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An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States

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Abstract. Regional estimates of biogenic volatile organic compound (BVOC) emissions are important inputs for models of atmospheric chemistry and carbon budgets. Since forests are the primary emitters of BVOCs, it is important to develop reliable estimates of their areal coverage and BVOC emission rate. A new system is developed to estimate these emissions for specific tree genera at hourly and county level resolution. The U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Eastwide Database is used to describe the areal extent, species composition, and tree diameter distributions of United States forests. Horizontal canopy occupancy by genera is then estimated as a function of diameter at breast height. Growing season peak foliar masses are derived from the empirical literature for canopies of deciduous and coniferous genera. A simple canopy model is used to adjust photosynthetically active solar radiation at five vertical levels in the canopy. Leaf temperature and photosynthetically active radiation derived from ambient conditions above the forest canopy are then used to drive empirical equations to estimate genus level emission rates of BVOCs vertically through forest canopies. These genera level estimates are then aggregated to regional levels for comparison with the regulatory model currently used and for input into air quality models. The proposed model yields isoprene emission rate estimates for specific countries that are 5 to 10 times higher (and total BVOC emission rates that are 3 to 5 times higher) than the Environmental Protection Agency BVOC emission rate model currently used. Emission estimates of isoprene and monoterpenes from the new system compare favorably with rates measured at various forested sites in the United States.

Introduction

Biogenic volatile organic compounds (BVOCs) are important influences on global tropospheric chemistry, regional photochemical oxidant formation, global carbon budgets, and atmospheric organic acid production [*Fehsenfeld et al.*, 1992]. According to the *National Research Council* [1991], the ozone problem in the United States is exacerbated by a policy that has emphasized control of anthropogenic volatile organic compound (VOC) emissions (such as those from motor vehicles and industrial sources) and has neglected the contribution that BVOC emissions make to ozone formation. Although these emissions are logistically difficult to control, they must be considered in deciding whether anthropogenic nitrogen oxides (NO_x) versus VOC should be controlled to reduce ambient ozone levels.

Current models such as the urban airshed model and the regional oxidant model use empirical algorithms for estimating BVOC emissions from general (deciduous and coniferous) forest categories [*Pierce et al.*, 1990]. Forests are thought to emit approximately 90% of BVOCs, with agricultural and scrublands contributing the balance [*Lamb et al.*, 1987]. BVOC emissions from forested areas are typically estimated by multiplying an emission factor expressed as micrograms of BVOC carbon per gram foliar dry mass per hour (μg-C g^{-1} h^{-1}) by biomass density and land area factors. For crops the emission rates are expressed as BVOC mass per unit time per unit land area. *Lamb et al.* [1993] estimates the U.S. annual total BVOC emission flux at 22 to 50 Tg. Uncertainty associated with these estimates is at least a factor of 3.

This paper describes a model to replace the current system for estimating hourly regional BVOC emissions from forests. The study area covers the 37 easternmost states. Its objectives are (1) to describe the use of the U.S. Department of

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Table 1. Foliar Densities for Each Forest Type, Divided Among Emission Categories

Forest Type	High Isoprene Deciduous	Low Isoprene Deciduous	Nonisoprene Deciduous	Nonisoprene Coniferous
Oak	185	60	60	70
Other deciduous	60	185	90	135
Coniferous	39	26	26	559

Densities are in grams per square meter. Data is from *Lamb et al.* [1987]. Note that a mixture of forest types is assumed to occur within each emission class. For instance, the oak (Quercus) forests are dominated by high isoprene emitting species but are also assumed to contain a smaller fraction of lower emitting species such as those in the maple (Acer) and pine (Pinus) genera.

Agriculture, Forest Service Forest Inventory and Analysis (FIA) Eastwide Database (EWDB) from *Hansen et al.* [1992] in determining regional forest source inventories, (2) to present a scheme for integrating the EWDB with the emission algorithms of *Guenther et al.* [1994], (3) to present resulting BVOC flux estimates, (4) to compare these emissions with those estimated from other systems, and (5) to compare emissions previously measured at specific forested sites with model estimates.

Methods

The approach currently used to estimate BVOC emissions on a regional basis in the United States combines foliar mass estimates published by *Lamb et al.* [1987] with land use coverage from the Geoecology Database [*Olson et al.*, 1980]. Foliar density (grams of dry foliage per square meter) is estimated for each county by multiplying foliar density factors with forest area derived from the Geoecology data. Foliar densities are provided for only three forest types to be consistent with available emission factors. Likewise, 106 natural community types reported in the Geoecology data are simplified to oak forests, other deciduous forests, coniferous forests, grassland/range, or barren lands. The Environmental Protection Agency (EPA) regulatory version of this system, the Biogenic Emissions Inventory System is described by *Pierce et al.* [1990].

Foliar densities for the three forest types are based primarily on data from the International Biological Program as reported by *Leith and Whitaker* [1975], *Rasmussen* [1972], and *Dasmann* [1976]. Foliar densities are apportioned into emission classes and reflect estimated emission class compositions for each forest type as shown in Table 1.

Biogenic emission fluxes were generated from the computed foliar mass using emission factors published by *Lamb et al.* [1993]. These factors, shown in Table 2, are given for each emission category and are based upon a synthesis of available emission measurements. BVOC emission rates increase exponentially (up to approximately 38°C for isoprene) with increasing leaf temperature, while isoprene emission rates also increase with increasing light intensity up to approximately 800 μmol m^{-2} s^{-1} [*Guenther et al.*, 1991; *Tingey et al.*, 1979, 1980].

The use of general emission rate categories by *Lamb et al.* [1987] was warranted at the time, since relatively few emission rates were measured from dominant vegetation types and the vegetation databases, likewise, were not specific enough to provide coverage by individual species or genera. More recently, however, a comprehensive database of genus specific emission rate estimates has been developed [*Guenther et al.*, 1994]. In addition, the Department of Agriculture Forest Service has compiled state level forest inventory data in consistent formats for the 37 easternmost states [*Hansen et al.*, 1992]. Using these databases, we develop methods similar to those mentioned by *Wells* [1981] to estimate the area occupied by each genus in the EWDB and resulting BVOC fluxes which vary as functions of forest canopy and meteorological conditions. The system is outlined in Figure 1 and described below.

Table 2. Forest Emission Factors Standardized for Moderate Sunlight (PAR = 800 μmol m^{-2} s^{-1}) and 30°C

Chemical Species	High Isoprene Deciduous	Low Isoprene Deciduous	Nonisoprene Deciduous	Nonisoprene Coniferous
Isoprene (C_5H_8)	13.6	5.95	0	0
α Pinene ($C_{10}H_{16}$)	0.06	0.05	0.07	1.13
Other monoterpenes	0.33	0.30	0.35	1.78
Other VOCs	1.82	1.44	1.54	1.35

Emission factors are in μg-C (g-foliar dry mass)$^{-1}$ h^{-1}. Data is from *Lamb et al.* [1993]. PAR, photosynthetically active radiation; VOC, volatile organic compound.

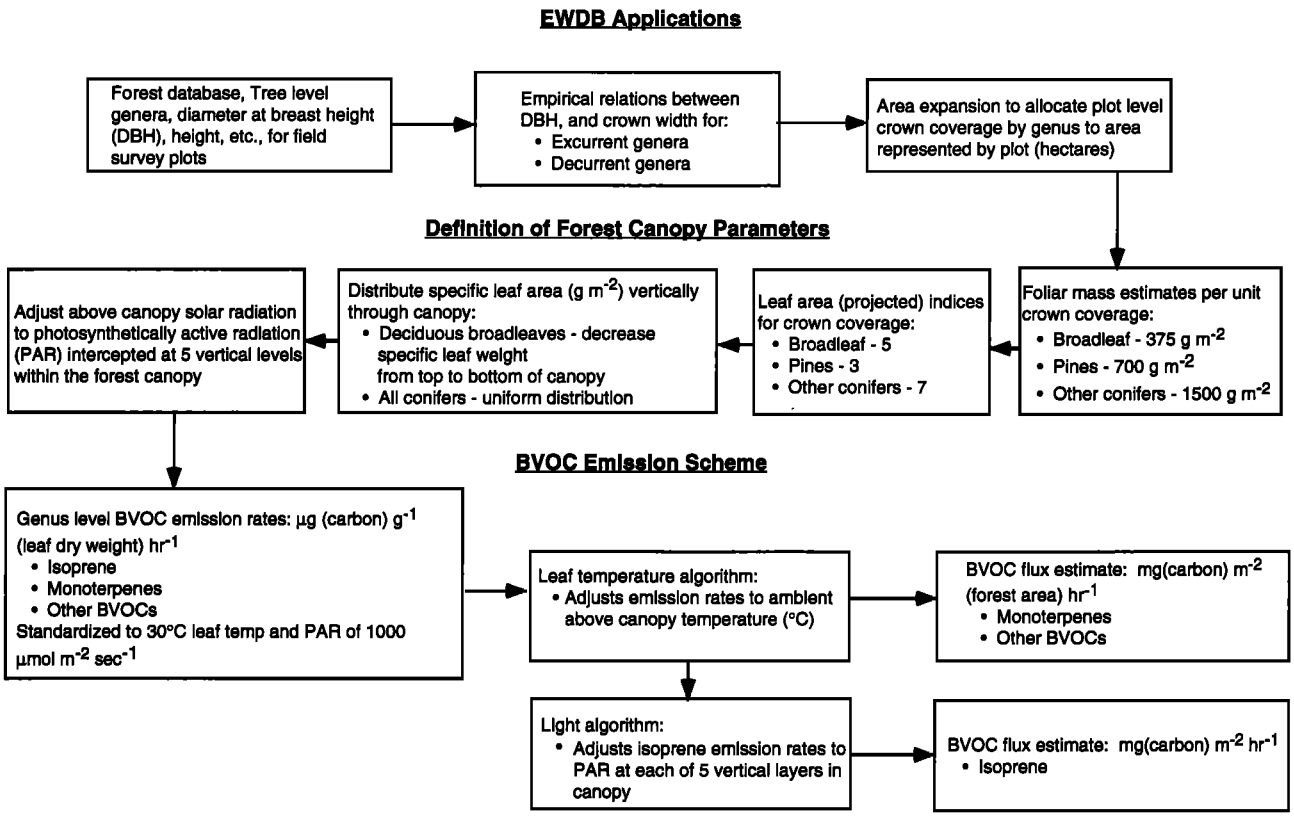

Figure 1. Flow diagram for proposed model of biogenic volatile organic compound (BVOC) emissions from forests.

Forest Characterization

Forest Extent and Crown Cover

The forest extent, species composition, and diameter distribution data used in this approach are obtained from the most recent EWDB [*Hansen et al.*, 1992] files that were available at the time the study began. Estimates of forest and nonforest area, timber volume, and species composition are all based on a two-phase sample of several hundred thousand sample plots (phase 1) systematically spaced on aerial photographs covering the 37 easternmost states. All sample plots are classified using aerial photo interpretation methods. A subsample of the plots (phase 2) is ground checked, and detailed measurements of forest vegetation are taken. The phase 1 sample provides the area estimates that are associated with each phase 2 sample plot. Phase 2 measurements provide information about conditions that can be observed only on the ground and provide a correction for misclassification and change between the time the photograph was taken and the inventory is being taken. The EWDB contains the data collected at the phase 2 plot and the area data obtained from the phase 1 sample. These areas tend to range from approximately 2,000 to 4,000 ha (5,000 to 10,000 acres) per ground sample plot. Each state is sampled on approximately a 10-year cycle.

Figure 2 shows the approximate density of forested ground plot locations in the EWDB. Vegetation was sampled at each location on a cluster of 5–10 subplots in a 0.4-ha (1 acre) area at each location. The diameter breast high (DBH) (i.e., the tree diameter at a height of 1.37 m (4.5 ft) above ground level) and height of trees identified within each cluster were measured and recorded. In some cases, areas that were commercially unproductive and areas where timber harvesting is prohibited, the data do not include tree level statistics. These areas include national and state parks, designated scientific, natural, and wilderness areas, and very unproductive swamps and ridge tops. Less than 1% of the forest land in the study area is classified as such. Forest statistics (species composition and DBH distributions) for these areas are approximated by interpolating between plots in surrounding forests within the same county. Also, some areas contain trees but are not classified as forests. The areas include land with trees inside an urban or suburban area plus windbreaks, shelter belts, and other small areas of trees less than 0.4 ha (1 acre) in size. The total area of these nonforest lands is approximately 1% of the study area. Emissions from trees in these areas were not considered in this study.

