5.0 REMOTE SENSING APPLICATIONS FOR BIOMASS IDENTIFICATION AND QUANTITATIVE ESTIMATION

5.1 Introduction

The purpose of this chapter is to review the principles, technologies, recent applications and directions of development of remote sensing methods, with emphasis on past and potential future uses of remote sensing for development of biogenic emission inventories.

Information is drawn primarily from literature published between 1990 and 1995. More than 1,550 references were surveyed, gathered from a computer literature search of 6500 journals. About 45 of those references deemed most applicable to the subject of biogenic emissions inventory development were gathered. In addition, individuals currently working in the area of biomass inventories were consulted. To facilitate further reading, the primary literature is extensively cited in the following discussion.

5.2 Background

Remote sensing encompasses a variety of technologies. Photography is the historic basis for much of remote sensing, but newer technology has been developed which measures reflectance from plant surfaces electronically. The range of measurable electromagnetic frequencies has been extended through the development of advanced instruments. Rapid development of instruments continues as does development of data manipulation techniques coupled with geographic information systems (GIS) databases (Figure 5-1).

Mission to Planet Earth is the name given to the international effort to elucidate factors which affect the total earth system (Wickland, 1991). The name reflects the satellite remote sensing emphasis of the several projects which are included in the Mission to Planet Earth. The three parts of the Mission are: 1) a series of satellites is to be launched in the mid-1990's for specific measurements; 2) a series of platforms housing an instrument package is to be launched in the late 1990's, called the Earth Observing System (EOS) and; 3) a series of geostationary platforms carrying advanced instruments

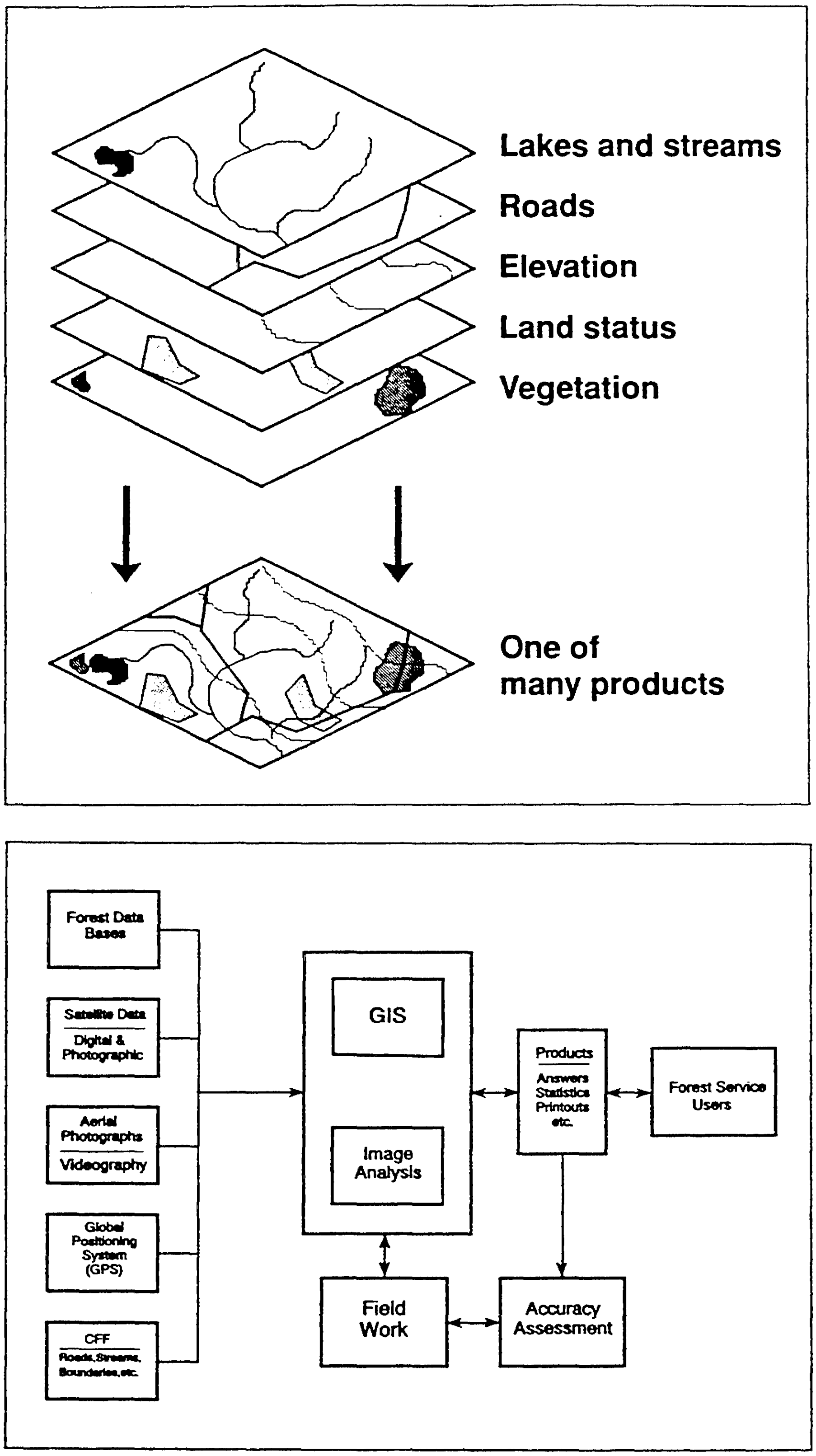


Figure 5-1. An example of the process of acquisition of remote sensing through analysis to a final product. Use of remote sensing by the US Forest Service (Lachowski *et al.*, 1992).

is to be launched beginning in the next century, called the Geostationary Earth Observing System (GEOS). Relatively rapid advances in instrumentation and concomitant data processing are now being spurred by plans for these projects. Contemporary budgetary considerations are likely to affect the timetable and other specifics of the Mission to Planet Earth.

One appealing aspect of remote sensing is the ability to gather data over large areas at low cost per unit area (Table 5-1). However, cost estimates must account for the time and money expended in bringing new technology through the development phase to a status of utility.

When considering remote sensing capability in the context of biogenic emission inventory development, it is important to distinguish between identification of plants and measurement of plant biophysical properties. Plants are easy to identify by a trained ground observer, who uses a variety of cues to make the determination of genus and species. Leaf shape, plant form, presence of flowers, texture of leaves and branches, color of bark, time of year, and subtle differences of green leaf coloration may all enter into an identification. The human eye can distinguish among 5 million colors and 200 levels of gray (Leckie, 1990).

Remote sensing has growing applicability to plant identification, with photography-based approaches still most useful. Photography, especially at close range, captures many of the visual cues helpful in identifying plants, and aerial photo interpretation by a trained observer yields valuable information. Species identity of plants with definitive signatures can be established. Signatures refer to the set of characteristics making an object recognizable on an image or photograph (Sabins, 1987). New spectrophotometric instruments allow discrimination among certain plant species under controlled conditions; refinements may allow extension to a wider range of species under field conditions. It is possible to separate structural classes such as deciduous trees, conifers and shrubs with certain non-photographic means.

Electronic instruments are generally designed to measure only one parameter, and consequently do not return the variety of cues useful to establish plant identity. The quantitative description of an individual parameter may far surpass visual description and

Table 5-1. Costs of remote sensing data (Leckie, 1990).

Sensor and data	Cost ($/km^2)
Black and white aerial photographs[a]	
1 : 12 500	9–16
1 : 50 000	2–4
Normal colour aerial photographs[a]	
1 : 12 500	12–22
1 : 50 000	3–4
MEIS II[b]	
1-m resolution	50
5-m resolution	7
Landsat MSS (1 : 1 000 000 colour transparency)	0.004
Landsat TM (1 : 1 000 000 colour transparency)	0.01
SPOT multispectral (1 : 500 000 colour transparency)	0.26
SPOT panchromatic (1 : 500 000 black and white transparency)	0.26
Landsat MSS (CCT)[c]	0.02
Landsat TM (CCT)[d]	0.11
SPOT multispectral (CCT)[c]	0.49
SPOT panchromatic (CCT)[c]	0.59
Landsat MSS (geometrically corrected CCT)[e]	1.16
Landsat TM (geometrically corrected CCT)[f]	2.15
SPOT multispectral (geometrically corrected CCT)[g]	1.68
SPOT panchromatic (geometrically corrected CCT)[g]	1.97

NOTE: Costs for satellite data are Canada Centre for Remote Sensing May 1988 prices. CCT, computer-compatible tape.

[a]Cost of aerial photography can vary greatly depending on the location and size of the area flown. Estimates are approximate ranges, derived from cost estimates from commercial aerial surveys of varying-sized areas in different locations across Canada.

[b]Cost is a commercial estimate based on a typical forest survey of 500 000 km^2. The cost of airborne linear array imager data from a new generation of imagers such as that proposed by Till *et al.* (1987) is expected to be considerably less. A new sensor would provide 2.5-m resolution data at approximately the same cost as 5-m resolution MEIS II data, and 1-m resolution data at least several times less costly than the MEIS II sensor.

[c]Raw full-scene data.

[d]Raw full-scene data in seven bands.

[e]Precision-corrected geocoded data. The area covered by a precision geocoded Landsat MSS or TM scene is one quarter of a 1 : 250 000 scale National Topographic System (NTS) map sheet, and therefore the number of hectares covered changes with geographic location. An area of 400 000 ha is used to calculate the cost per hectare for this table.

[f]Precision-corrected geocoded data for seven bands.

[g]Precision-corrected geocoded data. The area covered is one 1 : 50 000 NTS map sheet (i.e., 1/16 of a 1 : 250 000 map sheet). An area of 100 000 ha is used for this table.

include wavelengths unavailable to the eye. Biophysical properties may be described precisely, but establishing identity of a plant may be impossible based on only one or a few parameters.

Remote sensing would be most useful in estimating biogenic emissions if emissions could be linked to biophysical properties measurable by current technology. Such properties include crown spacing and variance, crown height, green biomass, total chlorophyll concentration, foliar water content and canopy water potential (Ustin *et al.*, 1991). However, emissions rates are highly species-specific, and direct linkages apparently do not exist between emission rate and those biophysical properties, such as plant water content, plant stress and chlorophyll content, which are amenable to current remote sensing technologies. Remote sensing can, however, prove useful in estimating foliar density, shading, and temperature, properties which can affect overall emissions.

Despite the attraction of remote sensing technology and the apparent advantage of its large scale, the data needs for biogenic emissions inventory development must be emphasized when considering the potential applications of this technology. These include: plant identity, land coverage of each species, leaf mass per unit area and emission rate per unit leaf mass. To date, the capacity of remote sensing methods to furnish these data remain limited for California airsheds. Developments are rapid, however, and reassessment will be necessary within 3-5 years.

5.3 Instrumentation

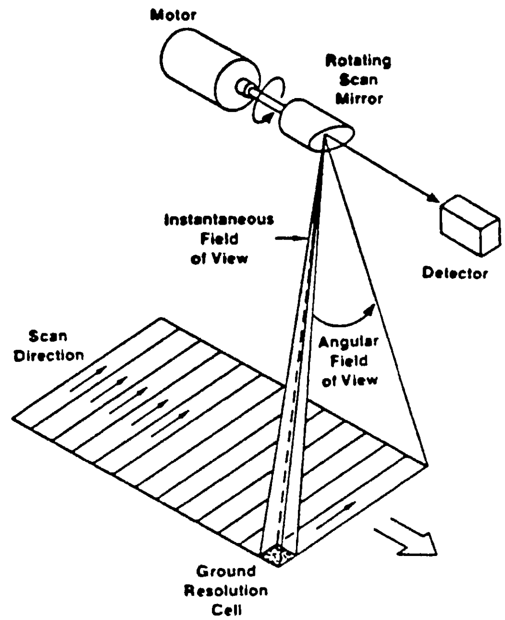
Remote sensing is based upon collection and measurement of electromagnetic radiation emanating from a surface. Broadly speaking, the wavelengths collected, the method of collection and the subsequent handling of the data define the technology. An important resulting factor is the minimum size of spatial resolution, which is defined as the ability to separate closely spaced objects on an image (Sabins, 1987). Instruments have been designed to measure wavelengths of interest in atmospheric, oceanic and terrestrial research. Application to plant cover may be incidental, and therefore only bands containing certain wavelengths may be useful. As an example, the specifications and uses of instruments proposed for inclusion on EOS platforms have been discussed in the literature (Sellers and Schimel, 1993; Ustin *et-al.*, 1991; Wickland, 1991).

The oldest remote sensing technology is photography. Photography is based on reflected light, captured by a camera and film, which stores the data by means of a chemical process. Images may later be converted to electronic data through digital processing. Film types vary in response. For example, color film has a range of about 400 nm to 700 nm while color infrared (CIR) film is sensitive from 700 nm to 900 nm (Sabins, 1987).

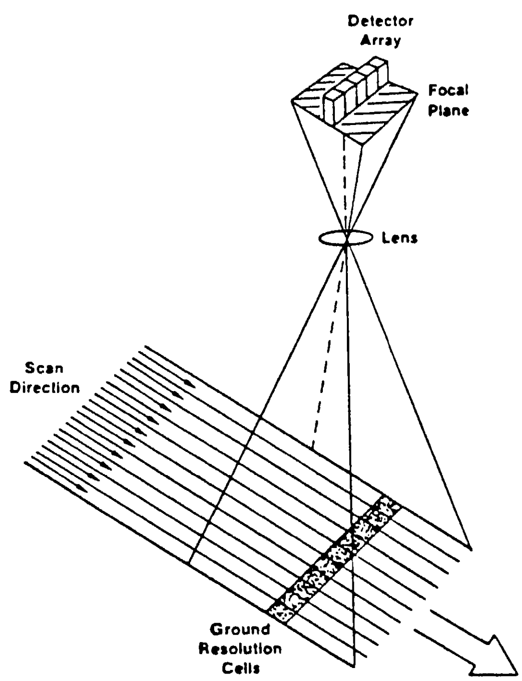
Video cameras process data electronically, usually for storage on magnetic tape. Wavelengths captured by video may be in the visible range or include portions of the infrared (IR). Video imaging from an aircraft platform can provide remote sensing data in almost real time. Video currently can have quality comparable to color photography (Marsh *et al.*, 1994).

Multispectral scanning may play a role similar to that of aerial photography (Figure 5-2). In these systems, the terrain is swept in a series of lines, with the light received recorded by electronic detectors and stored in a digital format. Multispectral scanning offers the advantage of wider spectral response and increased processing and display options compared to photography. There is, however, a tradeoff between spatial resolution and spectral resolution, with linear-array imaging spectrometers typically having a spatial resolution of 0.25-1 square meter while the resolution for normal color photography is 0.0025 square meters (Leckie 1990).

Radiometers are instruments which measure radiation over a range of wavelengths or series of wavelength bands, especially thermal radiation, while spectrometers are instruments which measure absorbed or reflected radiation as a function of wavelength (Sabins, 1987). Multispectral imagery gathers reflected sunlight in several bands, and, in applications to vegetation, is dependent on plant pigments, especially chlorophyll, cell structure, moisture content, leaf and branch orientation, and spatial distribution of vegetation components. Plant pigments strongly affect reflectance in the 400-700 nm range, while leaf mesophyll structure and cell walls affect reflectance in the 700-1300 nm IR range, and internal water in the 1300-3000 nm IR range (Leckie 1990).



