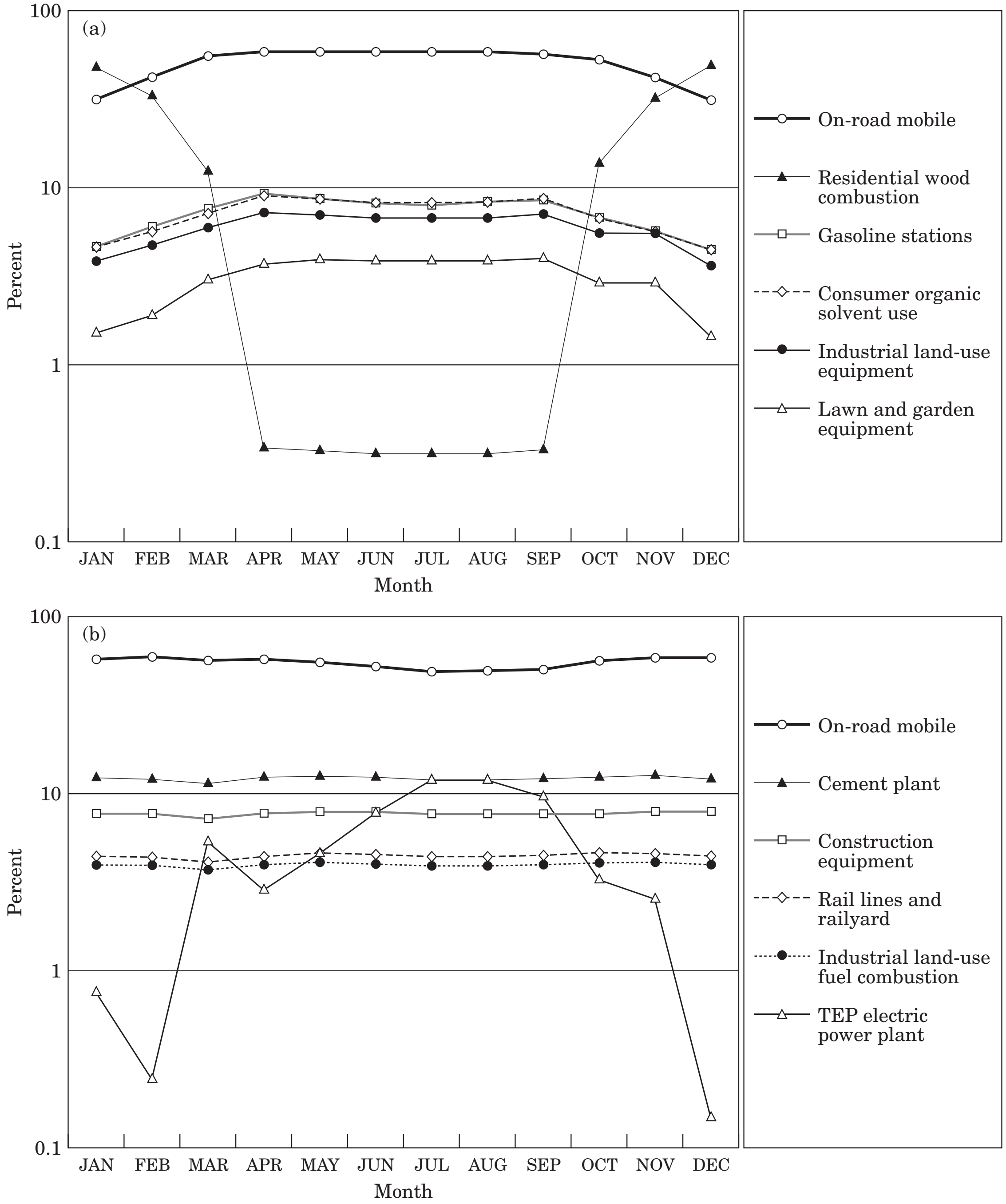

Figure 6. Month-to-month changes in relative contributions from (a) major VOC sources and (b) major NO_x sources in the Tucson region.

people and possibly cause a change in activities responsible for ozone precursor emissions. For example, emissions maps illustrate the dominance of on-road motor vehicles. Upon viewing these maps and other similar graphics, the vehicle-driving public might acquire an enhanced realization of the magnitude of automobile emissions and thus alter their driving behavior (i.e. reduce VMT).