The species composition and diameter distributions derived from the EWDB are used to approximate regional forest canopy coverage and foliar mass by genus. Foliage-stemwood allometric relationships (the power function estimating foliar mass as a function of DBH) have been used to quantify total biomass yields, forest nutrient status, and air pollution or defoliation impacts for site specific studies. *Guenther et al.* [1994] and *Geron et al.* [1992] discuss general application of these functions in estimating crown foliar mass. However, generalization from site to site for a given species can result in biased estimates, since the coefficients of the power function are variable with respect to specific stand and silvical characteristics [*Geron and Ruark*, 1988]. Shade tolerance, stand density, age, site quality, and com-

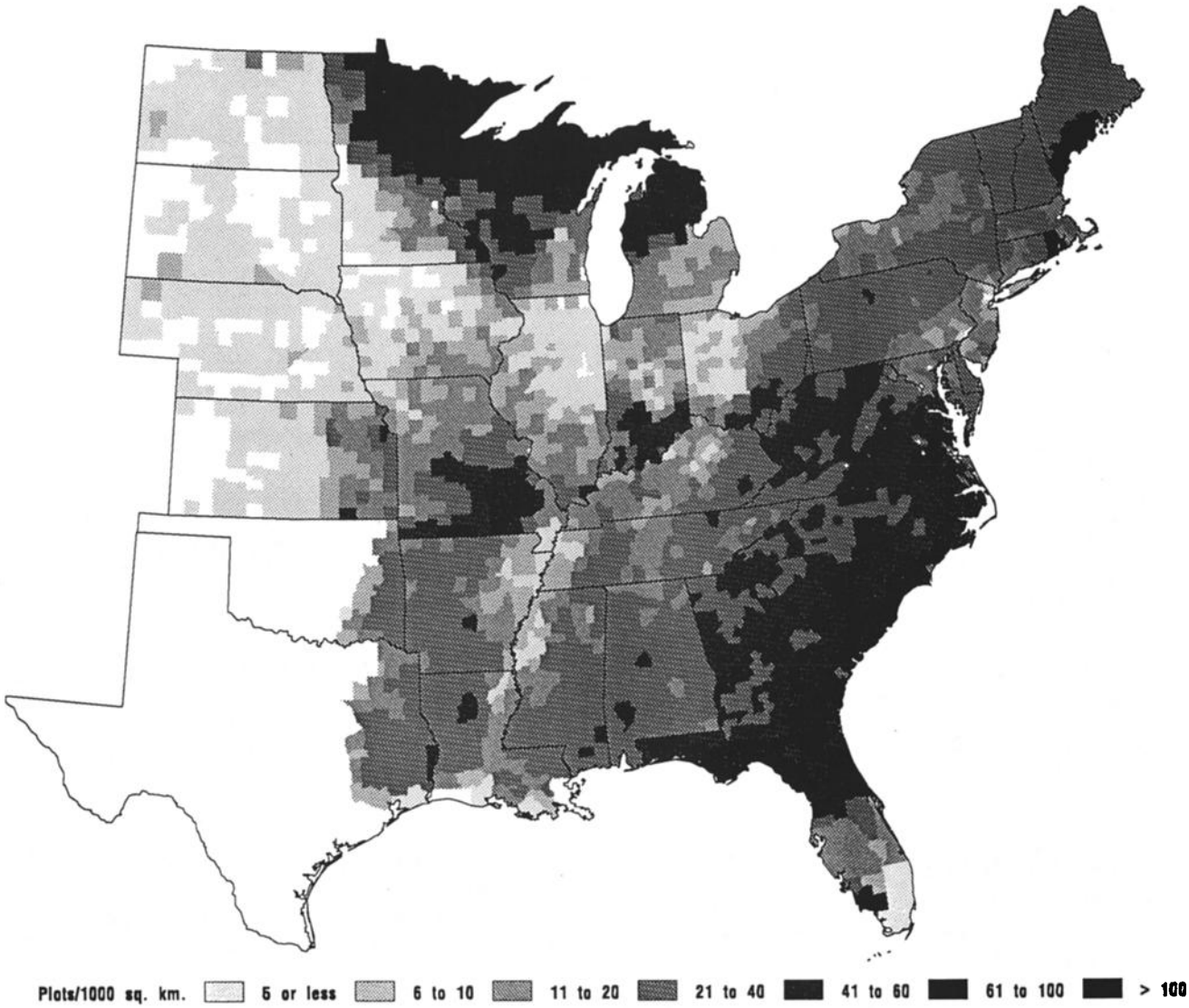

Figure 2. Density of sample plot locations in the Eastwide Database (EWDB) in number of sample points per 1000 km^2.

petition have been found to alter relative growth rates and therefore the parameter estimates of the allometric equation [*Satoo*, 1962]. Estimating foliage using this approach has been found to yield biases as large as 100% [*Marshall and Waring*, 1986].

Other measures such as stem diameter at the base of the live crown or sapwood cross-sectional area have been used to predict foliar mass or leaf area [*Espinosa Bancalari et al.*, 1987; *Keane and Weetman*, 1987; *Hungerford*, 1987]. These measures often explain much of the variability mentioned above. However, these measures are usually difficult to determine in the field and often necessitate extensive laboratory analysis to arrive at satisfactory estimates.

To ensure a reasonable level of stand foliar mass without the difficulties discussed above, linear regressions are used to estimate crown width as a function of DBH. Horizontal crown area is then calculated for all tree crowns in the overstory (those exposed to direct sunlight) for each plot in the EWDB. The overstory trees are determined by crown position recorded in the EWDB. Dominant, codominant, and intermediate crown positions receive direct sunlight from above, while suppressed understory trees do not. The understory trees account for less than 0.1% of the basal area (the sum of stem cross-sectional areas at 1.37 m tree height) within the EWDB and would therefore be insignificant contributors to BVOC emissions. The DBH-crown width relationships have been found to be independent of site quality, crown class, and stocking [*Minckler and Gingrich*, 1970]. Two equations (see Table 3) are established for (1) conifers and excurrent broadleaf genera (with narrow, conical crowns, such as Liquidambar, Populus):

$$\text{Crnwd} = 0.47 + 0.166\text{DBH} \quad (1)$$

and (2) decurrent broadleaf genera (with spreading spherical crowns, such as, Quercus, Carya):

$$\text{Crnwd} = 1.13 + 0.205\text{DBH} \quad (2)$$

where Crnwd is crown width (meters) and DBH is tree stem diameter (centimeters) at a height of 1.37 m. These equations

Table 3. Forest Emission Factors for Genera in the Eastwide Database and in the Database of *Guenther et al.* [1994] Standardized for Bright Sunlight (1000 μmol m^{-2} s^{-1}) and 30°C

Genus	Isop.	Mono.	OVOC	Dens.	Crnwd.	Sample Species (Common Name)
Abies	0.1	3.0	1.5	1500	C	Fir
Acacia	0.1	3.0	1.5	700	D	Acacia
Acer	0.1	1.6	1.5	375	C	Maple
Aesculus	...	...	1.5	375	D	Buckeye
Ailanthus	...	...	1.5	375	C	Ailanthus
Aleurites	...	...	1.5	375	C	Tung-Oil Tree
Alnus	...	...	1.5	375	C	European Alder
Amelanchier	...	...	1.5	375	C	Serviceberry
Asimina	...	...	1.5	375	C	Pawpaw
Avicennia*	0.1	0.1	1.5	375	D	Black Mangrove
Betula	0.1	0.2	1.5	375	C	Birch
Bumelia	...	...	1.5	375	C	Gum Bumelia
Carpinus	0.1	1.6	1.5	375	C	Hornbeam
Carya	0.1	1.6	1.5	375	D	Hickory
Castanea	...	...	1.5	375	D	Chestnut
Castanopsis	...	...	1.5	375	D	Chinkapin
Casuarina*	70.0	0.1	1.5	700	C	Australian Pine
Catalpa	...	...	1.5	375	D	Catalpa
Cedrus*	0.1	1.6	1.5	700	C	Deodar Cedar
Celtis	0.1	0.2	1.5	375	D	Hackberry
Cercis	0.1	0.1	1.5	375	C	Redbud
Chamaecyparis	0.1	0.2	1.5	1500	C	Port-Orford Cedar
Citrus*	0.1	1.6	1.5	375	D	Orange
Cornus	0.1	1.6	1.5	375	D	Dogwood
Cotinus	...	...	1.5	375	D	Smoke Tree
Crataegus	...	...	1.5	375	D	Hawthron
Diospyros	0.1	0.1	1.5	375	C	Persimmon
Eucalyptus*	70.0	3.0	1.5	375	D	Eucalyptus
Fagus	0.1	0.6	1.5	375	D	American Beech
Fraxinus	0.1	0.1	1.5	375	C	Ash
Gleditsia	...	...	1.5	375	D	Honeylocust
Gordonia	...	...	1.5	375	C	Loblolly-bay
Gymnocladus	...	...	1.5	375	D	Kentucky Coffeetree
Halesia	...	...	1.5	375	C	Silverbell
Ilex	0.1	0.2	1.5	375	D	Holly
Juglans	0.1	3.0	1.5	375	D	Black Walnut
Juniperus	0.1	0.6	1.5	700	C	Eastern Red Cedar
Laguncularia*	0.1	0.1	1.5	375	D	White Mangrove
Larix	...	...	1.5	375	C	Larch
Liquidambar	70.0	3.0	1.5	375	C	Sweetgum
Liriodendron	0.1	0.2	1.5	375	C	Yellow Poplar
Maclura	...	...	1.5	375	D	Osage-orange
Magnolia	0.1	3.0	1.5	375	D	Magnolia
Malus	...	...	1.5	375	D	Apple
Melia	0.1	0.1	1.5	375	D	Chinaberry
Morus	0.1	0.2	1.5	375	D	Mulberry
Nyssa	14.0	0.6	1.5	375	C	Blackgum
Ostrya	...	...	1.5	375	D	Hophornbeam
Oxydendrum	0.1	0.6	1.5	375	D	Sourwood
Paulownia	...	...	1.5	375	D	Paulownia
Persea	0.1	0.6	1.5	375	C	Redbay
Picea	14.0	3.0	1.5	1500	C	Spruce
Pinus	0.1	3.0	1.5	700	C	Pine
Planera	...	...	1.5	375	D	Water Elm
Platanus	35.0	0.1	1.5	375	D	Sycamore
Populus	70.0	0.1	1.5	375	C	Aspen
Prosopis	...	...	1.5	375	C	Mesquite
Prunus	0.1	0.1	1.5	375	C	Cherry
Pseudotsuga	0.1	1.6	1.5	1500	C	Douglas-fir
Quercus	70.0	0.2	1.5	375	D	Oak
Rhizophora*	0.1	0.1	1.5	375	D	Red Mangrove
Robinia	14.0	0.2	1.5	375	D	Black Locust

Table 3. (continued)

Genus	Isop.	Mono.	OVOC	Dens.	Crnwd.	Sample Species (Common Name)
Sabal*	14.0	0.1	1.5	375	C	Cabbage Palmetto
Salix	35.0	0.1	1.5	375	C	Willow
Sapium	...	...	1.5	375	C	Chinese Tallow Tree
Sassafras	0.1	0.1	1.5	375	D	Sassafras
Serenoa*	35.0	0.1	1.5	375	C	Saw Palmetto
Sorbus	...	...	1.5	375	D	Mountain Ash
Taxodium	0.1	3.0	1.5	375	C	Cypress
Thuja	0.1	0.6	1.5	1500	C	Western Red Cedar
Tilia	...	...	1.5	375	C	Basswood
Tsuga	0.1	0.2	1.5	700	C	Eastern Hemlock
Ulmus	0.1	0.1	1.5	375	D	American Elm
Vaccinium	0.1	0.1	1.5	375	C	Blueberry
Washingtonia*	14.0	0.1	1.5	375	C	Fan Palm

Emission factors are in μg-C (g-foliar dry mass)$^{-1}$ h^{-1}; Isop., isoprene; Mono., monoterpenes; OVOC, other biogenic volatile organic compounds; and Dens., foliar density in grams per square meter. Crnwd refers to the crown width equation used to calculate crown width as a function of diameter breast high where C is coniferous and excurrent deciduous genera and D is decurrent deciduous genera.