CROSS–TRACK SCANNER.



ALONG–TRACK SCANNER.

Figure 5-2. Examples of two multispectral scanner designs. Detectors record specific wavebands for each picture element (Sabins, 1987).

Band ratios or combinations can be used to derive information about vegetation identity or status. Advances have been made in reducing bandwidths, thereby improving discrimination. Radar is an active sensor, unlike the previously discussed passive sensors. Radar emits microwave radiation in several regions and measures the strength of the return signal. Different wavelengths may be employed depending on the desired result; materials vary in reflectance of given wavelengths. Radar reflection changes with both wavelength and angle of incidence. The bands commonly used in remote sensing are usually described by letters: Ka (0.8-1.1 cm), X (2.4-3.8 cm), and L (15.0-30.0 cm) (Sabins, 1987). In forests, longer wavelengths penetrate more deeply into tree canopies. The returning signal strength is dependent upon canopy surface structure, shape, size and orientation of the woody and leafy parts of the tree, and dielectric properties of the components, on which water content is influential. The utility of radar for mapping vegetation has not been fully explored, but presently radar is probably best utilized in combination with other remote sensing methods (Leckie 1990).

Lidar systems emit a laser pulse and record the amplitude of the return pulse in time. Lidar can be used to measure the height of tree canopies from aircraft by comparing the return from the top of the canopy to the return from the ground (Figure 5-3).

5.3.1 Specific Instruments

LANDSAT MSS

The Landsat Multispectral Scanner is a satellite-based instrument which measures reflectance in four bands. A summary of Landsat and Spot sensitivity is presented in Figure 5-4 and Table 5-2.

LANDSAT TM

The Landsat Thematic Mapper was designed to measure wavelengths reflected by vegetation. It gathers data in seven bands. Ground resolution is 30 m for bands 1-5 and 7, and 120 meters for band 6 (Sabins, 1987).

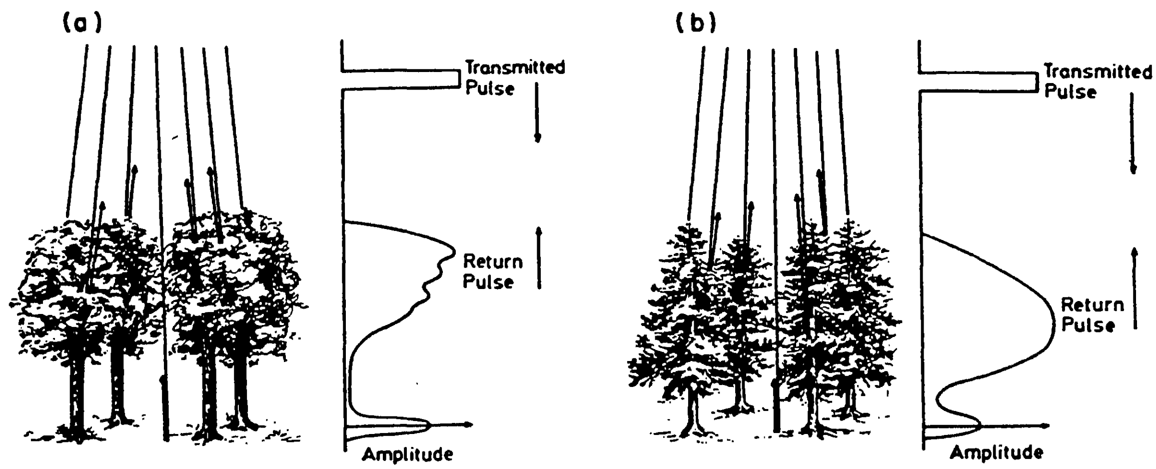


Figure 5-3. LIDAR imaging for determination of forest cover. LIDAR returns are shown for (a) hardwoods and (b) softwoods (from Leckie, 1990).

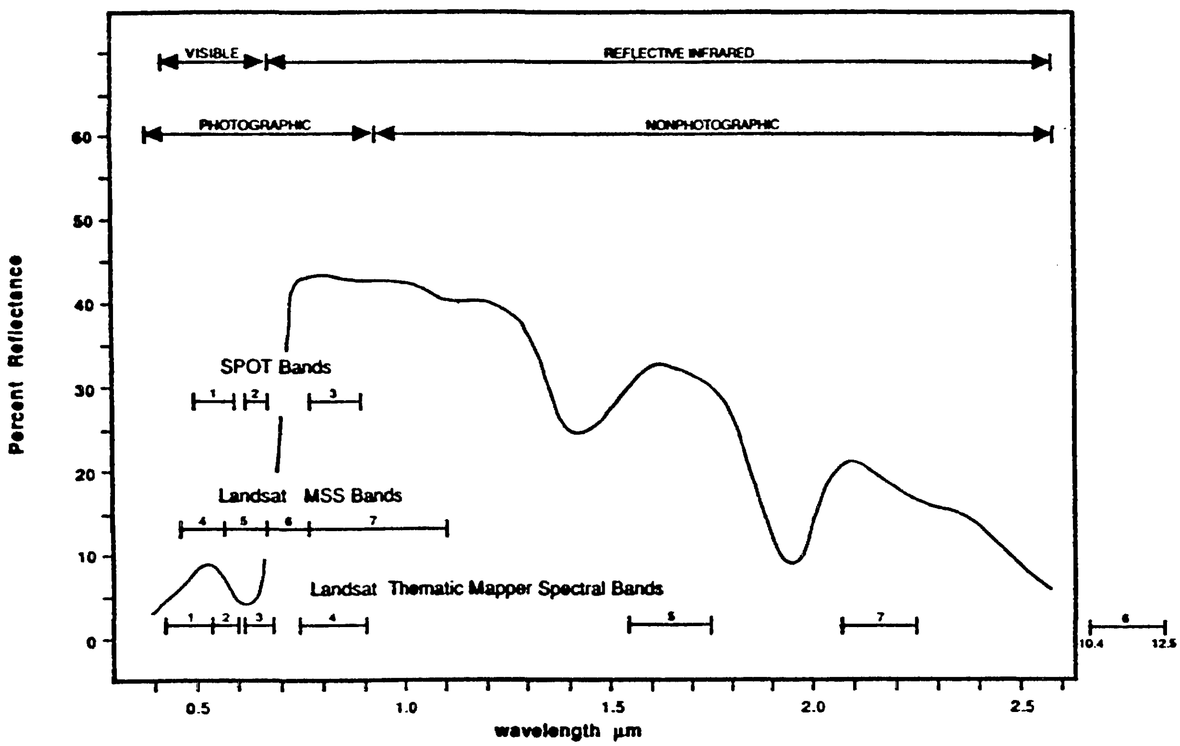


Figure 5-4. Wavelengths reflected from green plants in the visible and infrared regions, photographic and nonphotographic wavelengths are shown with Landsat TM, Landsat MSS and SPOT wavebands (Tueller, 1989).

Table 5-2. Landsat and SPOT spectral bands and corresponding characteristics of vegetation (data from Sabins, 1987; Leckie, 1990; Backhaus, 1989).

Band	Bandwidth (nm)	Spectral Feature and Utility
Landsat TM 1	450-520	absorption by leaf pigments (chlorophyll, xanthophyll, carotene).
Landsat TM 2	520-600	maximum of visible reflection of mature green leaves.
Landsat MSS 4	500-600	similar to Landsat TM 2.
SPOT MSS 1	500-590	similar to Landsat TM 2.
Landsat TM 3	630-690	absorption of chlorophyll, various reflection properties of growing or discolored leaves.
Landsat MSS 5	600-700	similar to Landsat TM 3.
SPOT MSS 2	610-680	similar to Landsat TM 3.
Landsat MSS 6	700-800	maximum of near IR reflection; reflection depends on leaf mass, plant morphology and structure.
Landsat TM 4	760-900	similar to Landsat MSS 6.
SPOT MSS 3	790-890	similar to Landsat MSS 6.
Landsat MSS 7	800-1100	similar to Landsat MSS 6.
Landsat TM 5	1550-1750	sensitive to water content of leaves and soil.
Landsat TM 7	2080-2350	similar to TM 5
Landsat TM 6	10400-12500	thermal infrared, sensitive to temperature of surfaces.

SPOT

The French SPOT satellite gathers data in three bands. Ground resolution is 20 meters in the multispectral mode (Sabins, 1987).

AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) is operative on National Oceanic and Atmospheric Administration (NOAA) weather satellites (Table 5-3). AVHRR collects reflected wavelengths in 5 bands with a ground resolution of 1.1 km. AVHRR can be used to estimate vegetative cover by comparing the red, band 1 (580-680 nm) and near-infrared, band 2 (720-1100) in a ratio, known as the normalized difference vegetation index (NDVI), calculated as (band 2-band 1)/(band 2+band 1). NDVI is also thought of as an index of "greenness." The utility of the NDVI arises in part from the normalization included in its definition. NDVI has been related to canopy photosynthesis and to primary productivity over a growing season (Kaufman and Tanré, 1992).

The value of AVHRR data arises from its daily availability, allowing comparisons to be made over time. Land cover types can then be identified by their phenology, but cover types with similar phenologies are not separable (Backhaus, *et al.*, 1989; Sabins, 1987; Townshend *et al.*, 1991). Phenology refers to the development of a crop, or plant species, as influenced by climate and weather. Plants exhibit different appearances and different spectral characteristics as they move from vegetative through fruiting stages, and then, for deciduous species, through senescence and leaf drop.

MODIS

The satellite-based Moderate Resolution Imaging Spectrometer (MODIS) is perhaps the sensor with greatest potential for monitoring global land cover (Townshend et al., 1991; Wickland, 1991). Plans call for its inclusion in the first EOS series of platforms. Two versions of the sensor will exist, the MODIS-N (nadir-pointing) and MODIS-T (tilting). The MODIS-N sensor has 19 bands in the reflective part of the spectrum with 7 designed for land cover applications. Five of the 7 bands are based on experience derived from the Landsat TM, with bandwidths more carefully chosen to

Table 5-3. Principal sensor characteristics of MODIS and AVHRR pertaining to land cover classification (Townshend *et al.*, 1991).

	AVHRR	*MODIS-N*		*MODIS-T*
		Center	*Bandwidth*	
Spectral bands for land cover applications	580–680 nm	470 nm	20 nm	32 bands
	725–1100 nm	555 nm	20 nm	(400–880 nm[b])
	1580–1750 nm[a]	659 nm	20 nm	
		865 nm	40 nm	
		1240 nm	20 nm	
		1640 nm	20 nm	
		2130 nm	50 nm	
	3 thermal bands	9 thermal bands		
IFOV (nadir)	1.1 km	500 m 250 m (659 and 865 nm)		1.1 km
Swath width	2700 km	2330 km		1500 km
Calibration	absent	lunar		lunar and solar
Radiometric quantization	10 bit[c]	12 bit		12 bit
Global frequency	1–2 days	1–2 days		2 days
View angle	55.4°	55°		45°
Tilt capability	none	none		±50°

[a]Proposed future spectral band.
[b]Bands selected primarily for ocean color purposes, but also of potential value for sensing soil and vegetation.
[c]Plans exist to increase the quantization to 12 bits from NOAA-K onwards.

minimize atmospheric effects and solar absorption (Fraunhofer lines). Bandwidth is 20-50 nm. The IR band at 1640 nm is expected to be of greatest utility because of its sensitivity to foliar water content, especially when combined in a ratio with the band centered at 1240 nm. It is possible to derive other band combinations. An atmospherically resistant vegetation index (ARVI) can be determined from MODIS data, and the same index used with Landsat and HIRIS data. ARVI will have the same sensitivity as the NDVI but will be four times less sensitive to atmospheric effects (Kaufman and Tanré, 1992). MODIS will have onboard calibration for all channels (Table 5-4).

HIRIS

The High Resolution Imaging Spectrometer (HIRIS) is an advanced instrument planned for inclusion on later EOS platforms (Wickland, 1991). It will measure the radiance from earth's surface from 400 nm to 2450 nm in 192 10 nm bands. Resolution will be 30 m. Improved classification of land cover types or communities may be possible with HIRIS data.

ASTER

The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) will be an instrument designed to gather information in the thermal infrared portion of the spectrum with spatial resolution as high as 15 m in certain bands (Wickland, 1991). Application to plants will be measurement of surface temperatures, which can be used to model evapotranspiration. ASTER is to be included on early EOS platforms.

AVIRIS

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) measures reflectance in the 400-2500 nm region in 224 bands, each with a bandwidth of 9.6 nm. From an altitude of 20 km (65,000 ft), the pixel size is 20 m and the swath width 12 km (Gao and Goetz, 1994).

Table 5-4. MODIS bands with attendant utility (Townshend *et al.*, 1991).

470 nm	detection of changes in chlorophyll/carotenoid ratios indicative of plant stress
550 nm	reflectance peak controlled by the presence of chlorophyll (Tucker, 1980)
659 nm	absorption by chlorophyll as well as tannin and anthocyanin
865 nm	related to physical structure of mesophyll layer
1240 nm	reflectance feature related to discrimination of forest types (Cox, 1983; Rock, 1982)
1640 nm	absorption due to leaf moisture content (Cox, 1983)
2130 nm	absorption due to leaf moisture content (Cox, 1983), foliar nitrogen and protein absorption (Petersen *et al.*, 1985)
	Band Combinations
659 nm and 865 nm	can be used in various combinations to derive vegetation indice such as the NDVI (Tucker, 1980; Running, 1990) useful for estimating absorbed photosynthetically active radiation (Sellers, 1985)
1240 nm and 1640 nm	can be used in to estimate leaf moisture content (Cox, 1983)

RADAR

Side Looking Airborne Radar (SLAR) radars can monitor soil moisture and are especially useful for land form definition. Spatial resolution of radar is proportional to radar wavelength divided by physical length of the antenna; in Synthetic Aperture Radar (SAR) the return signal is processed to simulate the signals received by a large antenna (Tueller, 1989).

5.3.2 Other Satellite- or Aircraft-Based Instruments

The Scanning Multifrequency Microwave Radiometer sensor (SMMR) gathered microwave data while the Coastal Zone Color Scanner (CZCS) gathered data over shortwave visible bands. However, data are no longer being acquired from either instrument. (Townshend *et al.*, 1991).

TIMS refers to the Thermal Infrared Multispectral Scanner, which has 6 bands in the 8200-11,700 nm range. The Airborne Imaging Spectrometer (AIS) has 128 bands from 1200-2400 nm, and Great Basin sagebrush communities had distinguishable spectral curves as measured by AIS (Tueller 1989).

5.3.3 Other Ground-Based Instruments

The Visible Infrared Reflectance Absorptance Fluorescence (VIRAF) spectrometer is an instrument for ground-truthing of remote sensing of terrestrial vegetation. The instrument takes spectra of reflectance, absorbance and fluorescence in the visible and near-infrared regions, 400-910 nm. Spectra of a wildtype tobacco plant, *Nicotiana tabacum* L., were distinctly different than those of an Aurea mutant when measured by this instrument (Buschmann *et al.*, 1994).

The Geophysical Environmental Research Inc. field spectroratiometer has 512 spectral bands between 400 and 2500 nm. Spectral resolution is about 4 nm in the visible and 10 nm in the IR. The Barringer hand-held ratioing ratiometer (HHRR) holds ten filters which can range from a bandwidth of 3 nm to Landsat Multispectral Scanner or Thematic Mapper bands, useful for obtaining response to mimic MSS or TM imagery (Milton and Mouat, 1989).