Input to air quality models to predict ambient ozone concentrations

The EI can also be used in both statistical and numerical air quality models to predict ambient ozone concentrations across the Tucson region. The resulting maps of ambient ozone concentrations can be used as public outreach tools and as

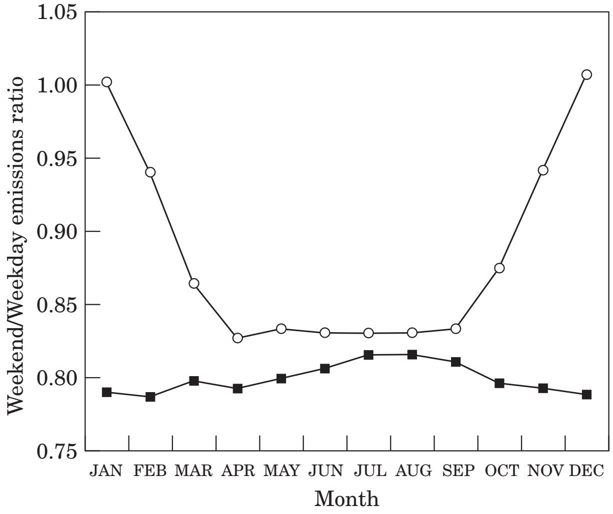

Figure 7. Month-to-month changes in weekday/weekend ratios of daily VOC (○) and NO_x (■) emissions in the Tucson region.

air quality planning tools. EIs that have been speciated, scaled to a specific year, month, and day, and hourly-resolved can be used as input to numerical models, such as the Urban Airshed Model (UAM) (Scheffe and Morris, 1993). The UAM and other numerical models also require a biogenic EI (Diem and Comrie, 2000). As mentioned previously, these models can be used to assess the impacts of proposed control measures on ambient ozone levels. Tucson's EI has already been used in the statistical modeling of ozone, which identified projected ozone 'hot spots' as well as optimal locations for the placement of additional air quality monitors (Diem and Comrie, 2001b).

Identification of sources requiring further investigation

The entire process of developing an EI provides those involved with an enhanced understanding of source-specific uncertainties, thereby leading to the identification of sources whose emissions estimates are in the most need of improvement. Sources in the Tucson region that fit into this category include on-road mobile, construction equipment, and lawn and garden equipment. Estimates of on-road motor vehicle emissions can be improved by using (1) more detailed traffic count data (i.e. month-, weekday-, and weekend-specific), (2) spatially varying fleet distribution data, (3) output from a transportation planning model that includes major roads and minor roads, rather than just major roads, (4) and the most recent EPA-approved mobile emissions model (e.g. MOBILE6). Much needed construction-related information includes year- and month-specific estimates of construction activity, for activity is constantly shifting across the region when viewed over a time period of several years. Data concerning the spatial and temporal occurrence of lawn and garden equipment use is also needed. Updating and improving Tucson's EI are continual and essential processes, especially if the inventory is to be used in modeling efforts or other projects related to air quality policy.

Selection of emissions reduction measures

Besides using results from numerical modeling studies to guide decisions regarding emissions control, more qualitative approaches can be employed. For example, if the new 8-hour ozone standard is promulgated, there is a strong possibility that Tucson might violate the standard and be redesignated as an ozone nonattainment area. This redesignation might cost Pima County (i.e. the Tucson MSA) over US$ 50 million per year (Keyes *et al.*, 2001). Consequently, local air quality planners are searching presently for cost-effective measures to prevent or delay nonattainment in the short-term. Finding a suitable emissions reduction measure in Tucson is a major challenge, for over the course of the ozone season peak ozone concentrations switch from being VOC-sensitive to NO_x-sensitive. Ozone concentrations change abruptly from increasing with an increase in ambient VOC concentrations (i.e. VOC-sensitive) in June to increasing with an increase in ambient NO_x concentrations (i.e. NO_x-sensitive) in August (Diem, 2000). This association of elevated ozone levels with both VOC- and NO_x-sensitive conditions translates into a need to reduce both VOC and NO_x emissions.

Results presented in this paper suggest that on-road mobile, which is the dominant anthropogenic source of both VOCs and NO_x and is also spatially prevalent, is the optimal source to target to reduce ozone levels in the short-term. Furthermore, on-road mobile remains the largest VOC source in the Tucson metropolitan area even after accounting for BVOC emissions, which can constitute over 10% of the emissions on a typical August day (Diem, 2000). In addition, there is a strong possibility that on-road mobile emissions have been underestimated since 'gross polluters' were not included in the EI. These motor vehicles typically represent less than 10% of the fleet yet they are responsible for half the total on-road mobile emissions (Guenther *et al.*, 1994).