*Genus not currently listed in the Eastwide Database.

were derived from several thousand measurements collected in the midwestern and southeastern United States [*Minckler and Gingrich*, 1970]. This approach is currently used to estimate expanded crown coverage in state level FIA data. *Minckler and Gingrich* [1970] noted that 100% horizontal canopy coverage represented 100% or full stocking. Maximum canopy foliar mass is reached at the time of crown closure and remains nearly constant thereafter [*Kinerson et al.*, 1977]. *Minckler and Gingrich* [1970] also noted that because of crown interlace and overlap, the calculated canopy area to ground area ratio was often greater than 1. This is also the case in the EWDB data. The crown areas on all plots where the canopy area to ground area ratio exceeded 1 were scaled down proportionally by genus such that the total crown area is equivalent to ground area.

Forest Foliar Mass

Foliar mass is then allocated to the horizontal canopy coverage using published values (determined by destructive sampling or leaf fall collection) from fully stocked stands [e.g., *Sollins et al.*, 1973; *Sprugel*, 1984; *Teskey et al.*, 1987; *Burton et al.*, 1991]. The values are 1500 g m^{-2} (dry weight) for Abies, Picea, Tsuga, and Pseudotsuga genera, 700 g m^{-2} for Pinus and other coniferous genera, and 375 g m^{-2} for deciduous stands. These values are generally correlated with foliage retention periods, since deciduous genera retain foliage for 1 year, Pinus generally retains foliage for 2 to 5 years, and Abies, Picea, Tsuga, and Pseudotsuga genera retain foliage for 5 to 10+ years [*Harlow et al.*, 1979]. Figure 3 shows reported foliar density values from typical stands for each of the three classes. These foliar density values are very similar to those used by *Lamb et al.* [1987], except for the Abies, Picea, Tsuga, and Pseudotsuga genera, which were assumed to carry levels similar to Pinus and other conifers.

We assume that foliage occupies the respective horizontal canopy area at these densities for each class. Allocating foliar mass in this manner allows open woodland and understocked stands to assume less foliar mass and canopy area per hectare than fully stocked stands, while maintaining realistic maximum foliar masses for fully stocked, closed canopy stands during the period of peak foliation. This method will more realistically approximate relative proportions of foliage in the respective emission rate categories compared to the arbitrary assignments made using the Geoecology [*Lamb et al.*, 1987] and EROS data [*Guenther et al.*, 1994].

BVOC Emission Rates

Standardized Emission Rates

The database of *Guenther et al.* [1994] (see Table 3) provides emission rates of isoprene and monoterpenes (μg-C (g-foliar dry mass)$^{-1}$ h^{-1}) standardized for bright sunlight (1000 μmol m^{-2} s^{-1}) and 30°C for dominant forest tree genera in North America. A third emission rate class aggregates all other volatile organic compounds (OVOC) with a lifetime, under typical tropospheric conditions, of less than 1 day. The rate for this class is currently assumed to be 1.5 μg-C (g-foliar dry mass)$^{-1}$ h^{-1}. Emission rates for species within a genus have generally been found to fall within ±50% of these emission rates [*Guenther et al.*, 1994].

Table 3 lists 75 genera, 65 of which are found in the EWDB. *Guenther et al.* [1994] published BVOC emission rate estimates for 49 of the 75 genera. Ten genera-assigned emission rates are not found in the EWDB and are designated by asterisks. These represent tropical genera or understory palms found only in the extreme southern United States.

Environmental Correction

Since BVOC emissions are strongly controlled by photosynthetically active radiation (PAR) and leaf temperature [*Guenther et al.*, 1993], empirical algorithms based on mechanistic processes developed by *Guenther et al.* [1993] were used to adjust emission rates to ambient PAR and tempera-

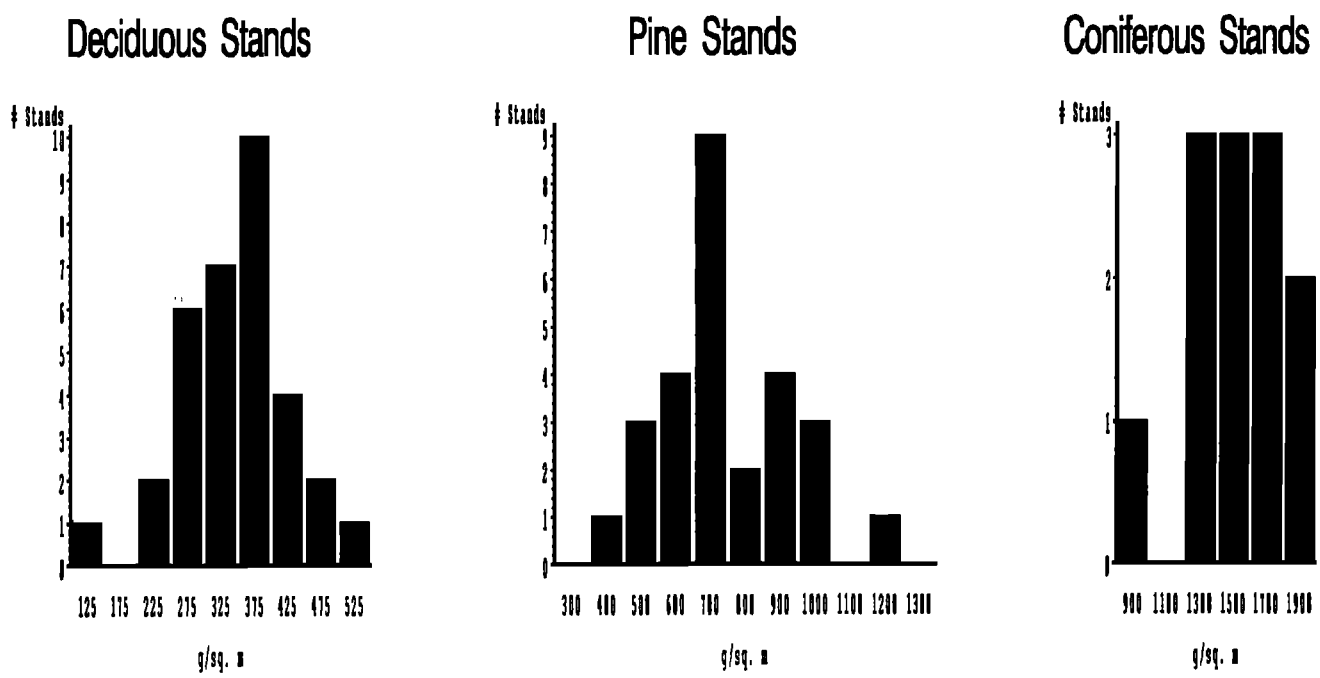

Figure 3. Frequency histogram of observed stand summer peak foliar mass (grams per square meter) for stands of deciduous, pine, and other coniferous genera. The values were determined from destructive analysis or litter fall sampling.

ture conditions. In this approach, we currently assume that leaf temperatures are equivalent to ambient air temperatures above the forest canopy. Isoprene emission rates are estimated as

$$I = I_s \cdot C_L \cdot C_T \tag{3}$$

where I is isoprene emission rate at temperature T and PAR flux L and I_s is the isoprene emission rate at the standard temperature of 30°C and PAR flux of 1000 μmol m^{-2} s^{-1}. The light correction factor C_L is estimated as

$$C_L = \frac{\alpha c_{L1} L}{(1 + \alpha^2 L^2)^{1/2}} \tag{4}$$

where L is PAR flux, and α (=0.0027) and c_{L1} (=1.066) are empirical coefficients derived from emission rate measurements of several species as discussed by *Guenther et al.* [1993].

The leaf temperature correction factor C_T is given by

$$C_T = \frac{\exp [c_{T1}(T - T_S)/RT_S T]}{1 + \exp [c_{T2}(T - T_M)/RT_S T]} \tag{5}$$

where R is the ideal gas constant (8.314 J K^{-1} mol^{-1}), T (K) is leaf temperature, T_s (=303 K) is the standard temperature, and T_M (=314 K), C_{T1} (=95,000 J mol^{-1}), and C_{T2} (=230,000 J mol^{-1}) are empirical coefficients. These coefficients were derived by fit to species of several genera [*Guenther et al.*, 1993]. These models performed substantially better than several others in predicting PAR and temperature effects on independent leaf level isoprene emission rates [*Guenther et al.*, 1993].

Short-term (e.g., hourly or diurnal) variations in emission rate of monoterpenes and other compounds classified as OVOC in Table 3 are primarily determined by leaf temperature, which controls vapor pressure of the essential oils of leaves. Emissions of these compounds are estimated as

$$M = M_s \cdot \exp [\beta(T - T_s)] \tag{6}$$

where M is monoterpene emission rate at leaf temperature T (K), M_s is emission rate at T_s (=303 K), and β (=0.09) is an empirical coefficient derived from several data sets as discussed by *Guenther et al.* [1993]. Emissions of OVOC are also assumed to be influenced by temperature in this manner. Long-term or seasonal influences of temperature on monoterpene and OVOC emissions are not currently understood. This is a focus of current experimental work.

Since PAR strongly controls isoprene emission rate, a simple algorithm to reduce PAR at lower levels within forest canopies has been developed. PAR is estimated at five levels within canopies as a function of above-canopy PAR and is given by

$$\text{PAR}_i = \text{PAR} \ (\exp \{-E_L \cdot \text{LAI} \ [(2i - 1)/10]\}) \tag{7}$$

where PAR_i is the PAR flux at canopy level i (i ranges from 1 to 5 with 1 being the upper layer), PAR is the above-canopy PAR flux, E_L (=0.42) is the light extinction coefficient for PAR, and LAI is the leaf area index (the ratio of square meters of projected leaf area to square meters of ground area).

E_L can vary from 0.28 to 0.84, with the higher values associated with coniferous stands having high branch retention [*Vose and Swank*, 1990]. For most stands, however, values are usually between 0.4 and 0.5. Isoprene emission rates are relatively insensitive to changes in E_L within this range.

LAI is assumed to be equal to 3 for pine stands, 5 for deciduous stands, and 7 for Abies, Picea, and Pseudotsuga

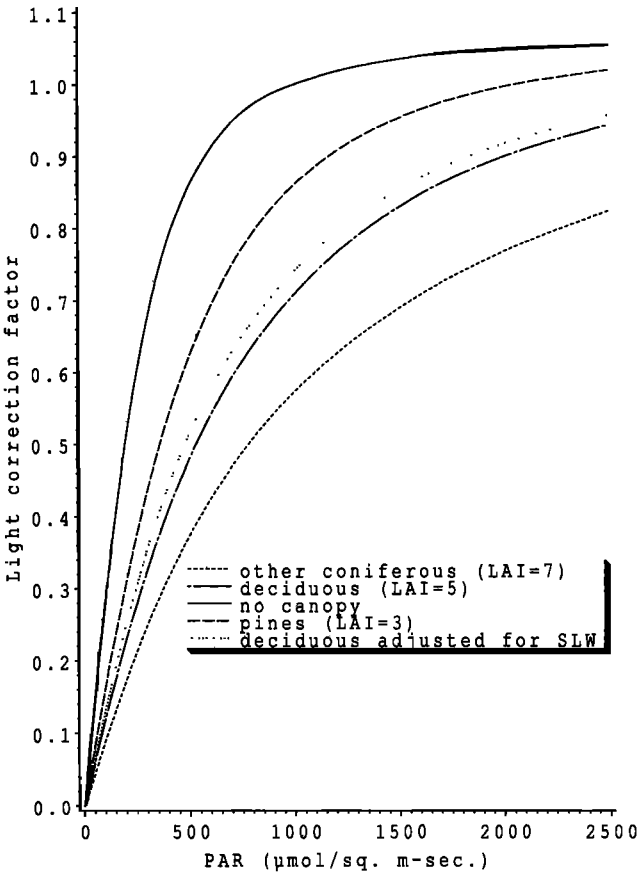

Figure 4. The effect of the simple canopy model and specific leaf weight (SLW) adjustments on relative isoprene emission rate for Pinus (leaf area index (LAI) = 3), deciduous genera (LAI = 5), and other coniferous genera (LAI = 7).

stands. These values are in good agreement with those derived from *Sollins et al.* [1973] and *Gholz* [1986] for mature (closed canopy) stands. Specific leaf weight (SLW) (grams per square meter dry weight) is also adjusted according to the equation of *Jurik* [1986] and is of the form

$$SLW_i = 63.109 + 37.838 \cdot \{\exp[-1 \cdot (i - 1)]\} \quad (8)$$

where SLW_i is the specific weight of leaves in layer i. Deciduous broadleaf foliage in the top canopy layer has SLWs nearly twice that of the lowest layer, since leaves in the upper canopy have much more photosynthetic and epidermal tissue per unit area than leaves in the lower canopy [*Monk et al.*, 1970; *Jackson*, 1966; *Jurik*, 1986]. The foliar mass is therefore skewed toward the upper canopy, which receives more sunlight, resulting in estimated isoprene emissions being about 10% higher than emissions would be without adjusting for vertical changes in SLW. Figure 4 illustrates the effect of the canopy and SLW adjustments on relative isoprene emission rates.