5.4 Current Utilization of Remote Sensing

The studies of Winer and co-workers (Winer *et al.*, 1983; Brown and Winer, 1986) and Horie and co-workers (Horie *et al.*, 1991) for the SoCAB and Sidawi and Horie (1991) for the SJVAB each had a remote sensing component, CIR photography, used to identify plant structural classes. The work of Tanner *et al.* (1991) for the SJVAB was based on Landsat imagery and data manipulation with GIS.

Remote sensing using aerial photography is the primary source for forest inventory in Canada. The US Forest Service (USFS) is presently acquiring GIS capability, which will move it from a paper map to a digital environment. Lachowski and co-workers from the USFS (1992) stated that satellite imagery was inadequate for many applications. Aerial photography and airborne video have been used much more extensively. Developments in technology may render satellite data more useful.

These sophisticated new technologies require a strong technological infrastructure, attended by large development costs. However, new remote sensing technologies are compatible with GIS, and the pace of improvement in sensor development and data processing is rapid (Leckie, 1990).

5.5 Plant Identification

5.5.1 Plant Identification Based On Photographic Or Video Signatures

Certain plants have a characteristic appearance when photographed in the visible or IR range, making them easily distinguishable from surrounding vegetation. A plant species may be especially recognizable if its phenology, and attendant signature, differ from surrounding vegetation.

Pricklypear, *Opuntia lindheimeri*, is an undesirable shrub on rangelands in the southwestern U.S. Pricklypear was clearly distinguished from surrounding vegetation using airborne video sensitive in the 1450-2000 nm range (Everitt *et al.*, 1991). Water in plant leaves absorbs strongly in that region. The wavelength band centered at 650 nm (visible) was not useful, except during winter, because surrounding vegetation had similar greenness. The band from 800-850 (IR) was not useful for a similar reason. The best time of year for discrimination was January-February, when most surrounding vegetation had no leaves.

A similar situation made it possible to identify Big Bend Loco and Wooten Loco, weeds of southwest U.S. rangelands (Everitt *et al.*, 1994). The high near-IR (760-900 nm) reflectance made these species easy to identify on color IR photographs. Big Bend Loco could also be distinguished on CIR and near-IR black and white video imagery. However, another plant, Spanish dagger, *Yucca treculeana* Carr., had similar reflectance to Wooten Loco on CIR photographs. Because Spanish dagger occurred infrequently, identification of Wooten Loco was not confounded.

It was possible to distinguish shin oak, *Quercus havardii,* from surrounding vegetation by using remote sensing (Everitt *et al.*, 1993). Shin oak had low reflectance in both the 630-690 nm and 760-900 nm regions, a characteristic not shared by associated vegetation. The study compared CIR, video imagery and SPOT satellite imagery. The best time of year to distinguish shin oak was June-September, which was the mature phenological stage. Computer classification of video and satellite images gave coverage estimates similar to those of photointerpreters.

Chinese tamarisk, *Tamarix chinensis*, is a non-native woody plant which invades riparian areas of the Southwest. Leaves of this tamarisk turn yellow-orange to orange-brown prior to leaf drop, unlike leaves of surrounding vegetation. This characteristic was used to distinguish Chinese tamarisk from associated plants with color and CIR photography. The plant did not differ in reflectance at other times of year from surrounding vegetation (Everitt and Deloach, 1990).

It was possible to identify genus and species of surface aquatic vegetation in a Swedish study (Andersson, 1990). Lakes were overflown and CIR images gathered. CIR photography was compared to data gathered by an aircraft-borne multispectral scanner and from Landsat. CIR photography was more useful than the latter in differentiating aquatic communities.

5.5.2 Plant Identification Based on Spectral Signatures: Capabilities

Spectral reflectance of different wave bands can be used to distinguish among plants. A number of factors affect reflectance from leaves, including pigment concentration, internal leaf structure, leaf water content, leaf age, pubescence and whether the leaf has been growing in sun or shade. Various stresses also affect leaf reflectance, because stresses such as salinity, drought, temperature and nutrient deficiency affect leaf morphology and pigment concentrations (Figures 5-5, 5-6, 5-7) (Gausman, 1985).

One approach has been to compare reflectance among several plant species to each wave band followed by statistical analysis to note where reflectance measurements differ, thus identifying which wave bands are needed for discrimination (Brown *et al.*, 1994). This method appeared to be effective for separation of seven weed species, including two grass species, and corn, which is also member of the grass family. Duncan's multiple range test was used to separate the mean reflectance values. Four bands, three in the visible and one in the near-IR, were found useful.

Five ecological states of a forested ecosystem in northern Minnesota (clearings, regeneration, deciduous, deciduous/conifer and conifer) had distinctive spectral signatures as measured by Landsat imagery. Spectral signatures were found to differ as a result of species differences in leaf optical properties and morphology, amount of crown closure and differences in understory leaves where canopies were open (Hall *et al.*, 1991).

Changes in vegetation may be ascertained by using reflectance in Landsat TM bands, which may be used singly or in combination. In a study of Portland area vegetation, a difference file was created by subtracting Band 7 values of one date from another (Green *et al.*, 1994). A second difference file was created by subtracting a vegetation index of Band 3/Band 4. This vegetation index is the inverse of a typical vegetation index of Band 4/Band 3. It was possible to identify areas which had lost or gained vegetation within a range of ± 30%.

Plant stress can be detected by remote sensing techniques. Chlorosis, that is yellowing of leaves, is easily recognizable. Chlorosis serves as an indicator of soil composition, specifically nutrient deficiencies or presence of toxic concentrations of

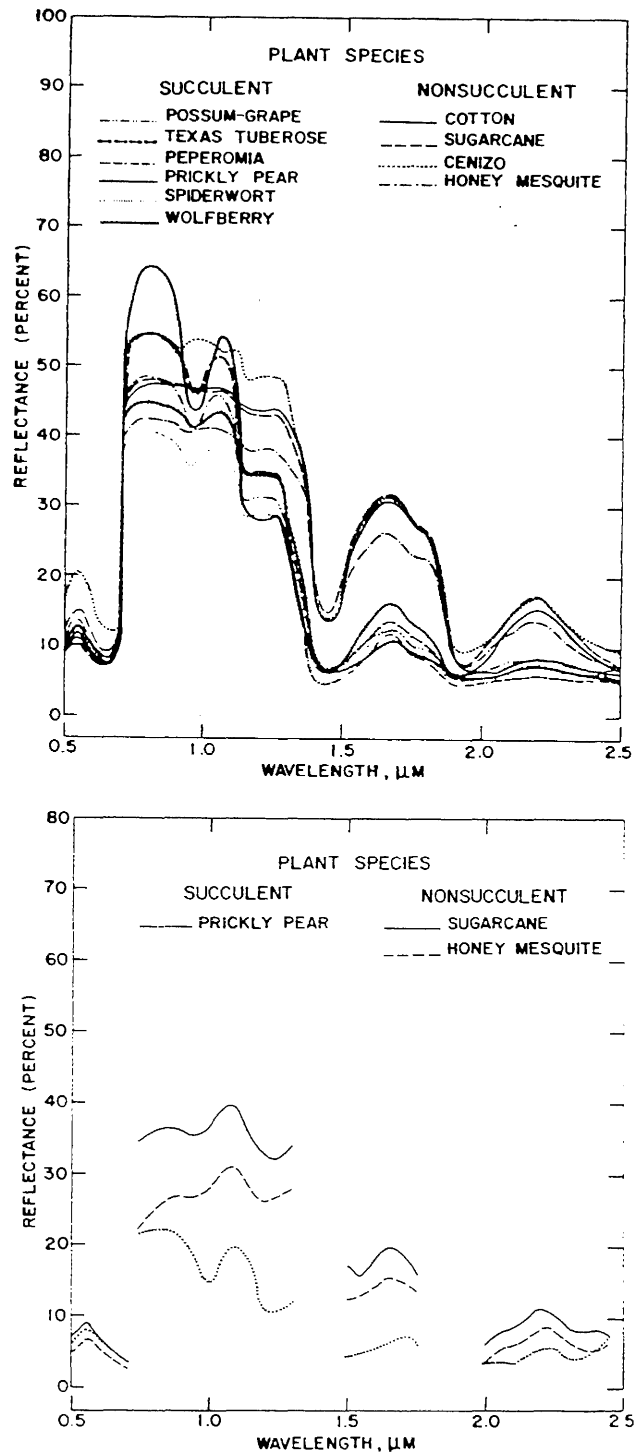


Figure 5-5. Reflectance from several plant species illustrating differences over visible and IR wavelengths from 500-2500 nm: (A) laboratory analysis of leaves from six succulent and four non-succulent plant species, and (B) field analysis of succulent prickly pear and non-succulent sugarcane and honey mesquite plant canopies (Gausman, 1985).

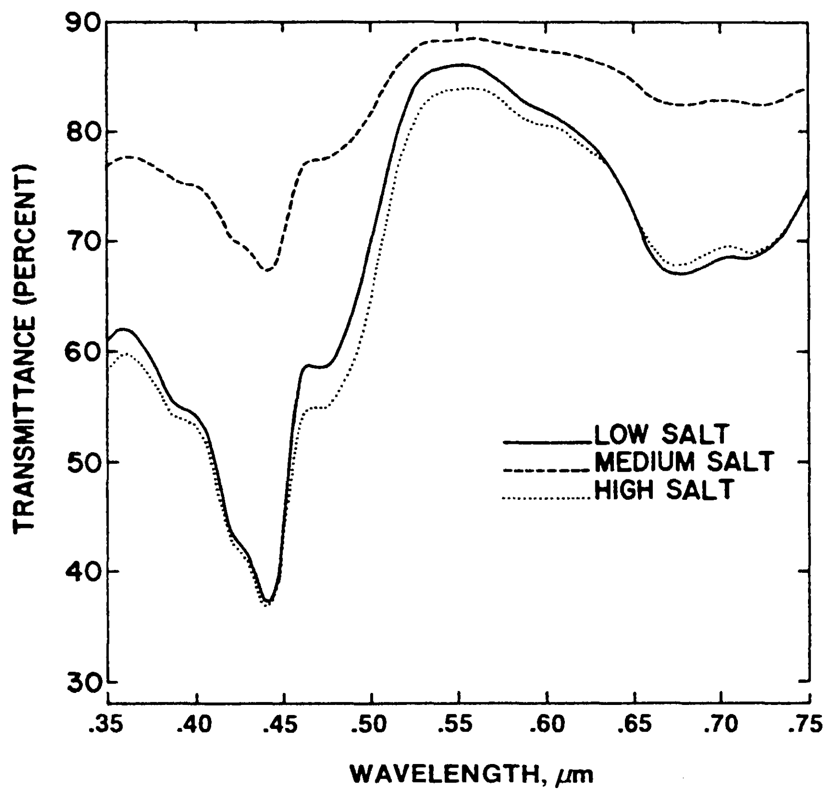


Figure 5-6. Effect of salinity on leaf reflectance of cotton (Gausman, 1985).

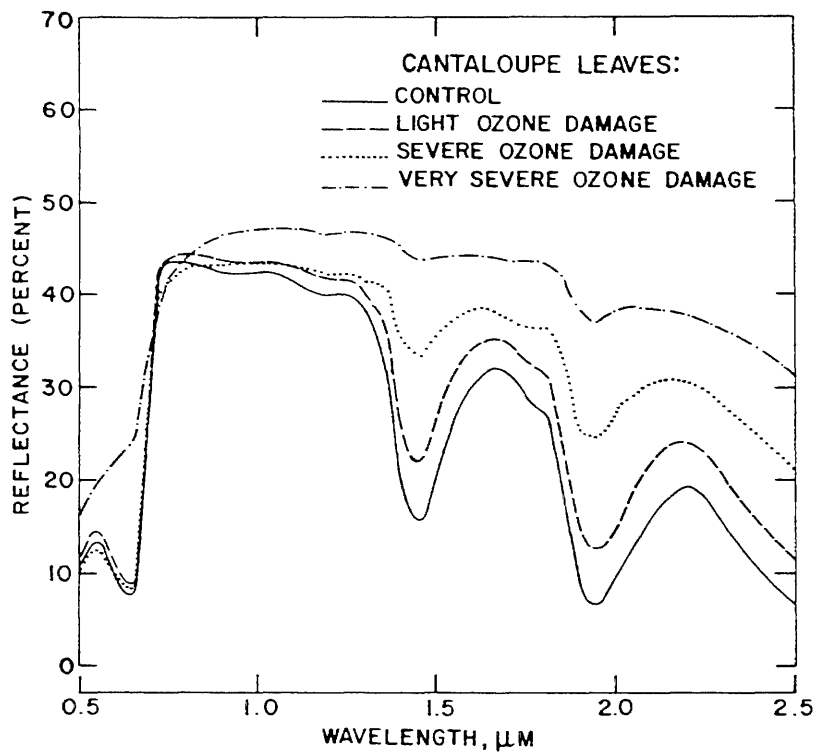


Figure 5-7. Effect of ozone on reflectance of cantaloupe leaves (Gausman, 1985).

elements. Nutrient status may in turn be an indicator of underlying parent material, and geomorphology (Milton and Mouat, 1989).

5.5.3 Plant Identification Based on Spectral Signatures: Limitations

Plants share many similarities in reflected wavelengths of visible, IR and microwave radiation which do not enhance discrimination among species. Similarities in absorption and reflection may overwhelm differences discernible by current instrumentation.

Similarities may be due to shared chemical composition of plants; leaves of different species have many compounds in common. Absorption by chlorophyll, water, cellulose, lignin and starch dominate the region between 400 nm and 2400 nm. In one study (Gao and Goetz, 1994), all leaf spectra examined contained strong absorption features near 1720 nm. Reflectance in the 1400-2500 nm region from vegetation was due to liquid water in the leaf tissues and dry material, such as lignin and cellulose. The shapes of absorption features for different types of leaves were slightly different. Water rather than dry matter was dominant in determining the reflectance over the range of wavelengths studied; reflectance of water alone could mimic that of vegetation. A golf course and pine trees shared features of strong water absorbance, and corresponding weak reflectance, at 940 nm, 1140 nm, 1380 nm and 1880 nm, in the data gathered by AVIRIS (Figure 5-8).

In a study by Curran (1989) spectroscopic measurements of dry leaves revealed 42 minor absorption features, many linked to O-H, N-H, and C-O stretches. Those bonds are found in components shared by many plants: starches, proteins, cellulose and lignin (Table 5-5). It is not possible to link the concentration of most plant components with a single wavelength; rather, a combination of wavelengths is used for determination of concentration. Protein, lignin and starch concentrations of dried plant materials are routinely determined by spectroscopic analysis, which gives results of precision comparable to wet chemical methods.