Two legitimate, proactive measures to reduce on-road mobile emissions include the identification of 'gross polluters' and mandatory vehicle maintenance and inspection. Remote sensing devices can identify 'gross polluters' and the subsequent proper repair and maintenance of those vehicles can reduce VOC and NO_x emissions (Guenther *et al.*, 1994). Based on the total number of registered vehicles (PAG, 2000), there are an estimated 60 000 'gross polluters' in the Tucson region. Keyes *et al.* (2001) also note that another cost-effective proactive measure to reduce emissions of both VOCs and NO_x is IM-240, which is an upgraded motor vehicle inspection/maintenance (I/M) program compared to the current program in the Tucson region. Supporting this finding is the fact that the current I/M program has not had a significant impact on on-road mobile emissions (Zhang *et al.*, 1996). Modeling studies are needed to verify the expected decrease in peak ozone concentrations with a decrease in on-road mobile VOC and NO_x emissions resulting from the above control measures.

Conclusions

This paper has described a GIS-driven process for enhancing an existing anthropogenic EI and demonstrated how the resulting multi-temporal and spatially-disaggregated EI can be used in ozone-specific, management applications in the Tucson region. The enhancement came primarily in the form of spatial allocation, which was performed with both the 'top-down' and 'bottom-up' methods to yield cell-specific emissions estimates. The 'top-down' method accomplished this task by spatially disaggregating a region-wide emissions estimate based on the value of an indicator variable in each cell. The 'bottom-up' method calculated emissions that were specific to entities with higher spatial resolutions than that of the cell or simply transferred the values for specific points to the associated cell. Estimating emissions for some sources involved both spatial allocation methods. For example, while estimating on-road mobile emissions, the 'bottom-up' method was used to produce emissions estimates for all major road segments while the 'top-down' method was used to spatially disaggregate an estimate of emissions from all minor road segments. In addition, TAFs were used to enhance the EI further by adding a multi-temporal component.

The EI has revealed that on-road mobile is the dominant, anthropogenic source of both VOCs and NO_x in the Tucson region. Spatially, most of the emissions occur within the City of Tucson, with on-road motor vehicles in the city responsible for over one-quarter of the region's VOC and NO_x emissions. Other major emissions sources include the following: VOCs from residential wood combustion, which occurs primarily during the winter months; NO_x emissions from construction activities and a local cement plant; and summertime NO_x emissions from an electric power plant. VOC emissions can sometimes be higher on weekends than on weekdays while NO_x emissions are always lower on weekends with the most noticeable weekday vs. weekend VOC emissions differences being triggered by increased residential wood combustion and increased lawn and garden equipment use on weekends.

The usefulness of the EI in a management setting has also been shown. The EI can serve as a public outreach tool, such as the visualization of emissions by the general public. It can be used as data input in both statistical and numerical air quality models. It can be used to identify sources requiring further investigation. Within the Tucson region, on-road mobile, construction equipment, and lawn and garden equipment were those sources. Finally, it can be used during the selection of appropriate emissions reduction measures. An important management-based conclusion of this study was that emissions reduction measures should be targeted towards on-road motor vehicles, especially 'gross polluters'.

Although it is recognized that the Tucson region's EI is undoubtedly error-laden, assessing the accuracy of the EI was beyond the scope of this study. Therefore, rigorous endeavors involving the EI, such as the numerical modeling of ambient ozone levels, should be preceded by some form of accuracy assessment of the EI. Validation techniques include inverse modeling (Chang *et al.*, 1996, 1997), chemical mass balance approaches (Vega *et al.*, 2000), observed relative mixing ratios (Harley and Cass, 1995), and direct flux measurement (Singer *et al.*, 1998).

Finally, spatial resolution should be considered more explicitly when developing EIs in the future. As has been illustrated in this paper, a spatially disaggregated EI can serve many more uses beyond the common practice of incorporation in photochemical modeling studies. Theoretically, an EI's utility should increase with an increase in spatial resolution. For instance, high-resolution EIs, such as those with cell sizes as small as tens of meters, would certainly improve the visualization of emissions. In addition, through detailed examinations of 'scales of effect', high-resolution EIs could also be used to determine optimal spatial resolutions for EIs used in modeling studies. As has been realized in this study, the major constraint to creating a high-resolution EI is the availability of emissions data and surrogate spatial data at equal or higher resolutions. Nevertheless, increased integration of a GIS with an EI represents one step towards enhanced spatial awareness.

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