Although vertical leaf temperature gradients also occur in forest canopies [*Lamb et al.*, 1994], transpirational cooling at upper levels also occurs. We currently assume that these leaf temperature influences induce minimal deviations from ambient air temperatures or are counteracting. Therefore they are not explicitly accounted for in this system.

Results and Discussion

Using the methodology described in the previous section, forest area, foliar density, and normalized BVOC emission fluxes have been calculated for every county in the EWDB. Since several hundred genera of vegetation may be present in any given ecosystem, one may wonder if such a scheme can adequately account for such diversity and resulting variability in BVOC emission rates. In order to address this issue, Table 4 shows the area covered by dominant genera within the EWDB. The 16 genera listed in Table 4 cover an estimated 107.6 million hectares, or 85.7% of the estimated 125.6 million hectares of total canopy area for the region. The total land area of the 2239 counties with the EWDB is 351.8 million hectares, 148.9 million (42%) of which are considered forest. Since the dominant canopy covers 125.6 million hectares, or 84% of the forest area, most eastern forests appear to have closed canopies. These forests are dominated by species within relatively few genera. By understanding BVOC emissions from genera such as Quercus, Carya, Pinus, and Liquidambar, we can better estimate their impact on regional photochemistry and other phenomena. To further rank the EWDB genera in terms of importance as BVOC emitters, a relative emission potential (REP) was calculated for each genus as total standardized BVOC emission rate (corrected for vertical attenuation of solar radiation) multiplied by percentage of total crown area occupied and foliar density. REP in Table 4 expresses the REP for each genus as a percentage of total REP for the study area. The genera Quercus, Liquidambar, Populus, Picea, and Pinus compose 92.5% of this potential, with Quercus dominating emissions because of its abundance and high isoprene emission rate.

Although 26 of the 75 genera in Table 3 have not been tested for BVOC emission rates, the calculated areal coverage of these genera is small. Only 3.5% of the estimated crown coverage is composed of these genera. The genera Ostrya, Tilia, Crataegus, and Larix compose most of this area. All genera covering significant areas within the study region have been tested for at least isoprene and monoterpene emission rates.

Lamb et al. [1994] use the Geoecology data discussed earlier and a more sophisticated canopy model to adjust both PAR and leaf temperature vertically through forest canopies. This model, the Biogenic Emission Inventory System (BEIS) is currently used as the EPA regulatory BVOC emission estimation system. Standardized hourly emission rates from these two systems for forests in selected regions under varying light and temperature conditions are compared in Table 5. Actual BVOC emission rate measurements have been made in these areas. Comparisons between predicted and actual emission rates are presented later in this paper and in future studies.

Table 5 reveals large differences in isoprene emission estimated between the two systems. The systems differ in their standardized emission rates, forest composition, vertical canopy environment models, and environmental correction algorithms. *Guenther et al.* [1994] discuss artifacts in previous isoprene emission rate factors that are likely to be responsible for underestimating leaf level isoprene emission rates derived from branch or seedling enclosure experiments. In some of these past studies, estimates of PAR outside of enclosures were assumed to be incident upon all

Table 4. Forest Coverage Statistics for Dominant Genera in the Eastwide Database

Genus	% of Total Crown Area	Cumulative %	Area, 10^6 ha	% Forest Area Covered	% Total Land Area Covered	REP
Quercus	26.8	26.8	33.6	22.6	9.4	68.2
Pinus	15.1	41.9	19.0	12.8	5.3	4.7
Acer	9.5	51.4	11.9	8.0	3.3	1.0
Carya	5.1	56.5	6.4	4.3	1.8	0.6
Ulmus	3.6	60.1	4.6	3.1	1.3	0.2
Liquidambar	3.0	63.1	3.7	2.5	1.0	7.9
Populus	3.0	66.1	3.7	2.5	1.0	7.5
Fagus	2.9	69.0	3.6	2.5	1.0	0.2
Cornus	2.7	71.7	3.4	2.3	1.0	0.3
Betula	2.6	74.3	3.3	2.2	0.9	0.1
Fraxinus	2.3	76.6	2.9	2.0	0.8	0.1
Abies	2.1	78.7	2.7	1.8	0.7	1.4
Nyssa	2.1	80.8	2.6	1.8	0.7	1.2
Picea	1.8	82.6	2.2	1.5	0.6	4.2
Liriodendron	1.7	84.3	2.2	1.5	0.6	0.1
Prunus	1.4	85.7	1.8	1.2	0.5	0.1

REP, relative emission potential.

leaves in an enclosure, which was probably not the case in measurements where dense cohorts of foliage were enclosed. *Guenther et al.* [1993] estimate that this induces a 75% underestimate in determining leaf level emission rates from branch enclosure experiments. For example, a densely foliated oak branch emitting 40 μg-C (g-foliar dry mass)$^{-1}$ h^{-1} at a leaf temperature of 30°C and PAR of 1000 μmol m^{-2} s^{-1} above the enclosure would correspond to a standardized leaf level emission rate of 70 μg-C (g-foliar dry mass)$^{-1}$ h^{-1} because of partial shading of some of the foliage within the chamber. This is approximately the same effect that light attenuation has on estimated vertically integrated canopy emission rates. For the sites in Table 5, biomass densities assumed in the two systems are nearly identical, since no spruce or fir are present. The BEIS assigns a fairly constant mix of forest types over the study area, resulting in little variation in emission rates between sites. Although the sum of monoterpene and OVOC estimated from the two models is comparable, isoprene and resulting total BVOC emissions are estimated to be 5 to 10 times greater at these sites under a range of environmental conditions. Such increases in modeled BVOC emission rates could have substantial impact on photochemical modeling analyses.

Figures 5a, 5b, and 5c show county average isoprene, monoterpene, and total BVOC emissions, respectively, for forested areas only. These emissions are corrected for canopy environment, ambient temperatures of 30°C, and high sunlight (1500 μmol m^{-2} s^{-1}). These conditions are typical of summertime days when high-ozone episodes may occur within this region. The plots reveal patterns associated with variability in forest genera composition.

Isoprene emissions from forests (Figure 5a) are highest in the south, especially in the Ozark mountain range and the Appalachian corridor because of the high density of oaks (Quercus spp) and gums (Nyssa and Liquidambar). A sharp decline in isoprene emissions occurs north of the Appalachians. This is

Table 5. Estimated Hourly Emission Rates (mg-C m^{-2} h^{-1}) of Isoprene, Sum of Monoterpenes and Other Volatile Organic Compounds and Total Biogenic Volatile Organic Compounds From the Two Systems for Forests in Selected Areas

		Temperature = 20°C						Temperature = 30°C					
		PAR = 500			PAR = 1500			PAR = 500			PAR = 1500		
Site	Model	Isop.	M&O	Total	Isop.	M&O	Total	Isop.	M&O	Total	Isop.	M&O	Total
Anderson	G	1.32	0.35	1.67	2.19	0.35	2.54	4.79	0.86	5.65	7.95	0.86	8.81
Co., TN	B	0.18	0.46	0.64	0.35	0.59	0.94	0.29	0.90	1.19	1.18	1.12	2.30
York	G	1.68	0.32	2.00	2.80	0.32	3.12	6.10	0.79	6.89	10.2	0.79	11.0
Co., PA	B	0.18	0.46	0.64	0.34	0.60	0.94	0.29	0.90	1.19	1.18	1.12	2.30
Choctaw	G	1.32	0.61	1.93	2.18	0.61	2.79	4.77	1.49	6.26	7.91	1.49	9.40
Co., AL	B	0.25	0.43	0.68	0.49	0.56	1.05	0.41	0.85	1.26	1.68	1.06	2.74
Emanual	G	1.21	0.62	1.83	2.01	0.62	2.63	4.40	1.54	5.94	7.30	1.54	8.84
Co., GA	B	0.18	0.46	0.64	0.34	0.60	0.94	0.29	0.90	1.19	1.18	1.12	2.30

Isop., isoprene; M&O, sum of monoterpenes and other volatile organic compounds; G, this system; B, Biogenic Emission Inventory System. Photosynthetically active radiation (PAR) units are μmol m^{-2} s^{-1}.

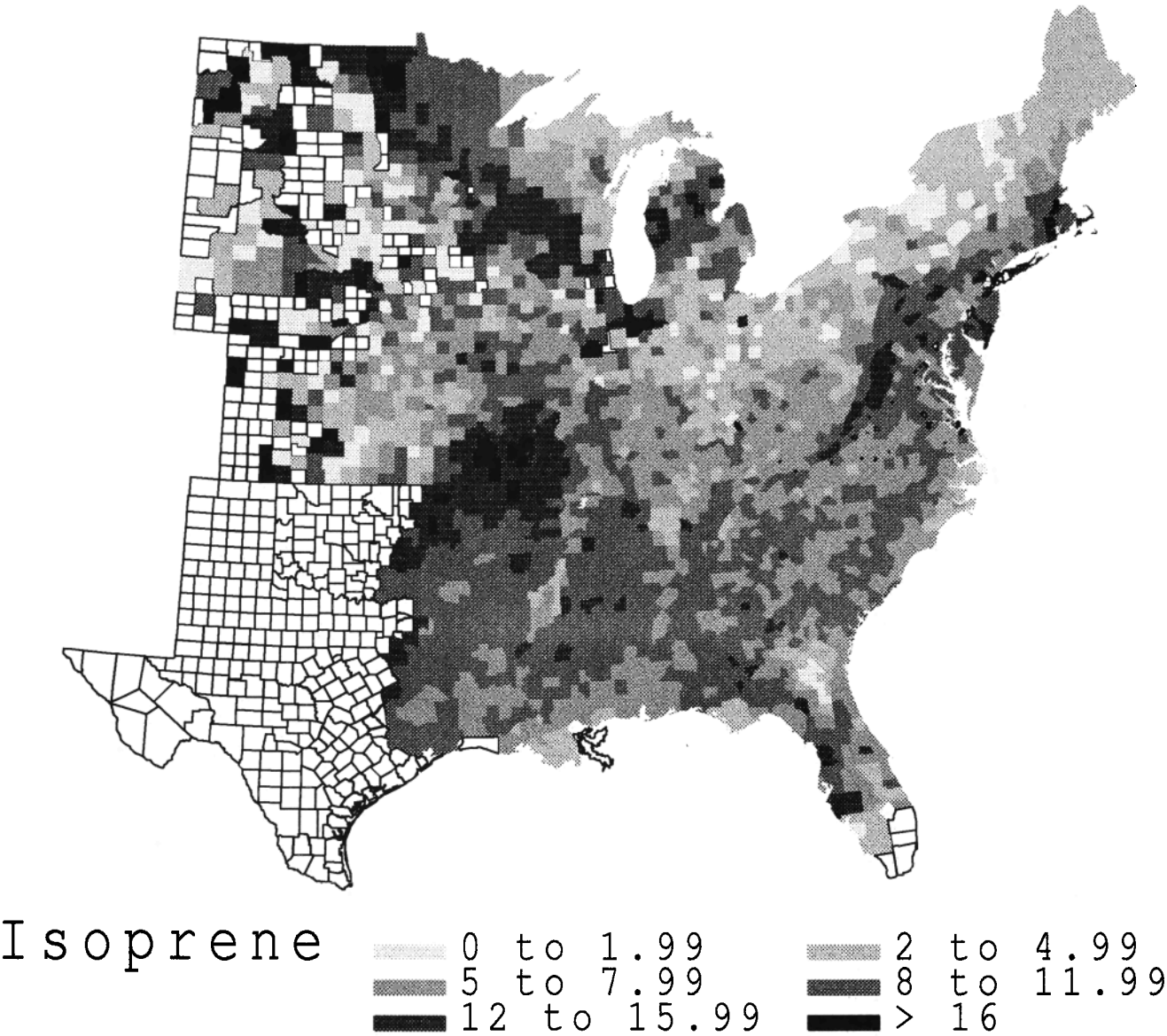

Figure 5a. County average isoprene emission rates (mg-C m^{-2} h^{-1}) for forested areas only. These emissions are corrected for canopy environment, ambient temperatures of 30°C, and full sunlight (1500 μmol m^{-2} s^{-1}). Empty counties outlined are those with no forest survey data in the EWDB.

primarily due to a transition to maple-beech-birch (Acer-Fagus-Betula) dominated forests with a smaller Quercus composition. The maple-beech-birch genera have all been found to be consistently low emitters of isoprene. Scattered parcels of oak woodlands also occur in the Plains region, causing higher emissions there. In the northern lake states and New England regions, isoprene emissions are also higher because of the abundance of spruce (Picea) forests. These forests emit isoprene at lower rates per unit foliage than oak forests but carry higher foliar masses. Isoprene emission rates in these regions differ substantially from those estimated by BEIS [*Geron et al.*, 1992] because of higher emission rates and foliar masses than are assumed for these forests in BEIS.