In addition to spectral similarities, confounding factors include the large variation of reflectance due to angle of illumination, and variability among trees of the same

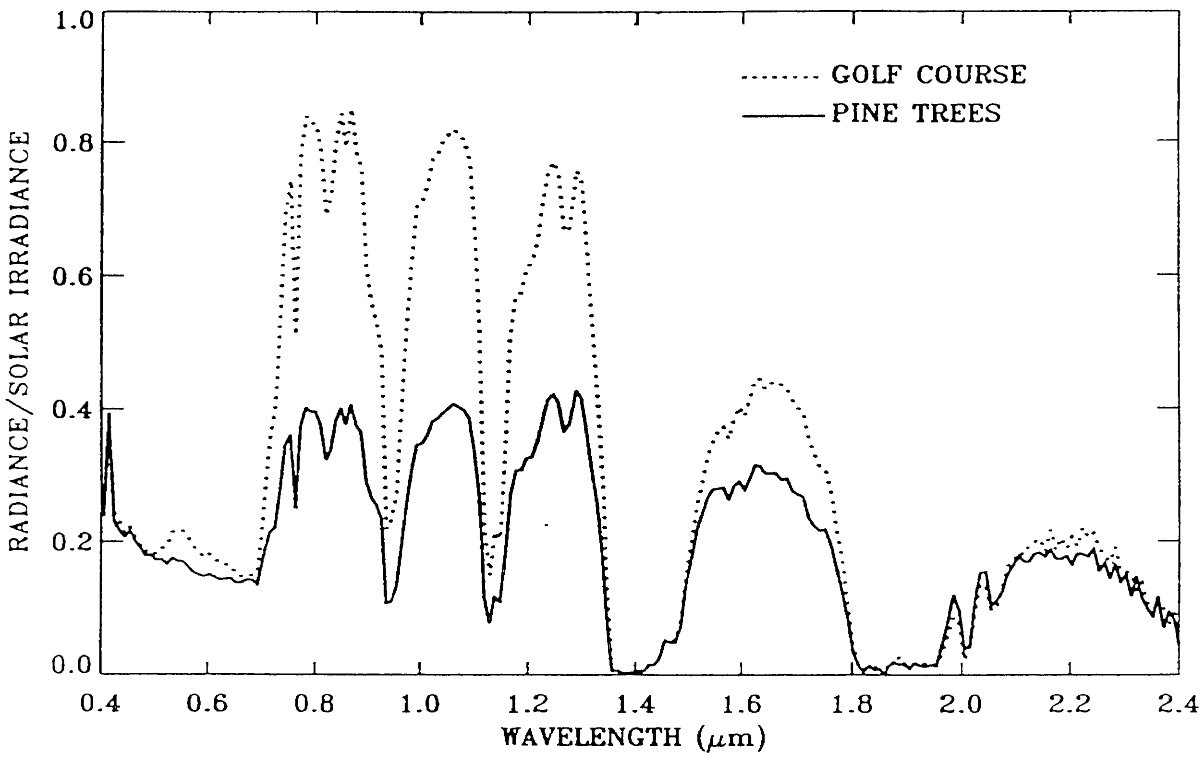


Figure 5-8. Comparison of AVIRIS data showing similar reflectance from a golf course and pine trees in Oregon. The valleys in the data represent absorption of sunlight by water (Gao and Goetz, 1994).

Table 5-5. Shared absorption features in plants related to foliar chemicals (Curran, 1989).

Wave length (μm)	Electron Transition or Bond Vibration	Chemical(s)	Remote Sensing Considerations
0.43	Electron transition	Chlorophyll a[a]	Atmospheric scattering
0.46	Electron transition	Chlorophyll b	
0.64	Electron transition	Chlorophyll b	
0.66	Electron transition	Chlorophyll a	
0.91	C—H stretch, 3rd overtone	Protein	
0.93	C—H stretch, 3rd overtone	Oil	
0.97	O—H bend, 1st overtone	Water, starch	
0.99	O—H stretch, 2nd overtone	Starch	
1.02	N—H stretch	Protein	
1.04	C—H stretch, C—H deformation	Oil	
1.12	C—H stretch, 2nd overtone	Lignin	
1.20	O—H bend, 1st overtone	Water, cellulose, starch, lignin	
1.40	O—H bend, 1st overtone	Water	
1.42	C—H stretch, C—H deformation	Lignin	
1.45	O—H stretch, 1st overtone, C—H stretch, C—H deformation	Starch, sugar, lignin, water	Atmospheric absorption
1.49	O—H stretch, 1st overtone	Cellulose, sugar	
1.51	N—H stretch, 1st overtone	Protein, nitrogen	
1.53	O—H stretch, 1st overtone	Starch	
1.54	O—H stretch, 1st overtone	Starch, cellulose	
1.58	O—H stretch, 1st overtone	Starch, sugar	
1.69	C—H stretch, 1st overtone	Lignin, starch, protein, nitrogen	
1.78	C—H stretch, 1st overtone/ O—H stretch/H—O—H deformation	Cellulose, sugar, starch	
1.82	O—H stretch/C—O stretch, 2nd overtone	Cellulose	
1.90	O—H stretch, C—O stretch	Starch	
1.94	O—H stretch, O—H deformation	Water, lignin, protein, nitrogen, starch, cellulose	Atmospheric absorption
1.96	O—H stretch/O—H bend	Sugar, starch	
1.98	N—H asymmetry	Protein	
2.00	O—H deformation, C—O deformation	Starch	
2.06	N=H bend, 2nd overtone/ N=H bend/N—H stretch	Protein, nitrogen	
2.08	O—H stretch/O—H deformation	Sugar, starch	
2.10	O=H bend/C—O stretch/ C—O—C stretch, 3rd overtone	Starch, cellulose	
2.13	N—H stretch	Protein	
2.18	N—H bend, 2nd overtone/ C—H stretch/C—O stretch/ C=O stretch/C—N stretch	Protein, nitrogen	
2.24	C—H stretch	Protein	Rapid decrease in signal-to-noise ratio of sensors
2.25	O—H stretch, O—H deformation	Starch	
2.27	C—H stretch/O—H stretch CH_2 bend/CH_2 stretch	Cellulose, sugar, starch	
2.28	C—H stretch/CH_2 deformation	Starch, cellulose	
2.30	N—H stretch, C=O stretch, C—H bend, 2nd overtone	Protein, nitrogen	
2.31	C—H bend, 2nd overtone	Oil	
2.32	C—H stretch/CH_2 deformation	Starch	
2.34	C—H stretch/O—H deformation/ C—H deformation/O—H stretch	Cellulose	
2.35	CH_2 bend, 2nd overtone, C—H deformation, 2nd overtone	Cellulose, protein, nitrogen	

species (Leckie 1990). Crops with similar phenology are similar in reflectance (Figure 5-9) (Fischer, 1994). Therefore, detailed description of foliar canopies is presently beyond the capability of current technology. Advances in both instrumentation and data processing are needed (Townshend *et al.*, 1991). However, the increased resolution of new instruments may lead to further difficulties in identification. This counterintuitive result occurs because microscale areas of nonuniformity of species or canopy closure of forest stands are revealed, causing difficulty in classification (Leckie 1990).

5.6 Plant Biophysical Properties

5.6.1 Radiation Bands And Plant Biophysical Properties

NDVI may be used to measure photosynthetic capacity. It was reported by Sellers as cited in Myeni *et al.* (1992), that the ratio of near-IR to red reflectance of a vegetation canopy, the NDVI, is proportional to photosynthetic capacity and stomatal conductance, when soil reflectance is low.

Moisture content of plants may be estimated by radar. Radar backscatter in the L and X bands from walnut trees revealed diurnal variation, but the pattern among wavelengths and polarization was complex. Interpretation of satellite data will require complex models which account for soil moisture status and canopy architecture (Weber and Ustin, 1991).

Several narrow band indices of spectroradiometry provided better physiological information than the NDVI (Peñuelas *et al.*, 1994). The ratio of reflectance at 550 and 530 nm was compared, (R550-R530)/(R550+R530), and followed diurnal changes in xanthophyll pigments and photosynthetic rates and nitrogen status. Other ratios followed total pigments, chlorophyll and water status.

5.6.2 NDVI and Plant Biomass

It is possible to measure areal coverage, but difficult to determine height or biomass on large-scale vertical aerial photographs (Tueller, 1989). The fraction of photosynthetic radiation absorbed by a plant canopy is a near-linear function of the NDVI in plant canopies where coverage of the ground is near 100%. In considering the

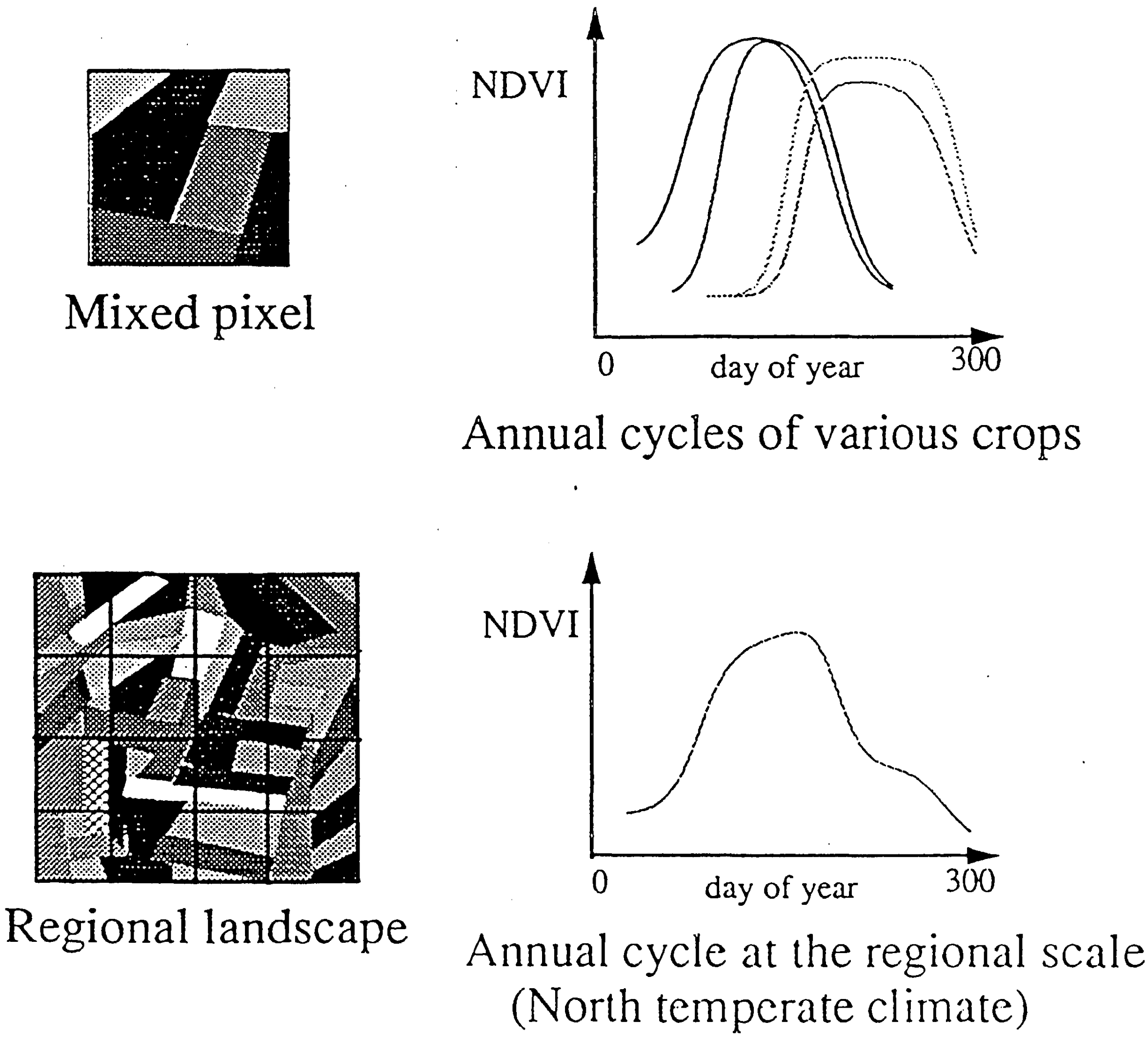


Figure 5-9. Temporal variability of the NDVI, illustrating the importance of phenology in discrimination among plant types, and the need to consider time of year in image classification (Fischer, 1994).

relationship when the ground cover was less than 100%, the pattern of leaf area distribution was found to be more of a determinant of canopy radiation than the amount of leaf area (Asrar *et al.*, 1992). Therefore, NDVI would not appear useful in gauging biomass of desert ecosystems where plants are separated by areas of bare ground. NDVI would probably not be a function of leaf area and would not be useful in plant stands of mixed composition and height where plants canopies are separated. In contrast, the NDVI was used to adjust biomass in a forest ecosystem (Cheung, 1991). Such an approach was possible because the forest stand had relatively uniform composition, and the amount of biomass was already known for reference areas.

5.7 Image Processing

Image processing involves manipulation of image data. Data from remote sensing measurements are often represented as pixels in GIS systems. Each pixel corresponds to a given amount of surface area at a specific location. Pixels with similar values for reflectance among specified wavelengths can be assigned to groups which correspond to land cover classes. The groups of pixels are referred to as spectral classes, and the land cover groups as information classes (Wang, 1990).

There are two main categories of digital image processing: image enhancement and image classification. Image enhancement is used to accentuate differences in ground composition of interest. The human eye can distinguish 5 million colors and 200 levels of gray. Enhancement also includes correction for atmospheric effects, calibration and, in some applications, transformation of digital data into false color (Leckie 1990).

Classification is the process of separation of data into homogeneous groups. In GIS mapping, picture elements (pixels) are the units classified. Image classification is either unsupervised or supervised. An unsupervised classification occurs when a computer separates data into groups based on mathematical relationships, but without a predetermined identity linked to physical or geographic features. Unsupervised classifications utilize a wide variety of mathematical methods to separate pixels into spectral classes. In most methods, each pixel is classified on the basis of its characteristics alone, rather than the context in which it is found, i.e. the properties of it neighbors.

In supervised classification, the spectral characteristics of each cover-type class are defined by statistics of pixels in a known area of that cover class, i.e. a training set. In other words, specific data are designated as representative of a group, such as coniferous forest, and data with similar characteristics are then classified as part of that group. The training sets may be identified through comparison with aerial photographs or ground observations. Another approach to identifying training sets was used in a regional forest cover study (Iverson *et al.*, 1994). TM data were used to classify a small area into forest or nonforest. That area was used as a training site for AVHRR data. Then, AVHRR data were used to estimate regional forest cover over two large regions in the eastern U.S. The regions had fragmented forest areas but uniform forest type and topography. For counties in the same ecoregion, or close to the training site, the correlation was high (r=0.96) between TM estimates and ground-based classification.

Obviously, training sets must accurately reflect characteristics of a group for accurate classification to be made, including temporal variability (Figure 5-10). In one study, classification of 900 km^2 of 1973 and 1983 Landsat images required only 1.62 km^2 of area to be examined by aerial photography or ground observations (Leckie, 1990; Hall *et al.*, 1991). In another study, unsupervised classification resulted in 83.3% accuracy (Pons and Solé-Sugrañes, 1994). Widely varying criteria have been used in classification, making it difficult to compare maps because similar, or the same, information classes may have different definitions (Townshend *et al.*, 1991).