Forest monoterpene emissions (Figure 5b) are highest in the northern spruce-fir-pine (Picea-Abies-Pinus) forests, again because of high foliar masses and emission rates associated with these genera. Likewise the abundance of pines and sweetgum found along the southern coastal plain and lower Piedmont contribute to higher emission there compared to the interior eastern United States.

Since isoprene emissions are approximately 2 to 5 times higher than monoterpenes and OVOC in most regions, the general pattern of total BVOC emissions (Figure 5c) resembles that of isoprene emissions (Figure 5a). Primary differences between estimates from this system and others are higher total emissions in the northernmost areas, lower relative emission rates in the Ohio Valley and the lower northeast, and pronounced peaks in total BVOC emission rates in the Appalachian and Ozark mountain ranges.

Figures 6a, 6b, and 6c show county level isoprene, monoterpene, and total BVOC emissions, respectively, from forests averaged over the entire county land areas. These emissions are also corrected for canopy environment, ambient temperatures of 30°C, and full sunlight (1500 μmol m^{-2}

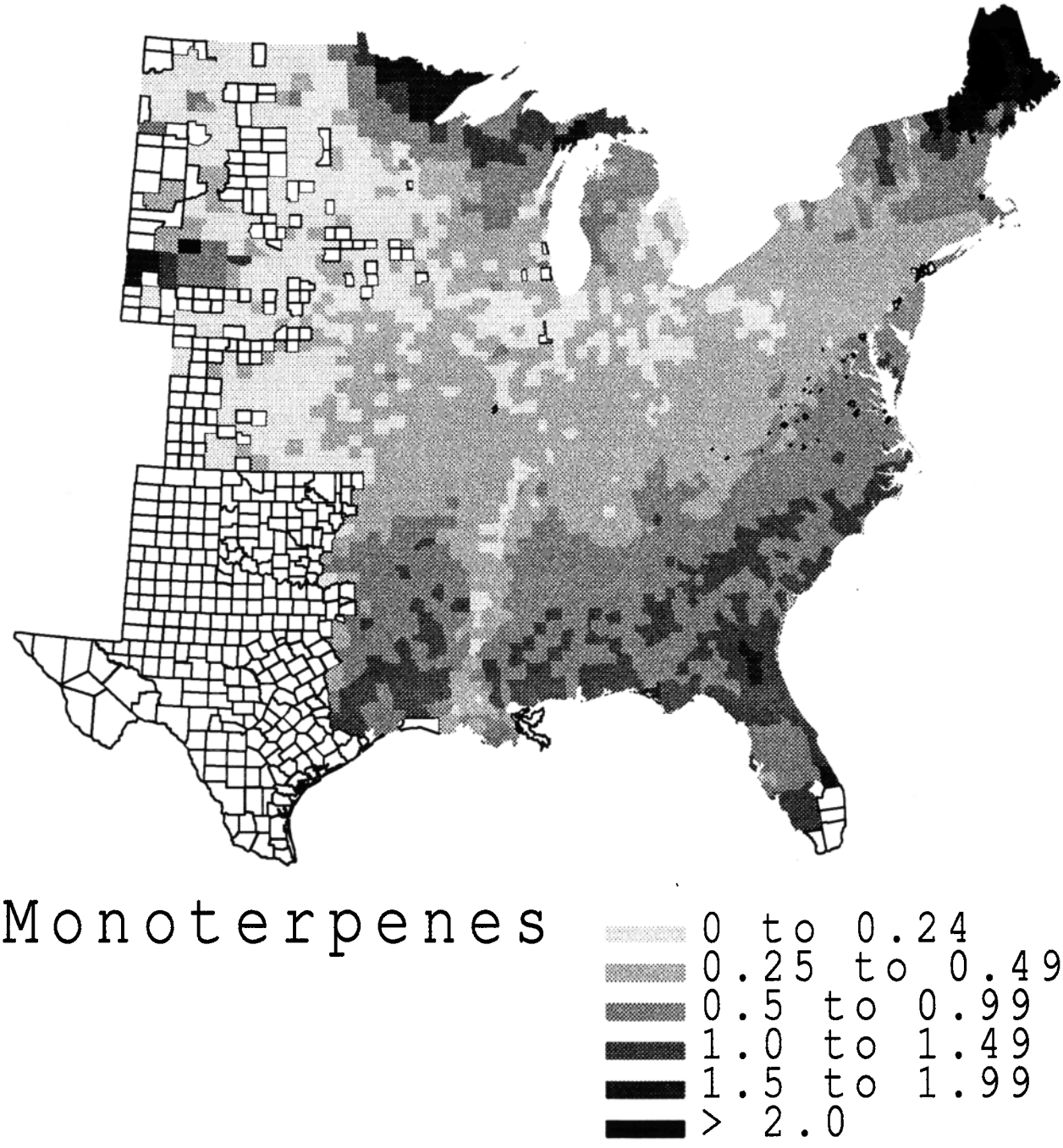

Figure 5b. Same as Figure 5a except for county average monoterpene emission rates.

s^{-1}). The plots reveal patterns associated with factors discussed above but are also impacted by the percentage of forest coverage within each county.

County average isoprene emissions (Figure 6a) are still highest in the South, especially along the Appalachian corridor and in the Ozark mountain range. Isoprene emission rates from these areas contrast even more sharply with those from the surrounding areas because of the high density of isoprene-emitting genera and large expanses of forested land. Forests in the Piedmont and mountain areas have not been converted to other land uses at the same rate as other regions. Secondarily high emissions are shown in the far northern counties because of significant areas in natural and managed spruce stands. Clearing of forests from the Ohio Valley to the Great Plains accounts for the uniformly low isoprene emission rates in these areas, even though small local forests may emit at high rates.

County average monoterpene emission rates (Figure 6b) show a pattern not noted in other regional estimates to date. The high foliar biomass levels and uniform expanses of spruce-fir-pine forests cause standardized emission rates to be higher than rates in the South. The southern coastal plain has secondarily high rates, but apparently the scattered nature of pine stands dilutes their impact on monoterpene emissions compared to the far northern portions of the study area. It should be noted that the area converted to commer-

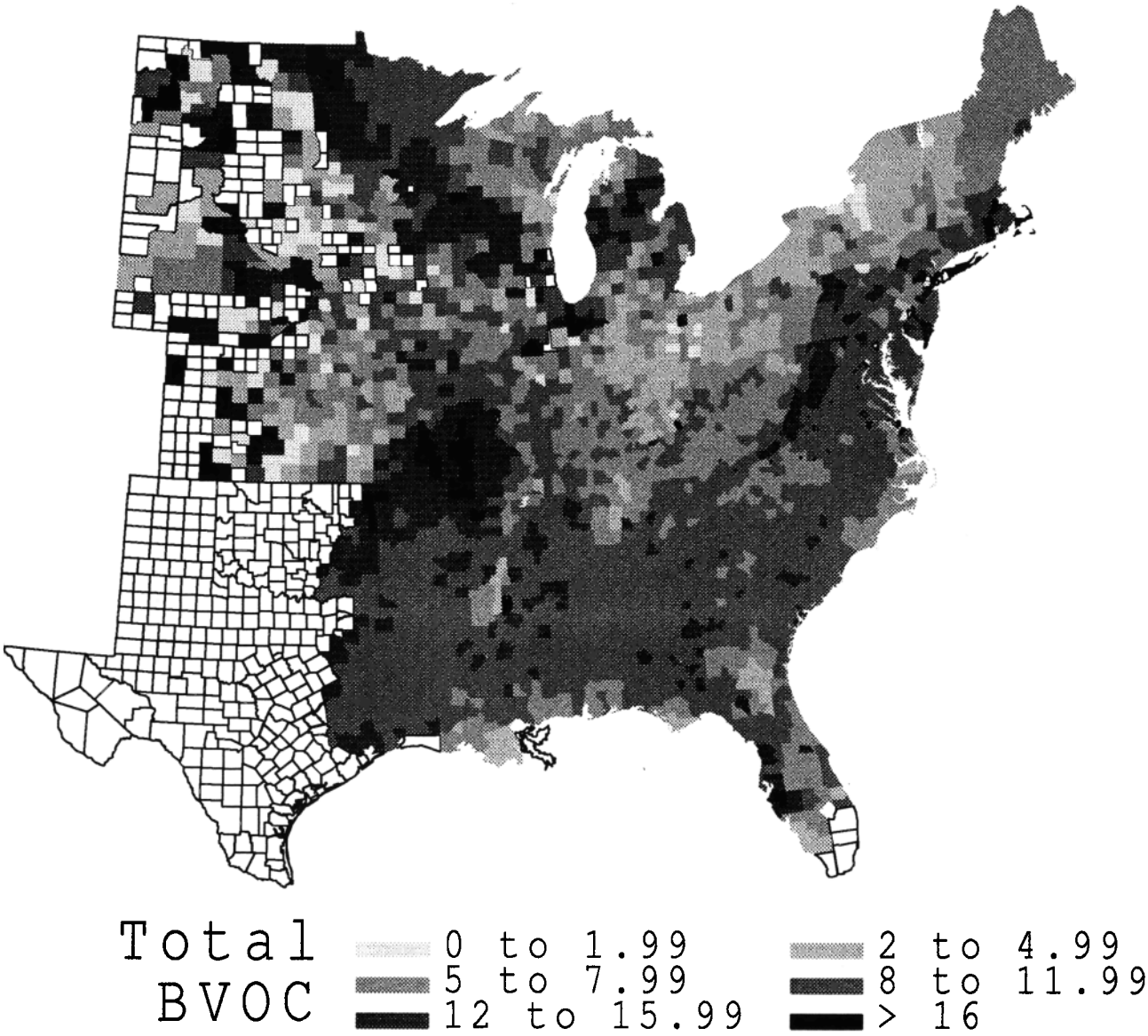

Figure 5c. Same as Figure 5a except for total BVOC emission rates.

cial pine forests is increasing at rapid rates in the south [*Forest Service*, 1988], possibly enhancing the future importance of monoterpenes in photochemistry.

Standardized (these regional comparisons do not consider differences in actual meteorology) comparisons of county average total BVOC (Figure 6c) emission rates are clearly influenced by the trends shown in Figures 6a and 6b. During meteorological conditions conducive to ozone episodes, New England and the northern portions of the lake states emit BVOC at estimated rates similar to those of southern forested regions. The photochemistry in urban air sheds such as Atlanta, St. Louis, and Boston, would appear to be more impacted by forest BVOC emissions than Chicago, Kansas City, or San Antonio. Likewise, rural photochemical effects of BVOC would appear to be greatest in southern mountain and Piedmont regions and northern boreal regions. Their effects in the agricultural areas of the Midwest and Plains regions are estimated to be minimal.

In order to assess the validity of the new system, isoprene and monoterpene emissions measured at specific sites in the United States were compared to corresponding model estimates. Isoprene emissions were measured from mixed forest and agricultural landscapes in western Alabama and eastern Georgia [*Guenther et al.*, 1994; K. J. Davis et al., Biogenic nonmethane hydrocarbon emission estimates from tethered balloon observations, submitted to *Journal of Geophysical Research*, 1993 (hereinafter referred to as Davis et al., 1993)] and deciduous (predominantly oak) forests in south central Washington [*Lamb et al.*, 1986] and southeastern Pennsylvania [*Lamb et al.*, 1985]. Monoterpene emissions were measured at the Alabama and Georgia sites, from a Douglas fir stand in northwest Washington [*Lamb et al.*, 1985] and a loblolly pine stand in north central North Carolina [*Arnts et al.*, 1978]. Various micrometeorological (e.g., energy balance/Bowen ratio, gradient, and tracer) techniques were used to quantify BVOC emissions over areas ranging in magnitude from tens to several thousands of hectares. Details of the measurement techniques applied can be found in the references cited above. Although the forests in Washington are outside the range of the EWDB, the new model is

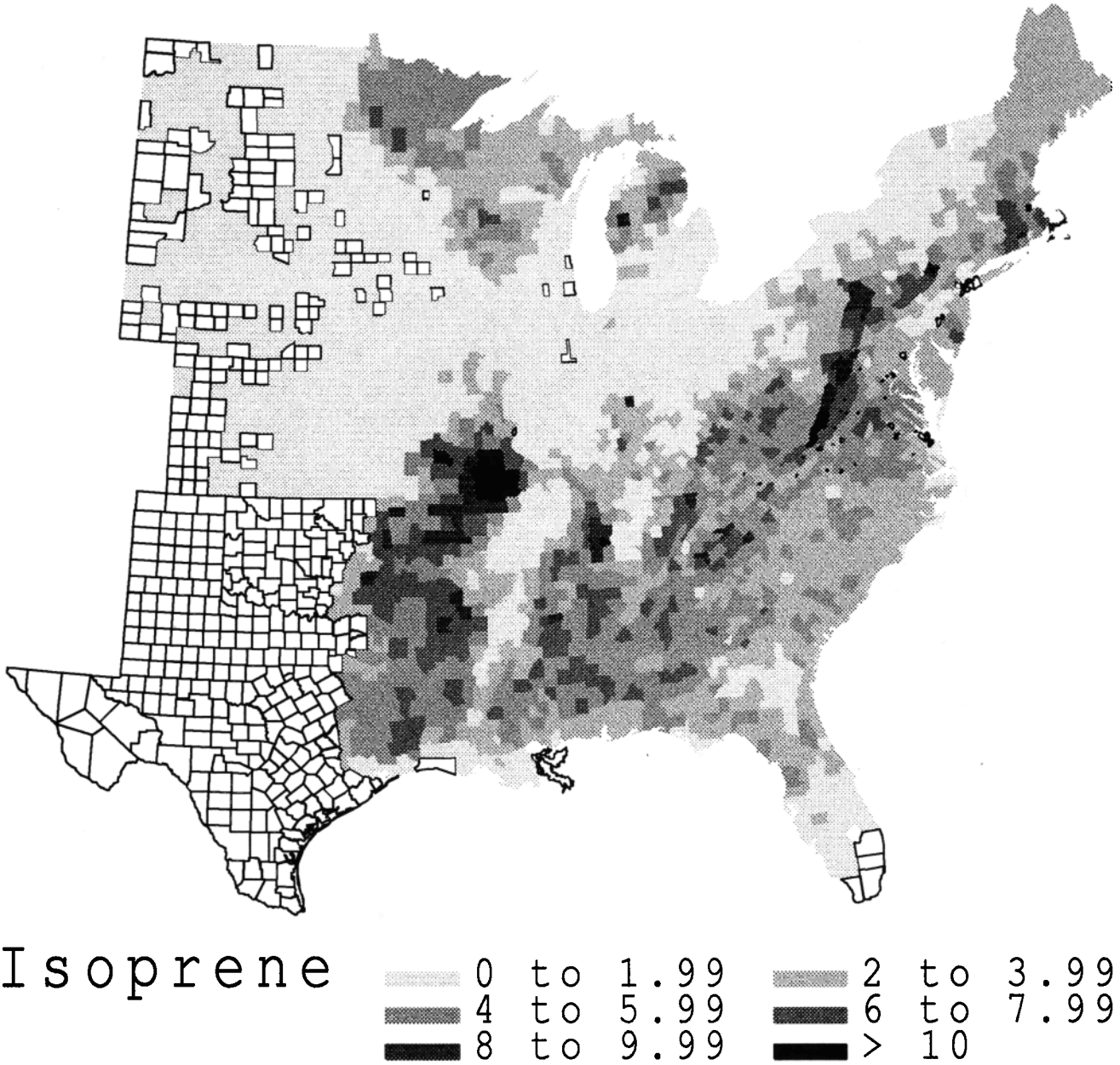

Figure 6a. County level isoprene emission rates (mg-C m^{-2} h^{-1}) from forests averaged over the entire county land areas. These emissions are also corrected for canopy environment, ambient temperatures of 30°C, and full sunlight (1500 μmol m^{-2} s^{-1}). Empty counties outlined are those with no forest survey data in the EWDB.

developed to estimate emissions from tree genera in this region as well. The emissions measured at these sites should represent reasonable data for model comparison.

Foliar mass estimates were derived by applying the crown area equations (1) and (2) and the density estimates from Table 3 to the DBH distribution data from either (1) the EWDB data in the vicinity of each site or (2) DBH distribution data collected by crews at each site during the emission measurement experiment. Foliar mass estimates at these sites were also developed using allometric equations between DBH and foliar mass and are reported by *Arnts et al.* [1978], *Guenther et al.* [1994], and *Lamb et al.* [1985, 1986]. Biomass estimates were in general agreement (±20%) for all sites except for the Washington oak and Douglas fir stands. It is likely that the Douglas fir foliar mass estimate of 830 g m^{-2} [*Lamb et al.*, 1985] is more realistic than the 1500 g m^{-2} we estimate, because the former was based on equations developed for trees specific to that site. Furthermore, stand level foliar mass data for fully stocked Douglas fir stands are limited (see Figure 3). For the Washington oak stand, however, the biomass estimate of 804 g m^{-2} from *Lamb et al.* [1986] was developed from allometric equations from other sites. This estimate is considerably higher than other estimates reported for deciduous stands. It is likely that the actual oak foliar mass at this site falls somewhere between the estimate of 375 g m^{-2} used here and the 804 g m^{-2} estimated by *Lamb et al.* [1986].

For the emission flux comparisons, local temperature and PAR data collected during the field experiments were used to estimate the environmental correction factors (equations

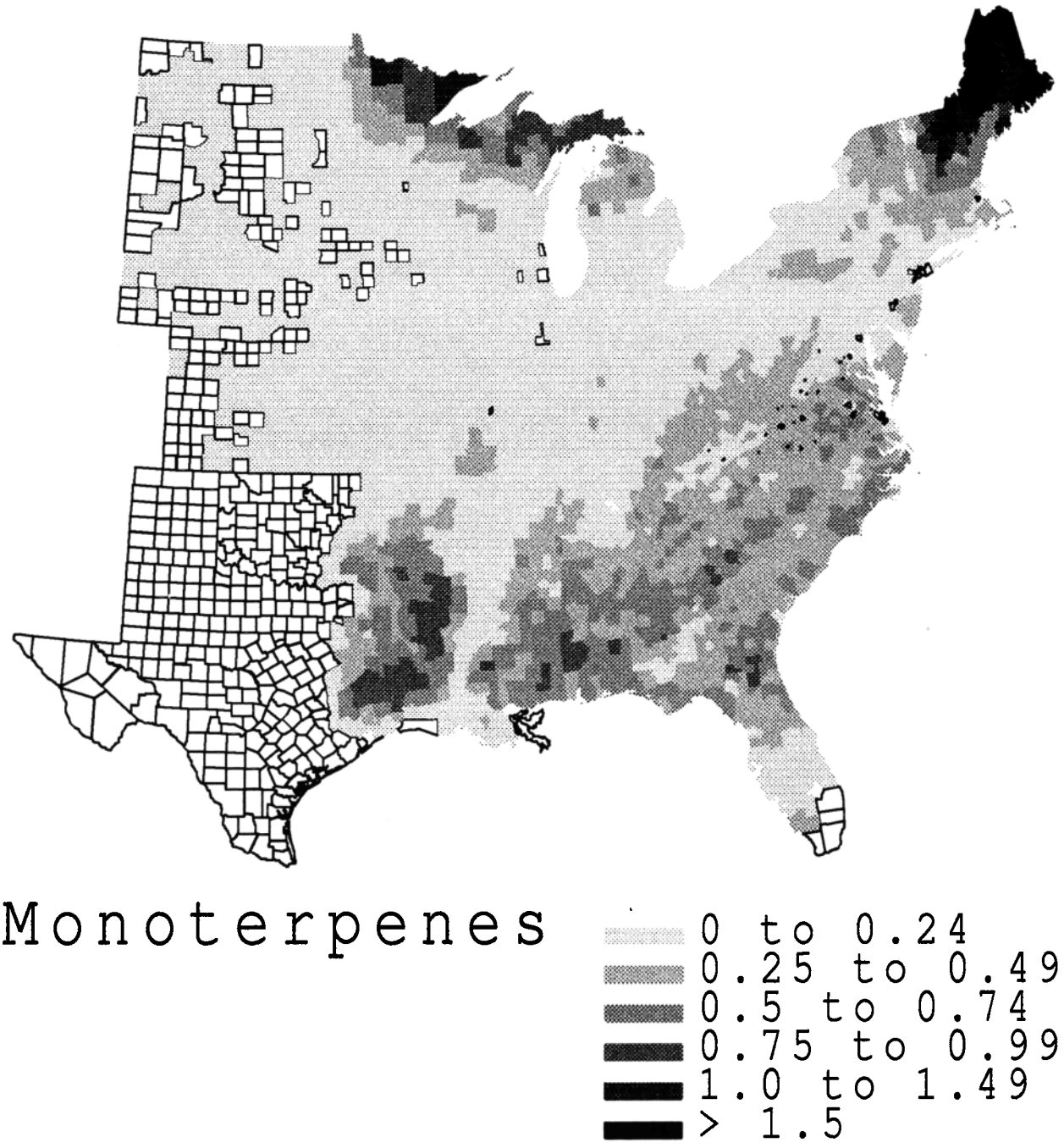

Figure 6b. Same as Figure 6a except for monoterpene emission rates.

(3)–(6)). Leaf area indices from Table 3 were used to attenuate PAR in equation (7) through forest canopies at each site. Figures 7a and 7b show the relationship between predicted and observed isoprene and monoterpene emission rates, respectively. In each case, 67% of predicted emissions are within 50% of measured rates. Figures 8a and 8b illustrate the distribution of model deviations from observed emission rates. Linear regressions fitting observed emissions as a function of predicted values among data from all sites yielded slope and intercept coefficients which were not significantly different from one and zero, respectively, indicating no significant prediction bias using the new system. The model estimates accounted for approximately 60% of the variability in observed monoterpene and isoprene emission rates. Among individual sites, however, some bias is evident. At the Alabama site, for instance, isoprene emissions measured at temperatures less than 30°C are consistently overestimated by the model, while at higher temperatures, the reverse is true. Observed isoprene emissions at the Pennsylvania site are uniformly lower than the model estimates for this site. It is interesting to note that if county level EWDB data is used instead of the localized forest survey, model predictions agree very well with observed values (data not shown). This does not necessarily indicate that the flux footprint estimated by *Lamb et al.* [1985] is incorrect, but it does give an indication of the importance of