5.7.1 Sources of Error in Image Processing

Remote sensing data are often transferred to GIS, and errors can arise during each stage of the process. Although error reduction may be focused on the method of data acquisition (Figure 5-11), the way the data are subsequently processed will also have a major impact on their ultimate utility (Figure 5-12). A common sequence is data acquisition, data processing, data analysis, data conversion, error assessment and final product presentation. Frequently absent is a quantitative description of error in the final

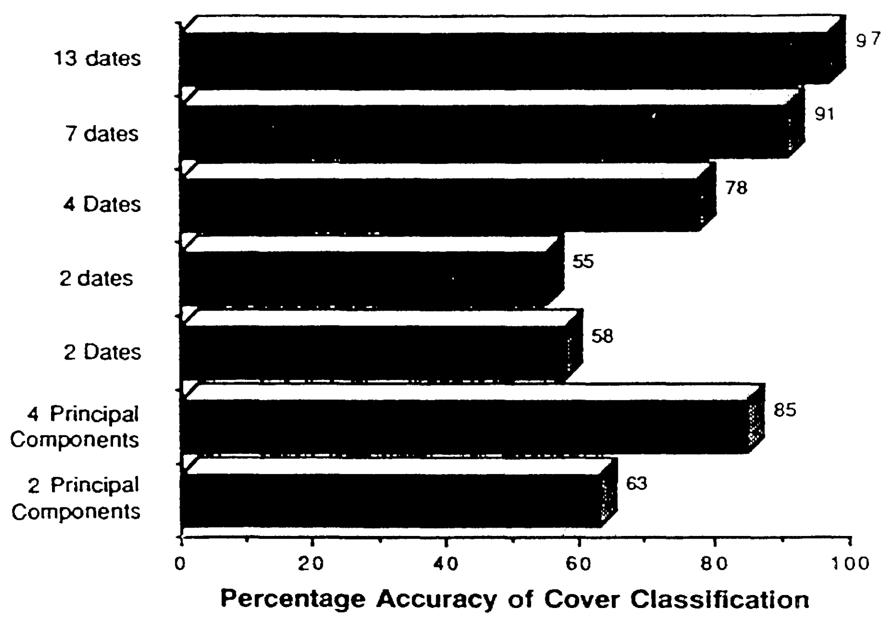


Figure 5-10. Improvement in classification accuracy of training set data depending on number of dates of imagery, or number of principal components necessary. This figure illustrates the importance of sufficient and representative data upon which to base image classification (Townshend *et al.*, 1991).

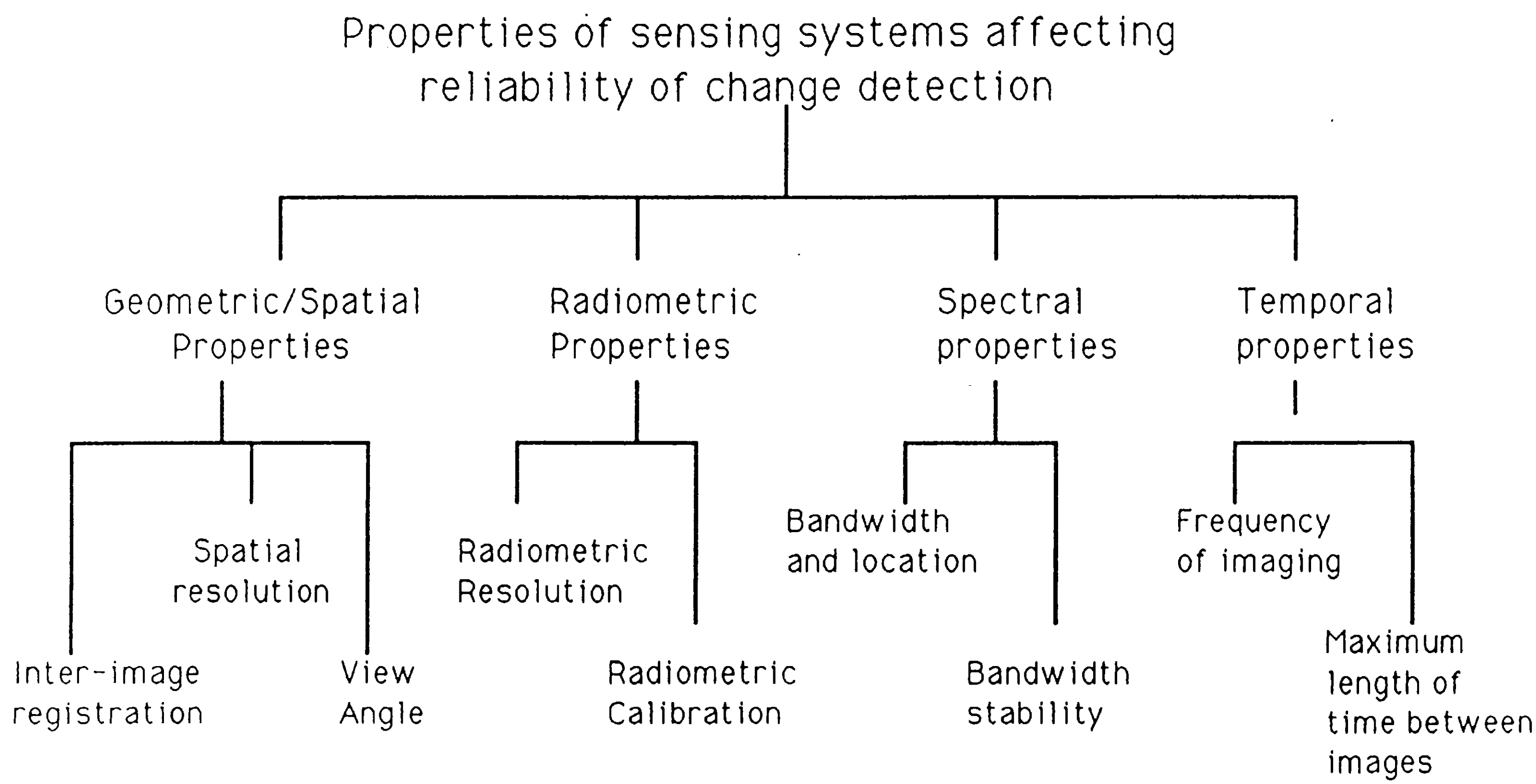


Figure 5-11. Sources of error in image acquisition (Townshend et al., 1991)

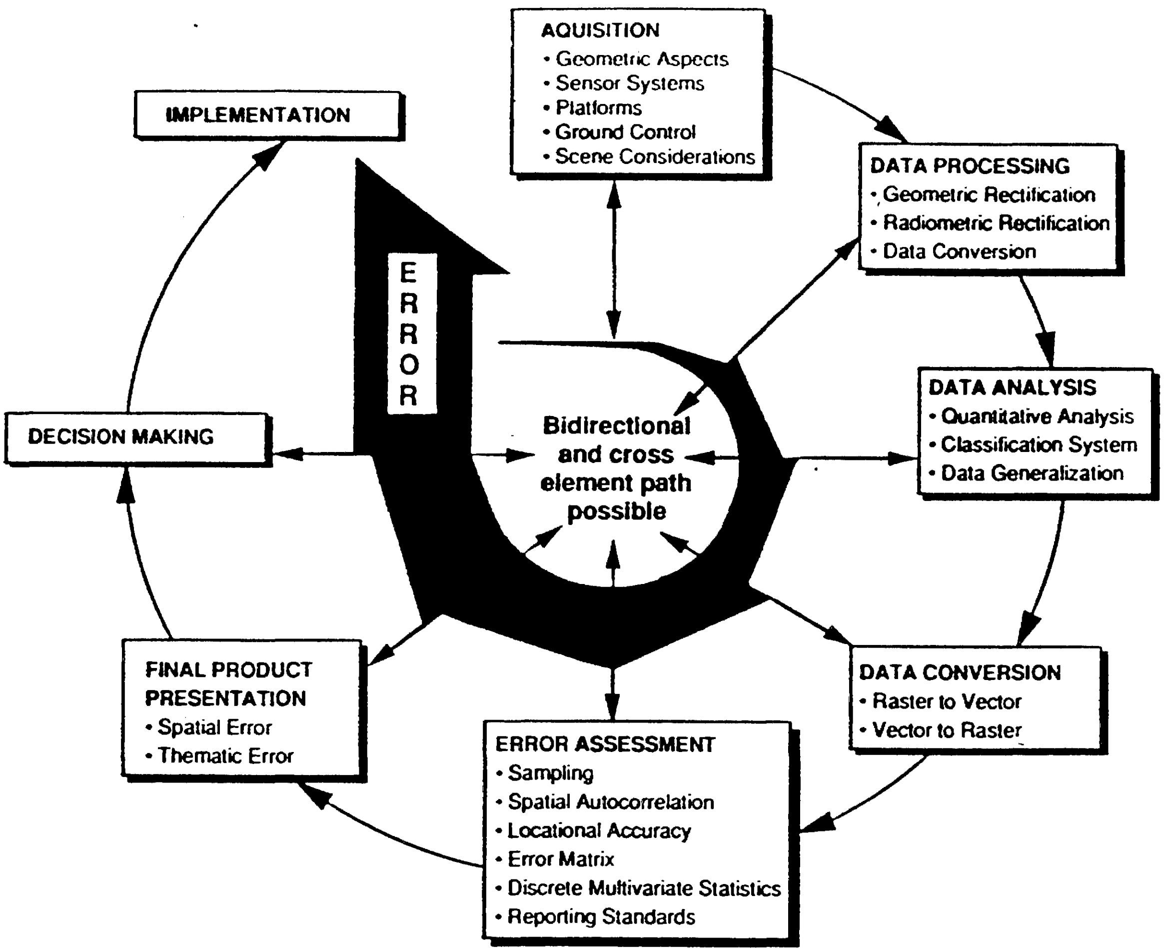


Figure 5-12. Progressive accumulation of error in remote sensing image processing (Lunetta *et al.*, 1991).

process (Lunetta *et al.*, 1991; Townshend *et al.*, 1991). According to Lunetta *et al.* (1991), "standardized procedures for establishing and reporting image geometric accuracy have not been developed by the remote sensing community."

Error originating at an early step is often carried through the process. For example, atmospheric conditions or turbulence affecting aircraft altitude may interfere with data collection and this source of error is best approached through instrumental corrections (Lunetta *et al.*, 1991). Satellite images taken at different times of day have different patterns of shadow, especially for regions of steep topography, which can mask differences in land cover. In a study by Pons and Solé-Sugrañes (1994) a radiometric correction technique removed the confounding introduced by shading and led to classification based on land cover only.

One of the major problems in interpreting satellite imagery has been identification and assignment of pixels bordering two distinct regions; a comprehensive discussion of this problem is beyond the scope of this chapter. The problem may occur in three situations: where a pixel falls in a transition zone, when a pixel has spectral similarities to two adjacent classes or where selected training areas have variations. Boundaries may change depending on pixel assignment, and where a large number of classes are present the boundary assignments may represent a significant source of error (Wang and Howarth, 1993).

Boundaries themselves may represent regions of interest, as in studies of flora or fauna which prefer the edges of a forest. Ecotones refer to transition zones between ecological systems. Raster-based GIS has provided ecotone detection and quantification in Minnesota (Johnston and Bonde, 1989). Vector-based GIS can also be used to gather ecotone information.

Error is also easily introduced when images are superimposed. Processing of multiple data layers is predicated upon congruence of each layer. Lack of spatial registration, in other words congruence, of images between different periods of time is the source of substantial error when comparing images from those periods (Townshend *et al.*, 1991).

Maps may be compared for changes in vegetation. In the past, comparisons were performed by overlaying maps on a light table. With GIS, comparisons of areas or pixel-by-pixel are possible. If images are compared to estimate changes in biomass, it is important to recognize which factors, other than changes in vegetation, can cause a difference in image properties. To be accurate, the overlay must be exact, classification must be based on the same criteria on both maps, and the techniques used to generate the map should not conflict. Data analysis must include recognition of the lifetime of the data set, especially when viewing plant communities, where coverage and spectral properties change over a growing season. Image differencing and principal components analysis are two methods used to compare maps (Green *et al.*, 1994).

Current classification allows a pixel to be assigned to only one data set which also leads to inaccuracy in two ways. First, the pixel may actually contain data which are representative of more than one set because the pixel lies in a transition zone, and two or more types of plant cover are actually present in the field. Assignment to one set presumes a sharp boundary and membership in one group only. Second, by assigning the pixel to one set and therefore ascribing to it the characteristics of the set, information is lost. Fuzzy classification, based on fuzzy set theory, is a classification technique which allows pixels to have partial membership in several classes. Conversely, classes may be composed of pixels with varying degrees of uniformity. Partial membership allows transition zones to be better represented. In conventional assignment, training sites are selected which are homogenous. With fuzzy classification, training sets may be used to generate statistical parameters for more than one class (Wang, 1990). Fuzzy classification may be quite useful in California, because of the variety of land covers and the heterogeneity of transition zones.

5.7.2 Comparison of Classification Methods

When assigning data to classes, it is important to have standardized, clearly defined classes, as well as field verification data and a mechanism to deal with boundary classification. These factors surrounding classification should be noted in final reports where GIS has been used. Also, a history describing how the final map was generated should be included. Other technical points in verifying classification accuracy, including a statistical method for quantitative error analysis are contained in the paper by Lunetta *et al.* (1991).

Statistical techniques exist to assess the classification accuracy of GIS data where different classification methods are used and results are compared to ground-truth information. Where agreement is poor, it may be from poor quality ground based information; a problem in class definition, where classes are not distinct or overlap results; or an unsuitable classifying method for the data set (Fitzgerald and Lees, 1994).

Some comparisons between computer-based classification and photointerpretation exist in the literature. It was found that a photointerpreter's estimate of pricklypear coverage (3.9%) from video IR was probably more accurate than a computer estimate (5%). Both estimates were checked with ground-truthing (Everitt *et al.*, 1991). Classification accuracy in a provincial city of Japan required a combination of bands, analyzing methods and data from several time periods (Takagi and Kenmochi, 1991).

5.7.3 Land Cover Comparison

Crop area estimates generated by remote sensing, field estimates, and a combination of the two were compared to crop census data in County Durham, Britain, for 1985 (Shueb and Atkins, 1991). Four crops were compared at the time of the study; other crops were not considered because they could not be distinguished for the date (May 31) of the remote sensing image acquisition. Of the four crops, it was difficult to separate winter barley from pasture because of similar appearance at that time of year. The estimate based on remote sensing, in this study Landsat data, differed by only 2% from the census data. Training sets for the four crop types were used to classify the image, which likely improved accuracy of classification. The study illustrated the difficulty of distinguishing vegetation of similar phenologies by remote sensing.

Forest cover estimates for the United States generated from satellite remote sensing were compared to state level inventories developed from ground surveys, and two older maps (Turner *et al.*, 1993). Satellite land cover estimates of areal coverage by vegetation type were made based on the NDVI derived from AVHRR data. The primary ground survey data were developed from aerial photography and site visits, and were considered the most reliable estimate available of U.S. forest cover. The older maps dated from 1964 and 1980, and contained estimates of forest cover which were considerably greater, more than 50% for many states, than either ground survey or satellite imagery. Use of satellite imagery appeared to give most accurate results where ecotones between vegetation types were narrow, where forest and adjacent vegetation types were distinctly different, and where areas of homogeneous vegetation were large. Close agreement between satellite imagery and ground survey data, ± 10%, was found for states with large areas of relatively uniform forest cover, such as Oregon. Satellite imagery yielded a value for forest cover 22% below that of ground survey data for California. By inference, satellite data would be expected to be less accurate for California regions in which zones of homogeneous vegetation are small and transition zones are large, without sharp demarcation between vegetation types.

5.8 Platforms

Platforms, whether satellite, aircraft or ground observation, are accessible given requisite funding. The choice of platform is dependent on the nature of the data desired, the instrumentation needed to provide the data, the level of detail required, and the urgency of data acquisition. The Mission to Planet Earth is emphasizing satellite platforms.

5.9 Laser-Induced Fluorescence of Chlorophyll

Laser-induced fluorescence of chlorophyll may eventually find application in remote sensing to ascertain plant health, estimate biomass or measure plant physiological properties. Biomass could be estimated by laser induced fluorescence because it yields a direct measure of chlorophyll content of plants without interference from other leaf components (Subhash and Mohanan, 1994).

Chlorophyll fluorescence has been studied since the 1930's. Chlorophyll of a pre-darkened leaf fluoresces if it absorbs a pulse of light of appropriate wavelengths. Fluorescence rises rapidly, followed by a slower decay, together known as the Kautsky effect after its discoverer. The fluorescence "decrease ratio" compares the slow fluorescence decay to the fast fluorescence rise. The ratio is an indicator of the prior level of photosynthesis, and therefore is a surrogate for plant vigor, or conversely plant stress. It is possible to induce fluorescence by laser light, and compare light emission at different wavelengths (Subhash and Mohanan, 1994).

Chlorophyll fluorescence and delayed fluorescence were used as indicators of plant health (Kharuk *et al.*, 1994). Carbon fixation rate was highly correlated with remotely sensed chlorophyll fluorescence. The ratio of fluorescence at 685 nm and 730 nm were found to be different in stressed vs nonstressed plants (Günther *et al.*, 1994). Water stress and carboxylation limitations affected the ratio of fluorescence at 690 nm and 730 nm (Valentini *et al.*, 1994).

Remote sensing of blue and red fluorescence signatures appeared to be a potential future tool for ascertaining the health of plants. Wheat leaves lacking chlorophyll as the result of growth in darkened conditions, or as the result of herbicide treatment, displayed spectra different from green leaves (Stober *et al.*, 1994).

A portable remote sensing system was designed which measured chlorophyll fluorescence of plants in the field following laser light pulses. It was found that remote sensing measurements were closely correlated with spectroscopic measurements made in close proximity (Cecchi *et al.*, 1994).

In a significant study (Subhash and Mohanan, 1994), the emission of rice plants deficient in one of thirteen essential elements was compared. No visible symptoms were apparent but rice plants differed in emission characteristics, depending on the identity of the absent nutrient, and depending on the wavelength used to stimulate emission (Figure 5-13). The study pointed out the potential application of fluorescence to identify nutrient deficiencies via remote sensing.

However, despite advances, the exact relationships of plant fluorescence to physiological properties are not known; therefore, the utility of laser induced fluorescence in biogenic emissions estimation seems remote at present.

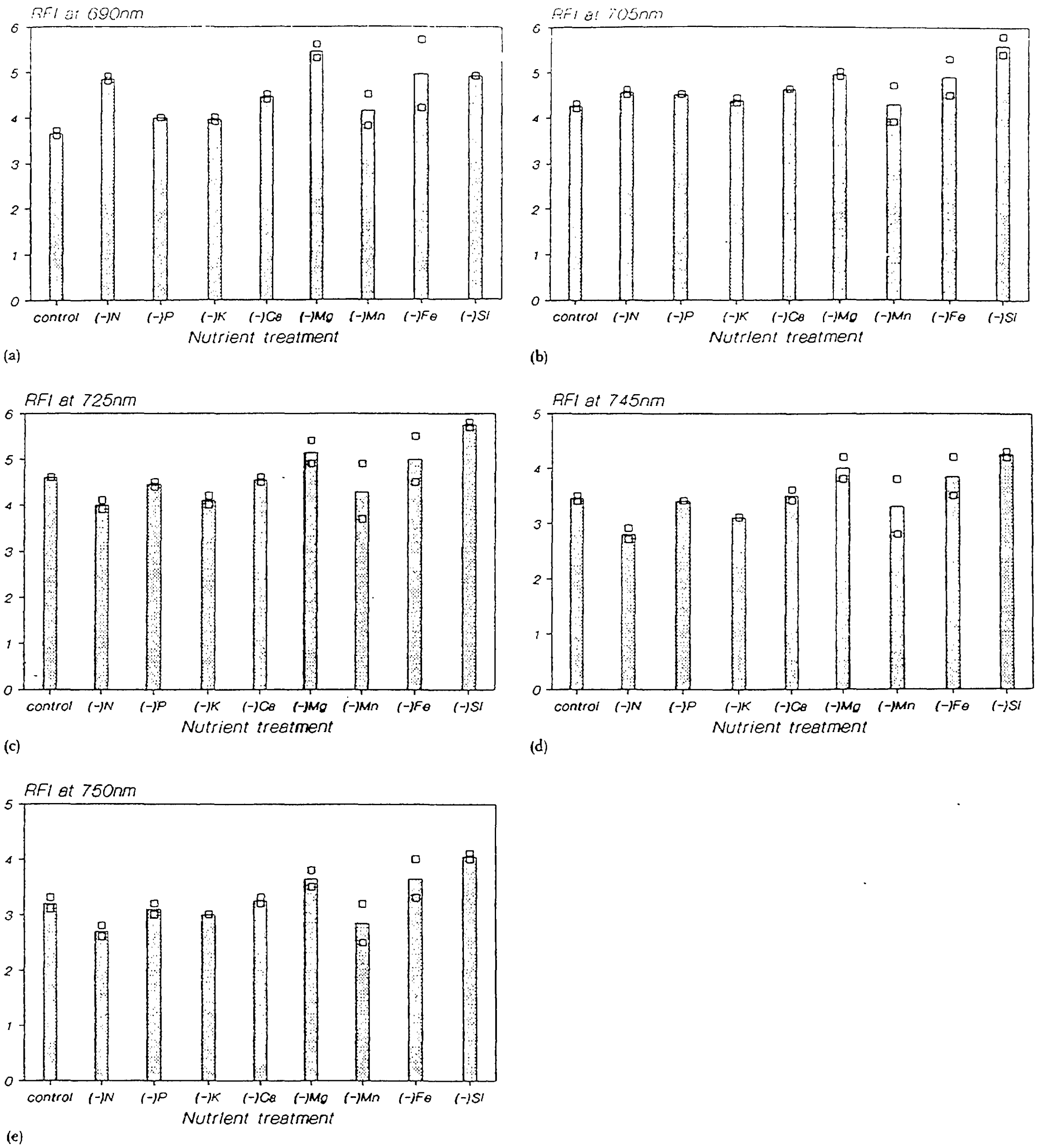


Figure 5-13. Nutrient stress in rice plants affected laser induced relative chlorophyll fluorescence intensity (RFI) at five wavelengths: (a) 690 nm; (b) 705 nm; (c) 725 nm; (d) 745 nm; (e) 750 nm. Nutrient deficiencies were not observed visually (Subhash and Mohanan, 1994).

5.10 Summary and Conclusions

Remote sensing technology has become a field of its own. Rapid development continues, fueled by interest in satellite-based systems, instrumentation and the computer capability to handle large volumes of data. Image enhancement and classification techniques continue to improve. At the time of this writing, remote sensing from satellite platforms offers the capability of determining land cover classes where spectral characteristics are well-defined and distinct. However, establishment of plant identity at the species level goes beyond the normal requests made of even advanced instrumentation. Aerial photography remains a useful technology where fine resolution is required.

Remote sensing is useful for identifying individual plant species where differences are obvious in terms of spectral characteristics or phenology. Because of the similarity of plant components, species identification in ecosystems is limited to situations where choice can be made among plant types, implying a priori knowledge exists. Biomass may be adjusted using remote sensing and the NDVI, but quantitative baseline values for biomass are needed from some other source. AVHRR data for quantifying cover estimation are most useful for large areas of homogeneous vegetation. California airsheds pose problems for remote sensing because of the variety of plant communities and breadth of transition zones.

Plant biophysical properties as inferred from chlorophyll content and water content are amenable to remote sensing. Unfortunately, no direct link shared among many plant species has been discovered between a measurable biophysical property and emission rate.

GIS maps or databases should contain a clear history of development, including criteria for classification and method of classification. Quantitative error estimation is possible, and recommended.

6.0 CRITICAL REVIEW AND EVALUATION OF BIOGENIC EMISSION INVENTORY MODELS

6.1 Background

As noted earlier in this report, tropospheric ozone is formed in the atmosphere by reactions between hydrocarbons and nitrogen oxide in the presence of sunlight. The elevated levels of ozone, relative to the natural background, observed in urban and rural areas of California are primarily the result of anthropogenic hydrocarbon and NO_x emissions. However, in some rural areas of the state, emissions of hydrocarbons and NO_x from natural sources may contribute to elevated ozone levels. Thus, effective control strategies for reducing ozone must account for the role of biogenic hydrocarbon and NO_x emissions when estimating how much reduction is needed to anthropogenic hydrocarbon and NO_x emissions. As noted in Section 2.0, biogenic emissions account for about 50 percent of the overall hydrocarbons and 12 percent of the overall NO_x emissions in the United States (Roselle, 1994). However, it should be emphasized again that biogenic sources of hydrocarbon and particularly NO_x tend to be widely distributed spatially, whereas anthropogenic sources are generally highly concentrated in urban regions and therefore contribute dominantly to air pollution problems experienced in those regions. Biogenic hydrocarbon sources include plants, shrubs, and trees, while biogenic NO_x emissions arise from the soil and are created by lightning flashes.

Photochemical air quality simulation models such as the Urban Airshed Model require spatial and temporal estimates of biogenic, as well as anthropogenic, hydrocarbon and NO_x emissions. To provide airshed model inputs, biogenic emission models have been developed that estimate emissions based on knowledge of the distribution of shrubs, trees, and other vegetation of particular areas and measured or estimated emission rates of various volatile organic compounds from those plants species, and NO_x emissions from the soil.

Biogenic emission inventory models that have been applied on a regular basis to estimate biogenic hydrocarbon and soil NO_x emissions for use in photochemical air quality simulation models such as the UAM include:

- U.S. EPA-released Biogenics Emission Inventory System (BEIS), which includes PC-BEIS and UAM-BEIS

- U.S. EPA BEIS-2 (including PC-BEIS-2 and UAM-BEIS-2) model, which has not yet been released

- Biogenics processor used in the SARMAP Geocoded Emissions Modeling and Projections (GEMAP) system

- South Coast Air Quality Management District Vegetation Emission Inventory System (VEGIES)

There are two versions of the BEIS and BEIS-2 models: PC-BEIS and UAM-BEIS, and PC-BEIS-2 and UAM-BEIS-2. While BEIS-2 has not yet been released, we believe the U.S. EPA will adopt BEIS-2 with at most minor changes. Thus, this review focuses primarily on the differences between BEIS-2, VEGIES, and GEMAP and provides limited descriptions of BEIS.

6.2 Objectives

The purpose of this chapter is to review selected biogenic modeling approaches, and identify the best methods for estimating biogenic hydrocarbon and soil NO_x emissions in California and for applying those estimates in a photochemical grid modeling system, such as UAM. For this evaluation, we examined the source code for each model to assess whether (1) the code accurately represents the science it is reported to be based on, and (2) to ensure (within resource limitations) that the code is error-free. In addition, we evaluated which model or model components better reflect the current state of knowledge, including an evaluation of the model inputs and model algorithms for modifying emission rates to account for environmental effects on vegetation emissions. We also evaluated each model's ability to utilize highly resolved inputs such as gridded land-use, vegetative cover type, and meteorological conditions such as temperature and wind, and provide highly resolved emission estimates to the UAM.

6.3 Model Evaluation

All of the biogenic emission models reviewed in this study estimate the emission rates of hydrocarbons based on the following formula:

$$Q_i = \sum_{j=1}^{n} \left[A_j \, BF_j \, EF_{ij} \, F_{ij}(S,T) \right] \tag{6-1a}$$

where Q_i is the species emission rate (μg/hr), A_j is the area (m^2) within a region of vegetation type j, BF_j is the leaf biomass factor (g/m^2) for vegetation type j, EF_{ij} is the species-specific emission factor for vegetation type j (μg/g leaf biomass/hr), and $F_{ij}(S,T)$ is a species-specific environmental adjustment factor (unitless) which accounts for differences in emission rates associated with solar radiation, leaf temperature, and leaf shading effects. The sections that follow highlight differences and the potential uncertainty associated with each of the factors (A_j,BF_j,EF_{ij},$F_{ij}(S,T)$) used to estimate the species emission rate in Equation 6-1 in each model.

The biogenic emissions model for soil NO_x is much simpler than the one used for hydrocarbons, and is denoted by the following equation:

$$Q_{NO} = \sum_{j=1}^{n} A_j \, BF_j \, F_{NO} \, (S,T) \tag{6-1b}$$

where Q_{NO} (μg/hr) defines the biogenic NO_x emission rate. In this formula, one inputs a standardized flux for NO_x denoted by BF_j (μg $NO_x/m^2/hr$), applicable to 30°C. The value of BF_j varies with land-use type. A_j is the area (m^2) occupied by land-use type j, and $F_{NO}(S,T)$ is the NO_x environmental adjustment factor. Note that all of the biogenic models (including those with soil NO_x modules) apply empirical formulas to adjust the emission rate for environmental factors such as solar radiation and temperature. Later in this section we provide an assessment of the algorithms used to make the environmental adjustments to the emission factors.

Sources of error in these models include the accuracy and precision of input data, systematic errors, and coding errors. In the following discussion we comment on uncertainty due to data and model formulation. In addition, we provide comparisons of biogenic emission model predictions and limited field study observations.

6.3.1 Overview of the Biogenic Models Reviewed in this Study

6.3.1.1 Biogenic Emission Inventory System

For the most part, PC-BEIS and UAM-BEIS are identical. Both use the same leaf biomass factors and plant-specific emissions, and both use the formulas developed by Tingey *et al.* (1979, 1980) to make environmental factor adjustments. However, there are a few important differences between these two models, the most important of which are that the UAM-BEIS includes a biogenic NO_x model, reads a table of adjustments so it can vary the leaf biomass on a month-by-month basis, and utilizes gridded inputs. PC-BEIS and UAM-BEIS both apply 15 to 20-year-old land-use files to allocate land-use percentages within a user-specified model domain as default (note that UAM-BEIS allows for the use of alternative gridded land-use data as inputs).

6.3.1.2 Biogenics Emission Inventory System-2

PC-BEIS-2 and UAM-BEIS-2 are new EPA models based on almost all new or improved methods and inputs. UAM-BEIS-2 accepts gridded temperatures; but, otherwise, PC-BEIS-2 and UAM-BEIS-2 are identical. Both models create land-use area coverage from recently compiled land-use files. Unlike UAM-BEIS, UAM-BEIS-2 does not accept gridded land-use. The models assign leaf biomass factors and species-specific emission factors (Guenther *et al.*, 1995), rather than the older data sets used to build the formulas applied by PC-BEIS and UAM-BEIS. Also BEIS-2 (used to refer to both PC-BEIS-2 and UAM-BEIS-2) uses environmental adjustment factors that are based on more recent research (Guenther *et al.*, 1991, 1993). BEIS-2 also has a soil NO_x emissions model.