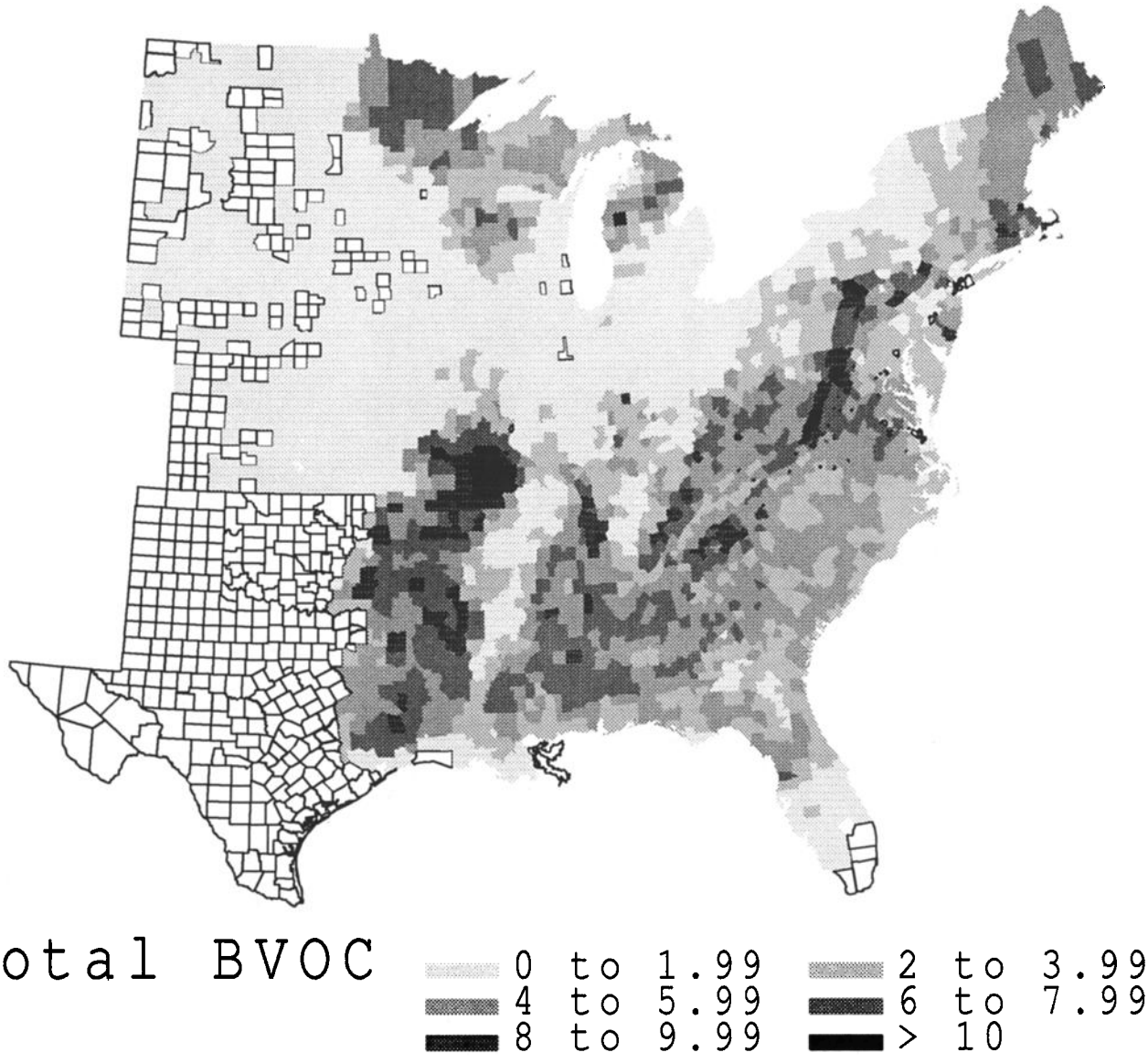

Figure 6c. Same as Figure 6a except for total BVOC emission rates.

proper site characterization in relating emission rates to landscapes. The Washington site yields the highest observed isoprene emission rate, corresponding to its composition of nearly 100% oak. On average, predicted rates agree reasonably well with observed values for this site, although individual measurements can deviate substantially from model estimates, as exhibited in Figure 7a. Isoprene emissions at the Georgia site are considerably lower than the standardized emission rates for forests in Emanuel County given in Table 5. This may be at least partially attributed to the low percentage of forests in the landscape surrounding this site. The EWDB indicates that the counties surrounding this site are only 36 to 41% forested. An independent analysis of Landsat satellite imagery for the area indicates that the area is 35% forested (J. Brockhaus, Computer Graphics Center, North Carolina State University, personal communication, 1993).

Observed monoterpene emissions show similar patterns with respect to model estimates. The model overestimates five of the seven emission rates for the Washington Douglas fir forest. This may be partly due to our likely overestimate of biomass density for this site. The model also underpredicts some emissions from the North Carolina loblolly pine stand. On the other hand, the model overpredicts emissions from another loblolly pine stand in eastern North Carolina [*Arnts et al.*, 1982] by a factor of roughly 2 to 4 (data not shown). It should be noted that α pinene was the only monoterpene emission quantified from these coniferous forests. However, the authors working at these respective sites found that α pinene composed roughly 80% of the total monoterpenes detected. These authors have speculated that factors such as relative humidity, terpene production and storage, and plant phenology may contribute to uncertainty in current model estimates of monoterpenes.

It should be noted that the error attributed to micrometeorological emission rate measurement techniques at the individual sites discussed above are typically of the order of ±50% [*Lamb et al.*, 1985; Davis et al., 1993]. *Guenther et al.* [1994] also estimates uncertainty for the genus level standardized emission rates to be ±50%. When considering these

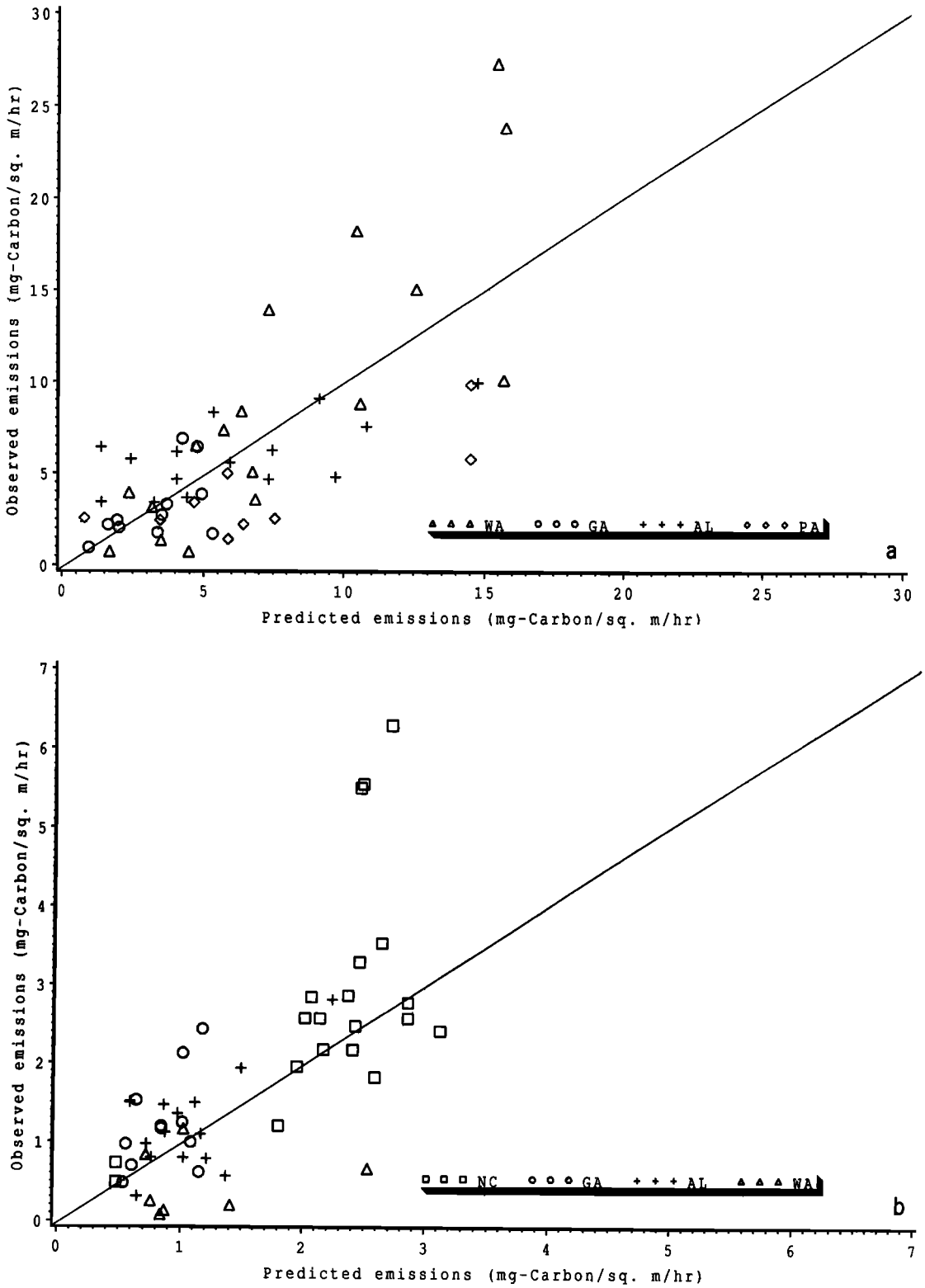

Figure 7. Predicted versus observed (a) isoprene and (b) monoterpene emission rates (mg-C m^{-2} h^{-1}) for four forested sites. Diagonal lines represent perfect agreement between observed values and model estimates.

factors, in addition to uncertainty in local biomass estimates and forest composition, model performance in general seems to be reasonable. Further developmental research is needed to improve both the accuracy of landscape level emission rate measurements and model performance.

Future Research

Results presented in this paper indicate that relatively few genera are estimated to be responsible for a large proportion of BVOC flux in any given region. Since large variation

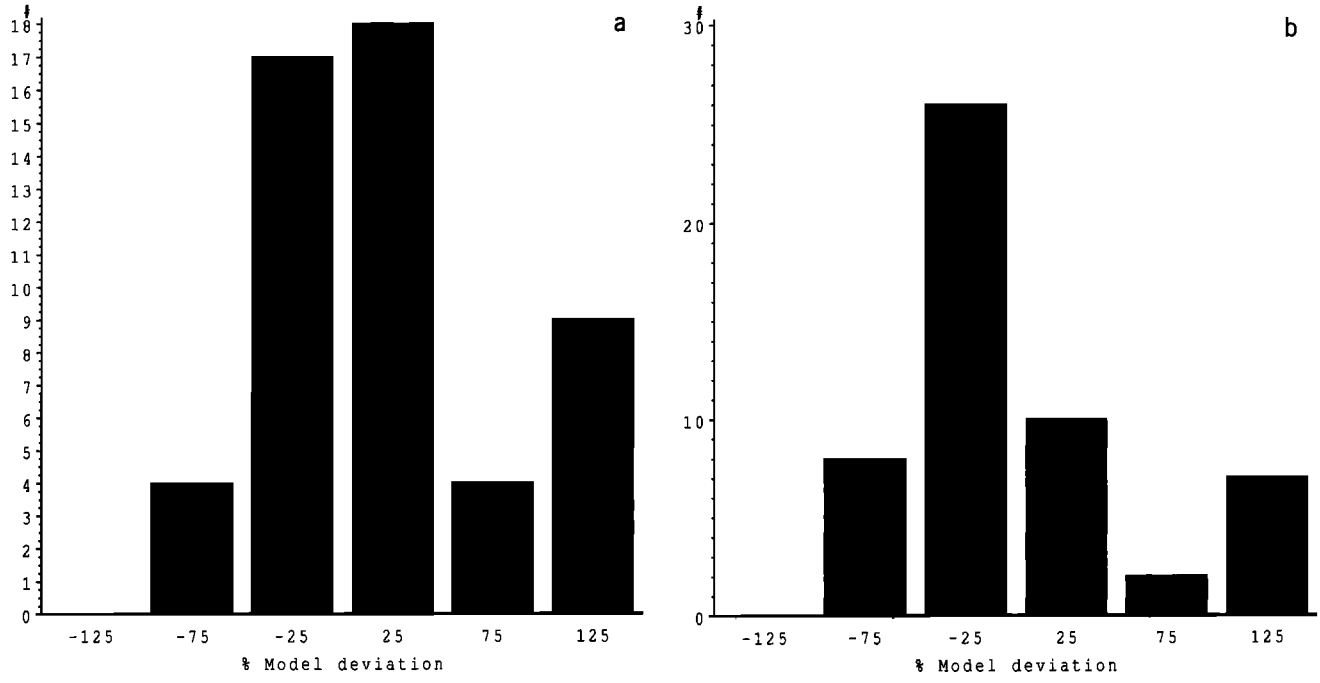

Figure 8. (a) Isoprene and (b) monoterpene model deviations calculated as [(predicted − observed)/observed] × 100. Values on horizontal axes represent class midpoint (e.g., 25 represents deviations from 0 to 50%).

(±50%) is currently associated with genus level emission rates, determining the variability between and within species in important genera (e.g., Quercus, Liquidambar, Populus, Picea, and Pinus) could be of value. Perhaps linkages of isoprene production to physiological processes could partially account for this variability. This could provide a link between models of productivity or photosynthesis and BVOC emission. More thorough empirical assessments of probability distributions associated with leaf and branch level emission rates could also enhance the realism of BVOC emission models, since use of arithmetic versus geometric mean emission rates can have significant impacts on BVOC fluxes when using systems with such high uncertainty. Analysis of the impact of using leaf level versus branch enclosure (cohorts of leaves) emission measurements could yield valuable results. Since branch enclosure techniques themselves can also feature leaf overlap, extrapolation to canopy level emission rates must be approached cautiously.

The OVOC category used currently assumes that all vegetation emits OVOCs at basically the same rate. This is obviously a gross simplification. Screening of predominant vegetation types in a nonintrusive manner for other reactive organic compounds, including polar and oxygenated substances, may improve model realism in this area. Recent findings by *Goldan et al.* [1993], *MacDonald and Fall* [1993], and *Ciccioli et al.* [1993] indicate that these types of compounds may be emitted in significant quantities from vegetation. This may require advanced analytical techniques capable of quantitating such compounds.

Recent work by *Sharkey et al.* [1992] and *Kuzma and Fall* [1993] indicates that there are also seasonal effects on emission rates. Isoprene emission rates are very low for several weeks following leaf-out and likewise decrease during leaf senescence. Experimental data and models would help quantify the seasonal variation in these emission rates.

Currently, little is known of BVOC emissions from agricultural crops such as corn, wheat, or soybeans. Recent work by *Sharkey et al.* [1992] calls into question rates previously assumed in BVOC emission models. Additional work using nonintrusive techniques could help determine realistic BVOC emission rates from crops. This may prove critical to air quality modeling in agricultural areas of the United States.

The satellite-derived EROS data used by *Guenther et al.* [1994] shows promise in delineating vegetation types in homogenous forested areas. By using relationships between vegetation indices and productivity, foliar mass, and leaf area, these data can be used to estimate canopy parameters needed for models of trace gas exchange. Development of such approaches will provide model inputs which reflect temporal and spatial variability due to climatic and site quality differences that are currently addressed only empirically. It is envisioned that spectral characteristics from the LANDSAT thematic mapper data could be coupled with survey information available from the EWDB or other urban forest inventories, including those derived from aerial photography.

Complex terrain in urban air sheds also needs to be better characterized. The EWDB describes only forest parcels 0.4 ha (1 acre) or larger. Urban vegetation in smaller tracts may contribute significant BVOC in urban areas such as Atlanta which have substantial tree cover.

Accounting for leaf angle, energy balance, and moisture at landscape scales in forest canopy architecture and microenvironment models will greatly influence the light and temperature environments of BVOC-emitting foliage, which

have been illustrated as the primary controls of BVOC emissions.

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References

Arnts, R. R., R. L. Kuntz, F. L. Mowry, K. R. Knoerr, A. C. Dudgeon, and R. L. Seila, Measurements of α-pinene fluxes from a loblolly pine forest, paper presented at 4th Joint Conference on Sensing of Environmental Pollutants, Am. Chem. Soc., Washington, D. C., 1978.

Arnts, R. R., W. B. Peterson, R. L. Seila, and B. W. Gay, Jr., Estimates of α-pinene emissions from a loblolly pine forest using an atmospheric diffusion model, *Atmos. Environ., Part A, 16*, 2127–2137, 1982.

Burton, A. J., K. S. Pregitzer, and D. D. Reed, Leaf area and foliar biomass relationships in northern hardwood forests located along an 800 km acid deposition gradient, *For. Sci., 37*, 1041–1059, 1991.

Ciccioli, P., E. Brancaleoni, M. Frattoni, A. Cecinato, and A. Brachetti, Ubiquitous occurrence of semi-volatile carbonyl compounds in tropospheric samples and their possible sources, *Atmos. Environ., Part A, 27*, 1891–1901, 1993.

Dasmann, R., *Environmental Conservation*, 4th ed., International Union for the Conservation of Nature and National Resources, Morges, Switzerland, 1976.

Espinosa Bancalari, M. A., D. A. Perry, and J. D. Marshall, Leaf area-sapwood area relationships in adjacent young Douglas-fir stands with different early growth rates, *Can. J. For. Res., 17*, 174–180, 1987.

Fehsenfeld, F., et al., Emissions of volatile organic compounds from vegetation and their implications for atmospheric chemistry, *Global Biogeochem. Cycles, 6*, 389–430, 1992.

Forest Service, Department of Agriculture, The South's fourth forest: Alternatives for the future, *Forest Resour. Rep. 24*, 512 pp., Washington, D. C., 1988.

Geron, C. D., and G. A. Ruark, Comparison of constant and variable allometric ratios for predicting foliar biomass of various tree genera, *Can. J. For. Res., 18*, 1298–1304, 1988.

Geron, C. D., T. E. Pierce, and T. L. Birth, An alternative method for estimating biogenic VOC emissions in EPA region 1, paper presented at International Conference on Tropospheric Ozone: Nonattainment and Design Value Issues, Environ. Prot. Agency, Boston, Mass., Oct. 28–30, 1992.

Gholz, H. L., Canopy development and dynamics in relation to primary production, in *Crown and Canopy Structure in Relation to Productivity*, edited by T. Fujimori and D. Whitehead, pp. 224–242, Forestry and Forest Products Research Institute, Ibaraki, Japan, 1986.

Goldan, P. D., W. C. Custer, and F. C. Fehsenfeld, The observation of a C_5 alcohol emission in a North American pine forest, *Geophys. Res. Lett., 20*, 1039–1042, 1993.

Guenther, A. B., R. K. Monson, and R. Fall, Isoprene and monoterpene emission rate variability: Observations with eucalyptus and emission rate algorithm development, *J. Geophys. Res., 96*, 10,799–10,808, 1991.

Guenther, A. B., P. R. Zimmerman, P. C. Harley, R. Monson, and R. Fall, Isoprene and monoterpene emission rate variability: Model evaluations and sensitivity analyses, *J. Geophys. Res., 98*, 12,609–12,617, 1993.

Guenther, A. B., P. R. Zimmerman, and M. Wildermuth, Natural volatile organic compound emission rate estimates for U.S. woodland landscapes, *Atmos. Environ.*, in press, 1994.

Hansen, M. H., T. Frieswyck, J. F. Glover, and J. F. Kelly, The eastwide forest inventory database: User's manual, *Gen. Tech. Rep. NC-151*, 48 pp., Forest Serv., Dep. of Agric., St. Paul, Minn., 1992.

Harlow, W. M., E. S. Harrar, and F. M. White, *Textbook of Dendrology*, 6th ed., 510 pp., McGraw-Hill, New York, 1979.

Hungerford, R. D., Estimation of foliage area in dense Montana lodgepole pine stands, *Can. J. For. Res., 17*, 320–324, 1987.

Jackson, L. W. R., Effect of shade on leaf structure of deciduous tree species, *Ecology, 48*, 498–499, 1966.

Jurik, T. W., Temporal and spatial patterns of specific leaf weight in successional northern hardwood tree species, *Am. J. Bot., 73*, 1083–1092, 1986.

Keane, M. G., and G. F. Weetman, Leaf area-sapwood cross-sectional area relationships in repressed stands of lodgepole pine, *Can. J. For. Res., 17*, 205–209, 1987.

Kinerson, R. S., C. W. Ralston, and C. G. Wells, Carbon cycling in a loblolly pine plantation, *Oecologia, 29*, 1–10, 1977.

Kuzma, J., and R. Fall, Leaf isoprene emission rate is dependent on leaf development and level of isoprene synthase, *Plant Physiol., 101*, 435–440, 1993.

Lamb, B., D. Gay, H. Westburg, and E. Allwine, Biogenic hydrocarbon emissions from deciduous and coniferous trees in the United States, *J. Geophys. Res., 90*, 2380–2390, 1985.

Lamb, B., D. Gay, H. Westburg, and E. Allwine, Isoprene emission fluxes determined by an atmospheric tracer technique, *Atmos. Environ., Part A, 20*, 1–8, 1986.

Lamb, B., A. Guenther, D. Gay, and H. Westburg, A national inventory of biogenic hydrocarbon emissions, *Atmos. Environ., Part A, 21*, 1695–1705, 1987.

Lamb, B., D. Gay, H. Westburg, and T. Pierce, A biogenic hydrocarbon emission inventory for the U.S. using a simple forest canopy model, *Atmos. Environ., Part A, 27*, 1673–1690, 1993.

Leith, H., and R. H. Whitaker (Eds.), Primary productivity of the biosphere, in *Ecological Studies*, vol. 14, pp. 237–264, Springer-Verlag, New York, 1975.

MacDonald, R. C., and R. Fall, Detection of substantial emissions of methanol from plants to the atmosphere, *Atmos. Environ., Part A, 27*, 1709–1713, 1993.

Marshall, J. D., and R. H. Waring, Comparison of methods of estimating leaf area index in old growth Douglas fir, *Ecology, 67*, 975–979, 1986.

Minckler, L. S., and S. F. Gingrich, Relation of crown width to tree diameter in some upland hardwood stands of southern Illinois, *Res. Note NC-99*, 4 pp., Forest Serv., Dep. of Agric., North Central Forest Exp. Stn., St. Paul, Minn., 1970.

Monk, C. D., G. I. Child, and S. A. Nicholson, Biomass, litter, and leaf surface area estimates of an oak-hickory forest, *Oikos, 21*, 138–141, 1970.

National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, 489 pp., National Academy Press, Washington, D. C., 1991.

Olson, R., C. Emerson, and M. Nunsgesser, Geoecology: A county-level environmental data base for the conterminous United States, *Rep. ORNL/TM-7351*, Oak Ridge Natl. Lab., Oak Ridge, Tenn., 1980.

Pierce, T., B. Lamb, and A. van Meter, Development of a biogenic emissions inventory system for regional scale air pollution models, paper presented at Proceedings of the 83rd Air and Waste Management Association Annual Meeting, Air and Waste Manage. Assoc., Pittsburgh, Penn., 1990.

Rasmussen, R., What do the hydrocarbons from trees contribute to air pollution?, *J. Air Pollut. Control Assoc., 22*, 537–543, 1972.

Satoo, T., Notes on Kittredge's method of estimation of amount of leaves of forest stand, *Jpn. J. For., 44*, 267–272, 1962.

Sharkey, T. D., P. J. Vanderveer, and F. Loreto, Biogenic hydrocarbons: Measurements on corn and kudzu in 1992, paper presented at Emission Inventory Issues in the 1990s, Air and Waste Manage. Assoc., Durham, N. C., 1992.

Sollins, P., D. E. Reichle, and J. S. Olson, Organic matter budget and model for a southern Appalachian liriodendron forest, Ph.D. thesis, Univ. of Tenn., Knoxville, 1973.

Sprugel, D. G., Density, biomass, productivity, and nutrient cycling changes during stand development in wave-regenerated balsam fir forests, *Ecol. Monogr., 54*, 165–186, 1984.

Teskey, R. O., B. C. Bongarten, B. M. Cregg, P. M. Daugherty, and T. C. Hennessey, Physiology and genetics of tree growth response to moisture and temperature stress: An examination of the

characteristics of loblolly pine (Pinus taeda L.), *Tree Physiol.*, *3*, 41–61, 1987.

Tingey, D. T., M. Manning, L. C. Grothaus, and W. F. Burns, The influence of light and temperature on isoprene emission rates from live oak, *Physiol. Plant.*, *47*, 112–118, 1979.

Tingey, D. T., M. Manning, L. C. Grothaus, and W. F. Burns, Influence of light and temperature on monoterpene emission rates from slash pine, *Plant Physiol.*, *65*, 797–801, 1980.

Vose, J. M., and W. T. Swank, Assessing seasonal leaf area dynamics and vertical leaf area distributions in eastern white pine (Pinus strobus L.) with a portable light meter, *Tree Physiol.*, *7*, 125–134, 1990.

Wells, C. G., Methods of estimating foliar biomass, in *Atmospheric Biogenic Hydrocarbons*, vol. 1, pp. 107–119, Ann Arbor Science, Ann Arbor, Mich., 1981.

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