6.3.1.3 Geocoded Emissions Modeling and Projections (GEMAP) System

The biogenic emission processor within GEMAP is based on the BEIS code and has been applied to the SJVAQS/AUSPEX region (shown in Figure 6-1) by Tanner *et al.* (1992). Note that this model does not include a soil NO_x emission module. The application to the SJVAQS included updating the land-use and emission factors available as defaults in BEIS. Satellite imagery was used to divide the AUSPEX region into 39 vegetation classes. The distribution of species in these vegetation classes was estimated from California Department of Forestry data. Leaf biomass factors and species-specific emission factors were assembled from literature sources and unpublished data. About 120 species-specific emission factors are included. A few emission experiments were also conducted as discussed in Section 4.0. This model uses the Tingey *et al.* (1979, 1980) formulas for environmental adjustments. GEMAP has also been used in the Lake Michigan Ozone Study (LMOS), but our review focuses on its application in California.

6.3.1.4 Vegetation Emission Inventory System

VEGIES (Causley and Wilson, 1991) was developed to model biogenic VOC emissions in the South Coast Air Basin. Of the models reviewed, VEGIES applies the most complete plant species emission factor database - more than 400 plant-specific emission factors for isoprene and monoterpenes, although available documentation was insufficient to determine the precise source of the emission factors. VEGIES applies environmental adjustments similar to those in BEIS, UAM-BEIS, and GEMAP, except for employing a unique solar radiation factor, which is described later. VEGIES lacks a soil NO_x emission model. Documentation for VEGIES did not identify the source for land-use coverage for the SCAQMD.

6.3.1.5 General comments

The biogenic models reviewed in this study are quite extensive. For example, PC-BEIS consists of 1717 lines of code. UAM-BEIS, PC-BEIS-2, UAM-BEIS-2 and VEGIES contain more than 3600, 1700, 4900, and 3200 lines of code, respectively. The

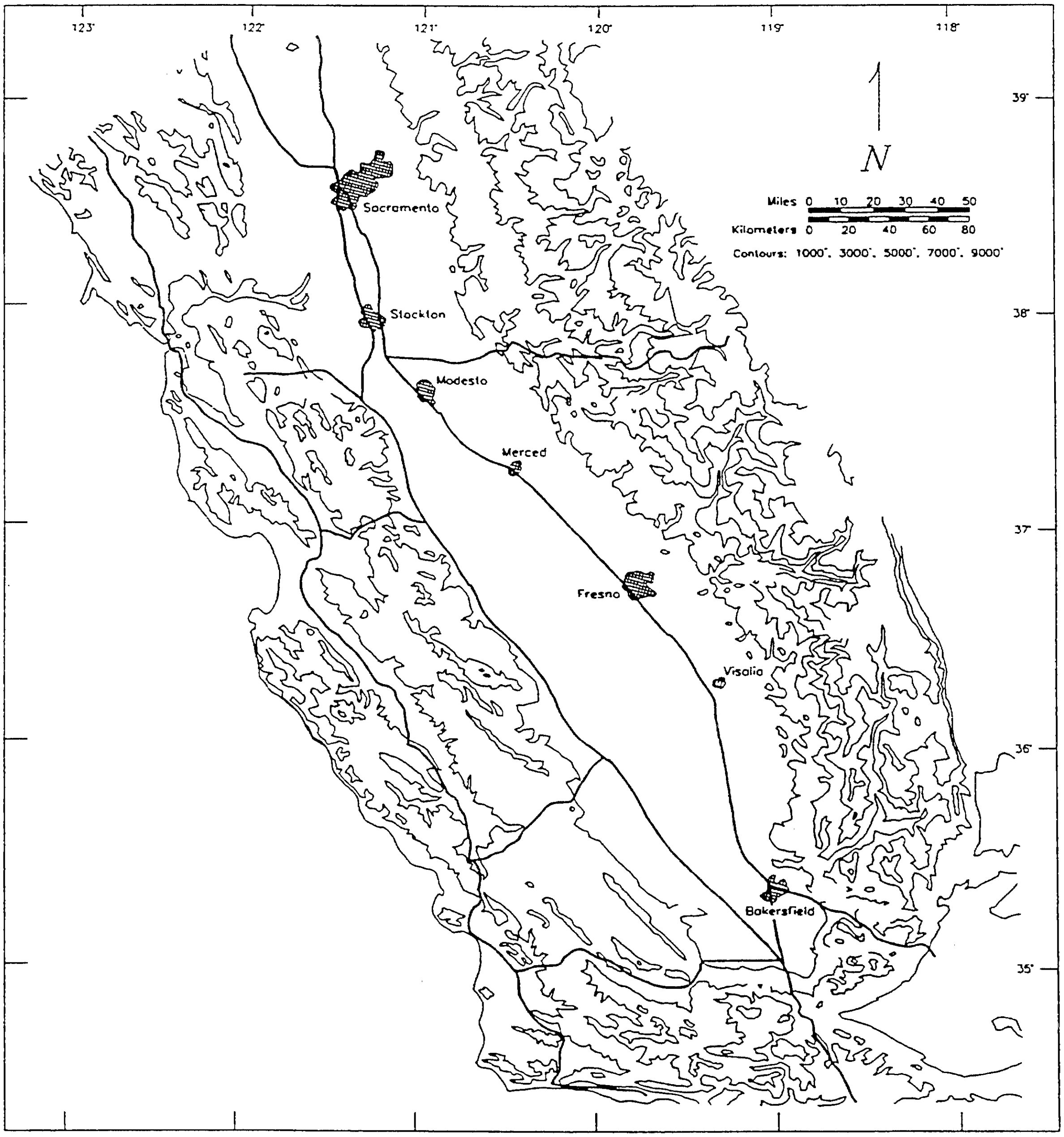


Figure 6-1. SJVAQS/AUSPEX emission inventory and modeling domain (Ranzieri and Thuillier, 1994).

biogenics processor of GEMAP has more than 600 lines of FORTRAN code and 2400 lines of SAS code.

The BEIS family of models and VEGIES are FORTRAN-based computer codes and can be run on any computer with a FORTRAN compiler. Because GEMAP is written in both SAS and FORTRAN, it requires additional computer resources (including a SAS license). The BEIS family of models includes "default" inputs (e.g., land-use distribution) for use throughout the United States. Note, however, BEIS-2 has only been applied in the eastern United States by the U.S. EPA.

Although critiques of computer code are subjective, there are general standards for writing sound computer programs (for example, see ANSII, 1978). In general, well written computer source code should contain roughly two lines of comments per line of source code. Comments are vital for at least two reasons: they indicate the thought process and logic of the programmer and facilitate future updates by other programmers. Source codes should also be modular enough such that when changes are made (e.g., to biomass factors or environmental factor equations) the entire program does not need to be re-written, rather only one module needs to be replaced. All of the biogenic models reviewed in this study contain a certain amount of comments, but they do not define each important parameter found in the code, or units of all parameters common to more than one module (e.g., m^2, g/s). Another facet of good programming is to always have the program check the input data provided by the user. If the user accidentally inputs erroneous data, when possible the program should either warn the user and continue or stop.

6.3.2 Model Critique

The following sections provide comparisons of the modeling approaches used by the PC-BEIS and UAM-BEIS, PC-BEIS-2, UAM-BEIS-2, VEGIES, and GEMAP, on a parameter-by-parameter basis. The sections begin with a description of how each biogenic model estimates the parameter. This is followed, when applicable, by a discussion of the strengths and weaknesses of each approach. The discussion of these parameters are presented in the following order:

- Land-use coverage
- Leaf biomass values
- Plant-specific emission factors for isoprene, monoterpenes, and OVOC (other volatile organic compounds)
- Environmental factors

The primary focus of this critique is model formulation. In this section, we provide a detailed review of environmental adjustment algorithms, with a brief summary of model inputs presented first. Our comments on model inputs, including land use, leaf biomass, and emission factors, are limited and are only intended as a means of describing the differences between the various models. Additional discussion of land-use, leaf biomass factors, and emission rates applicable to the use of these models for California's airsheds are found in the preceding chapters.

6.3.2.1 Model Inputs

6.3.2.1.1 Land Use

The area within a region associated with vegetation type j, A_j, is generally input into the models as a function of land use. PC- and UAM-BEIS rely upon the Geocology data set (circa 1980) for determining land-use coverage (Pierce, 1994).

PC-BEIS-2 and UAM-BEIS-2 rely upon U.S. Forest Service (USFS) data to develop county coverage of land-use types in the eastern United States, and uses the United States Geological Survey (USGS) AVHRR data set to develop county coverage of land-use types in the western United States. These two sources of land-use data were combined because EPA found the AVHRR data set did not adequately represent the heterogeneous nature of farms and woodlands in the eastern United States. The USFS data provided better heterogeneous detail, but it only covered 37 eastern states. Based on this information, only the AVHRR data set contains information on land-use coverage for California. However, since the AVHRR data set does not adequately represent the heterogeneous nature of farms and woodlands in the eastern United States, it is also unlikely to do so in California.

It is important to note that UAM-BEIS allows the user to input their own gridded land-use data instead of the defaults described above. However, UAM-BEIS-2 does not have this important option. This may result in an inaccurate representation of modeling domains with heterogeneous land areas; and, thus, an inaccurate spatial allocation of the emissions.

For GEMAP, Tanner *et al.* (1992) divided the San Joaquin Valley Air Quality Study (SJVAQS) AUSPEX region into 39 vegetation types. This was accomplished using satellite images from late spring, summer, or fall from 1984 to 1985, the summer of 1990, and late fall 1984. As expected, agriculture encompassed the largest area.

The documentation received with VEGIES did not describe its source of information for land-use data.

6.3.2.1.2 Leaf Biomass Factors

Another critical model input is the leaf biomass factor for vegetation type j, BF_j. In BEIS-2 (Geron *et al.*, 1994), leaf biomass factors for forest canopies are allocated based on published values (determined from destructive sampling and leaf fall collection) from fully stocked stands. For BEIS-2, the leaf biomass factors are 1500 g/m^2 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. Geron *et al.* (1994) report these biomass factors to be very similar to those used by Lamb *et al.* (1987) and applied in BEIS, except for the Abies, Picea, Tsuga, and Pseudotsuga genera, which were assumed by Lamb *et al.* (1987) and BEIS to have factors similar to Pinus and other conifers. Thus, biomass factor assignments for Abies, Picea, Tsuga, and Pseudotsuga genera in BEIS (700 g/m^2) are only half of those used in BEIS-2 (1500 g/m^2).

There is a considerable amount of uncertainty associated with the leaf biomass factor for different plant species. Frequency histograms of observed summer peak foliar mass for stands of deciduous, pine, and other coniferous genera, as reported by Geron *et al.* (1994) and shown in Figure 6-2, exhibit a considerable range in reported foliar mass,

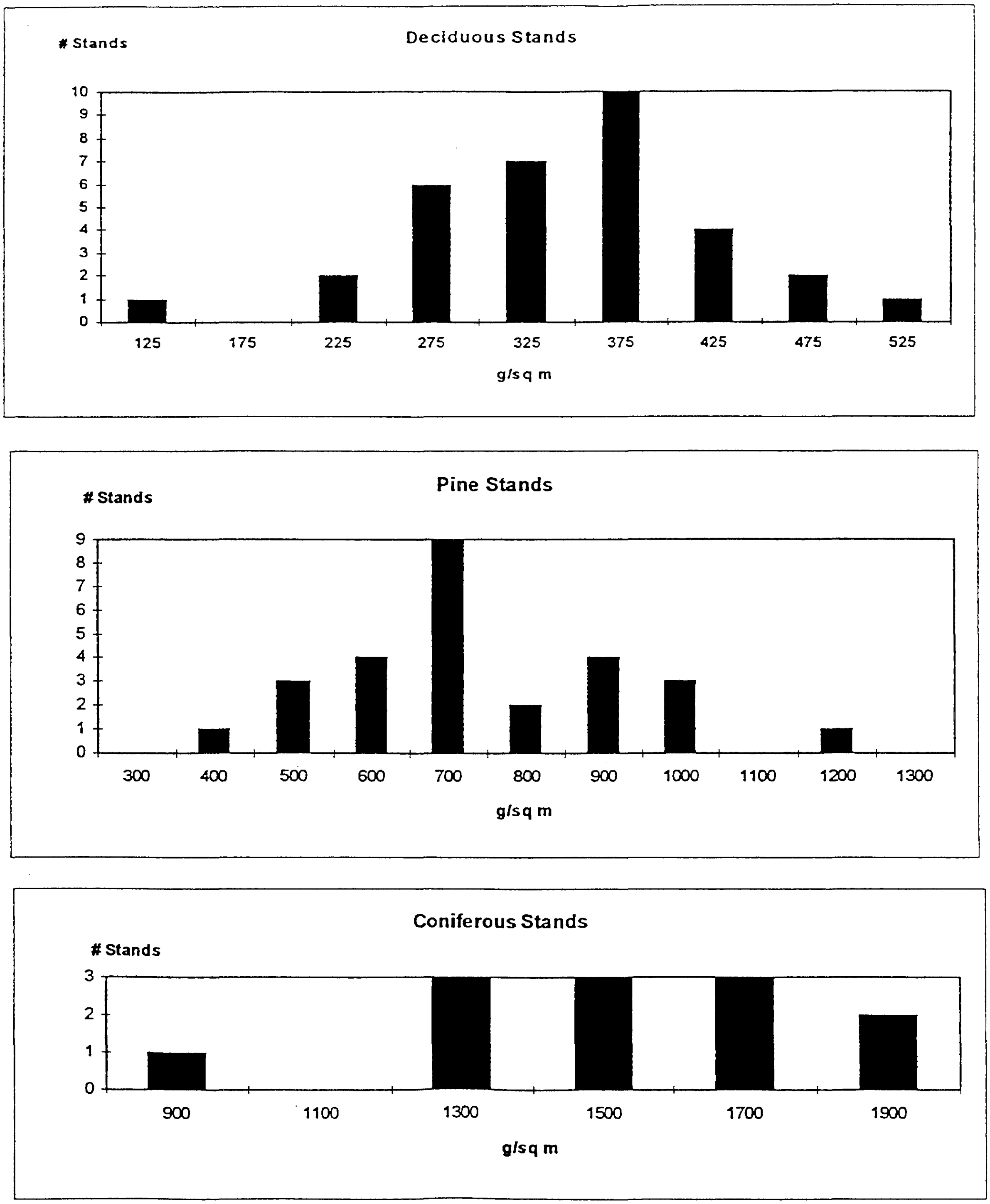


Figure 6-2. Frequency histogram of observed stand summer peak foliar mass for stands of deciduous, pine, and other coniferous genera. The values were determined from destructive analysis or litter fall sampling (from Geron *et al.*, 1994).

BF_j. The range of biomass factors observed in deciduous (125 to 525 g/m^2) and pine (400 to 1200 g/m^2) stands is a factor of 3, and the range of biomass factors reported in coniferous stands (900 to 1900) is a factor of 2. Thus, the uncertainty in applying the BEIS-2 values for deciduous (375 g/m^2), pine (700 g/m^2), and coniferous (1500 g/m^2) forests is at least 60 (e.g., 100 x (375-125)/375), 70, and 40 percent, respectively. (This uncertainty also applies to PC-BEIS and UAM-BEIS.). These biomass factors are also based on fully stocked canopies. Overprediction errors of the actual biomass factor are expected at sites where the forest canopy is not fully stocked. The error in applying a biomass factor for fully stocked canopies to young canopies is not known. BEIS-2 can be run using either summer or winter biomass data. Only UAM-BEIS incorporates information to change the leaf biomass on a month-by-month basis. Documentation of the biomass factors for VEGIES was not available.

For GEMAP, Tanner *et al.* (1992) estimated area coverage of various plant species for each of the 39 vegetation types that were classified from satellite imagery. This was principally done using California Department of Forestry data. Biomass factors were assembled from literature sources and a limited amount of unpublished data. In some cases, where a biomass factor did not exist for a particular species, a surrogate value was used. This surrogate value was usually determined from a related species. Using the leaf biomass factors for each particular species and the distribution of species within each vegetation type, an average biomass factor was determined for each vegetation type. Furthermore, for the agriculture vegetation class, which is the largest, county-specific species distributions were used. For further discussion of these biomass factors, see preceding chapters.

6.3.2.1.3 Emission Factors

Species-specific emission factors for vegetation type j, EF_{ij}, are perhaps the most important model inputs. The emission factors for BEIS-2 are taken from Geron *et al.* (1994), which is based mostly on studies in the eastern United States. BEIS-2 allocates hydrocarbon emissions to isoprene, monoterpenes, and an OVOC (other volatile organic compounds) category. Pierce (1994) has commented there is often a difference in measurements of VOC emissions from similar species from California vs. other parts of the United States. Specifically, Pierce notes that isoprene emissions reported from oak by University of California at Riverside researchers (Arey *et al.*, 1995) are significantly lower than measurements taken elsewhere in the United States in the last few years. However, earlier measurements by Winer *et al.* (1983) for the SoCAB agree with eastern measurements. At present there appears to be an unresolved difference between oak emission rates measured for eastern vs. western species which may or may not be related to the differences between species and/or environmental conditions. We did not review individual emission factors for PC- and UAM-BEIS as part of the model review. Specific recommendations for emission factors are found in preceding chapters.

Similar to the BEIS models, GEMAP estimates biogenic emissions by allocating these emissions to isoprene and monoterpenes and to an OVOC category. Tanner *et al.* (1992) assembled a database of about 120 emission factors for use in the SJVAQS/AUSPEX region from Sidawi and Horie (1992). Additionally, Tanner *et al.* (1992) made emission measurements of several prominent species including blue oak, foothill pine, and tarweed. Tanner *et al.* (1992) also assigned surrogate emission factors for another 20 plant species based on the emission factors of similar plant species.

VEGIES utilizes species emission factors for isoprenes and monoterpenes. An OVOC category is created within VEGIES by splitting monoterpenes into several compounds (olefin, α-pinene, β-pinene, d-limonene, myrcene, and carene). Review of the code block in VEGIES that splits monoterpenes into OVOCs showed that the splitting is done differently for each plant structural class (coniferous, broadleaf deciduous, broadleaf evergreen, shrub, palm, ground cover, and agriculture). VEGIES was specifically developed to estimate biogenic hydrocarbon emissions for the SoCAB. It includes information for over 400 different emission factors for various species in this region compiled by Sidawi and Horie (1992), including the earlier data of Winer *et al.* (1983). Causley and Wilson (1991) report that more than 85 percent of the biogenic hydrocarbon emissions in the SoCAB were from broadleaf evergreens and shrubs.

6.3.2.1.4 Discussion

The GEMAP and VEGIES emission factors seem to be the most relevant for California since each set of factors was developed specifically for regions in California. The GEMAP emission factors apply to a large area of the agricultural portion of California, while the VEGIES emission factors are most applicable to the urban and suburban portions of the SoCAB. However, it is also worth noting the majority of emission factors for both of these models were compiled from the same original work (e.g., Winer *et al.* 1983). Thus, many of the emission factors are the same in both models.

BEIS-2 uses mostly eastern United States data and the number of emission factors and the specificity of the genera are less than in GEMAP and VEGIES. For example, BEIS-2 uses one emission factor for oak, while VEGIES uses emission factors for four types of oak and GEMAP uses emission factors for 18 different types of oak. Tables 6-1 and 6-2 provide a comparison of the broadleaf evergreen and shrub species-specific emission factors in VEGIES and BEIS-2. These are the most prominent species in the SoCAB.

As the tables show, there are considerable differences in the estimates of isoprene and monoterpene emission factors in these models. In general, the emission factor differences between VEGIES and BEIS-2 are on the order of a factor of 2. There are a few cases in which the difference in emission factors estimated by these models is a factor of 5. There are also cases where one model applies an emission factor value of 0.0 and the other applies a non-zero value. Surprisingly though, there appears to be no overall bias between these models, since neither model consistently reports higher emission factors than the other. GEMAP provides over 25 different emission factors for agricultural crops that are prevalent in the San Joaquin Valley (based on Winer *et al.*, 1989, 1992), while BEIS-2 has emission factors for only a few of these species. Thus, in its current form, BEIS-2 cannot be expected to predict emissions for agricultural crops as well as GEMAP.

Table 6-1. Comparison of broadleaf evergreen emission factors under standard conditions (µg-C/g-biomass/hr).[a]

Plant Species	VEGIES (SCAQMD) Isoprene	VEGIES (SCAQMD) Monoterpene	BEIS-2 (Eastern United States) Isoprene	BEIS-2 (Eastern United States) Monoterpene
Orange	0.00	0.73	0.10	1.60
Eucalyptus	6.16 33.88	0.00 5.87	70.00	3.00
Shamel Ash	0.00	0.00	0.10	0.10
Magnolia	0.00	5.28	0.10	3.00
Acacia	0.00	0.00	0.10	3.00
Chinaberry	8.8	0.53	0.10	0.10
Persea	0.00	0.00	0.10	0.60
Prunus	0.00	0.00	0.10	0.10
Quercus (Oak)	11.44 43.12	0.00 0.00	70.00	0.20
Willow	14.96 205.04	0.00 0.00	35.00	0.10
Ulmus	0.00	0.00	0.10	0.10

[a] Biogenic emission factors of isoprenes and monoterpenes are given for about 400 plant types in VEGIES and about 125 plant types in BEIS-2 as reported by Geron et al. (1994). Because of the greater number of plant types listed in VEGIES compared to BEIS-2, there was often two biogenic factors given by VEGIES for one BEIS-2 plant type. For example, VEGIES lists emission factors for four types of oak: canyon live oak, holly oak, cork oak, and interior live oak, and the range of values listed were 13.0 and 49.0 µg-C/g-biomass/h. Geron et al. list one emission factor value for oak of 70.0 µg-C/g-biomass/hr.

Table 6-2. Comparison of shrub emission factors under standard conditions (μg-C/g-biomass/hr).[a]

Plant Species	VEGIES (SCAQMD) Isoprene	VEGIES (SCAQMD) Monoterpene	BEIS-2 (Eastern United States) Isoprene	BEIS-2 (Eastern United States) Monoterpene
Acacia	0.00 0.00	3.96 0.00	0.10	3.00
Fraxinus	0.00	0.00	0.10	0.10
Ilex	2.64	2.64	0.10	0.20
Juniperus	0.00	0.62	0.10	0.60
Magnolia	0.00	5.28	0.10	3.00
Mesquite	0.88	0.00	0.00	0.00
Prunus	0.00	0.00	0.10	0.10
Quercus	13.20	0.00	70.00	0.20
Willow	14.96	0.00	35.00	0.10

[a] Biogenic emission factors of isoprenes and monoterpenes are given for about 400 plant types in VEGIES and about 125 plant types in BEIS-2 as reported by Geron et al. (1994). Because of the greater number of plant types listed in VEGIES compared to BEIS-2, there was often two biogenic factors given by VEGIES for one BEIS-2 plant type.

Hydrocarbon emission factors for vegetation can be a source of considerable uncertainty due to natural variability. For example, Table 6-3 shows that measurements of isoprene emissions from a deciduous forest vary from between about 6 to 14 μg-C/g-foliar mass/hr. The distribution of species in the deciduous forests that were measured presumably have a significant impact on this variability. Thus, detailed characterization of species within a vegetation type is necessary for reducing uncertainty.

Table 6-3. Forest emission factors (μg-C/g-biomass/hr) at PAR 800 and 30°C (Geron *et al.* 1994).

Species	High Isoprene Deciduous	Low Isoprene Deciduous	Nonisoprene Deciduous	Nonisoprene Coniferous
Isoprene	13.60	5.95	0	0
Pinene	0.06	0.05	0.07	1.13
Monoterpenes	0.33	0.30	0.35	1.78
OVOC	1.82	1.44	1.54	1.35

6.3.2.1.5 Summary

Earlier sections of this report provide more detailed discussions of biogenic model inputs (e.g., land-use or vegetative type data, biomass factors, and emission factors). In this section we briefly summarized the inputs used in the models under review in this study. Of the databases applied to estimate land-use coverage in these models, the preferred source would be one that is most current, such as satellite imagery or aerial photography, provided adequate "ground-truth" validation of the interpreted land-use distribution is conducted. The work of Tanner *et al.* (1992) in applying GEMAP to the SJVAQS/AUSPEX region provides a starting point from which additional land-use characterization techniques can be applied. Tanner *et al.* (1992) also provides detailed information on biomass factors for a large area of California, which appears to exceed that used in either BEIS or BEIS-2. Furthermore, as was discussed above, there is considerable uncertainty associated with the biomass factors used in BEIS-2. This uncertainty could be reduced considerably by the methods applied in Tanner *et al.* (1992), which determine biomass factors for each vegetation type specific to the composition of known species in the region.

6.3.3 Environmental Adjustment Factors

6.3.3.1 Hydrocarbon Emission Environmental Adjustments

6.3.3.1.1 Solar Radiation and Temperature Effects

All of the models reviewed (e.g., PC-BEIS, UAM-BEIS, VEGIES, and GEMAP), with the exception of BEIS-2, base their environmental adjustment factors on work conducted by Tingey *et al.* (1979, 1980), which showed the environmental factors most affecting biogenic species emissions for isoprene, monoterpenes, and other volatile organic carbons are solar radiation and temperature. Tingey *et al.* (1979, 1980) developed the following formulas for the species-specific environmental adjustment factors:

$$\begin{aligned}
&\textit{Isoprene:} && F_i\,(S,T) = \frac{10^P}{e};\; p = \frac{a}{1 + e^{[-b(T-c)]}} - d \\
&\textit{Monoterpenes:} && F_i\,(S,T) = e^{[0.07(T - 30^\circ C)]} \\
&\textit{OVOC:} && F_i\,(S,T) = e^{[0.07(T - 30^\circ C)]}
\end{aligned} \qquad \textbf{(6-2)}$$

where S denotes solar radiation and T defines the air temperature (°C). The parameters a, b, c, and d are empirical coefficients that vary as a function of the solar radiation intensity.

In VEGIES, however, note that the code (specifically the computer file named corfac.f) multiplies the above-identified Tingey environmental factors for monoterpenes and OVOC by a diurnal factor multiplied by a solar radiation factor,

$$\begin{aligned} diurnal &= f_i\left(\frac{S_i}{S_{i,diurnal}}\right) & S_i > 0 \\ diurnal &= f_i & S_i < 0 \end{aligned} \qquad \textbf{(6-3)}$$

where f_i is a diurnal factor that varies from a low of 0.6 at 5 a.m. (and 6 a.m.) to a high of 1.4 at 2 p.m. S_i is the solar radiation intensity for hour i, and $S_{i,diurnal}$ is the solar radiation intensity value at hour i. Recall that Tingey *et al.* (1979, 1980) apply no adjustment to monoterpene or OVOC emissions for solar radiation. The apparent departure in VEGIES from the published literature concerning the lack of influence of sunlight on monoterpene emissions is, in fact, noted within a comment in the VEGIES code (the relevant section is shown in Appendix A with the comment in bold print), which states, "Monoterpene emission factors are not sensitive to solar intensity. The adjustment here may be incorrect."

While examining the VEGIES computer code, we found the diurnal factor f_i to be represented by an array length of 23. This allows VEGIES to vary the value of f_i on an hour-by-hour basis such that f_i is 2.3 times higher at 2 p.m. than at 5 a.m. When this diurnal factor is coupled with the solar radiation factor ($S_i/S_{i,diurnal}$), the combination produces adjustments that are physically unrealistic. For example, as shown in Table 6-4, the olefin emissions (a subset of monoterpene emissions) predicted by VEGIES are 7 times lower at the hour after sunrise compared to 1 hour earlier (before sunrise) and 10 times lower at the hour before sunset when compared to olefin emissions the hour after sunset. In Table 6-4, we also note the maximum olefin emission rate occurs at 1700 hours (early evening) and continues quite high following sunset. It appears the application of this adjustment factor produces unusual changes in olefin emissions over the day, which appear to be physically unrealistic.

Table 6-4. Winter olefin emissions (tons) reported by SCAQMD (1991) by hour of day, compared to average ambient temperature, solar radiation.

Hour of Day	Solar Radiation[a]	Temperature (K)	Olefin Emissions (tons)
1	0	280.6	0.12
2	0	279.7	0.11
3	0	279.0	0.10
4	0	278.5	0.08
5	0	278.2	0.07
6	0	278.1	0.07
7	0.017	278.5	0.01
8	0.074	280.0	0.03
9	0.125	282.4	0.04
10	0.164	285.3	0.07
11	0.182	288.1	0.09
12	0.091	290.4	0.07
13	0.152	292.0	0.13
14	0.113	292.5	0.13
15	0.065	292.3	0.09
16	0.017	291.9	0.04
17	0	291.1	0.39
18	0	288.6	0.31
19	0	285.3	0.23
20	0	284.0	0.20
21	0	282.8	0.18
22	0	281.7	0.16
23	0	280.6	0.14
24	0	279.7	0.12

[a] Units cannot be established from SCAQMD (1991)

6.3.3.1.2 Leaf Canopy Model

PC-BEIS, UAM-BEIS, and GEMAP apply the same canopy model (Gay, 1987) to compute a layer-by-layer change in the leaf temperature. VEGIES does not adjust leaf temperature for canopy effects. Gay's model is based on a leaf energy balance equation given by Gates and Papian (1971), which can be expressed simply as follows:

$$Q_{leaf} = IR + L + C \qquad \textbf{(6-4)}$$

where Q_{leaf} is the radiant energy absorbed by the leaf (including solar energy S and infrared energy from the ground and nearby leaves), IR is the infrared energy emitted by the leaf, L is the latent heat loss or gain, which depends mostly on the relative humidity and somewhat on the wind speed, and C is the convective heat loss or gain, that depends on the wind speed and the difference between leaf temperature and air temperature.

This equation is solved iteratively in PC-BEIS, UAM-BEIS, and GEMAP to determine a value for the leaf temperature that causes the equation to balance. The PC-BEIS documentation states "modeled leaf temperatures near the top of the canopy on sunny, light windy days can be as much as 8°C warmer than the ambient temperature. Leaf temperatures in the lower portion of the canopy tend to be a couple of degrees cooler than the ambient temperature."

Although this model is based on equations and coefficients found in the literature, it has not been subjected to a rigorous validation. As noted above, the inputs to this model include wind speed, temperature, relative humidity, and cloud cover. The input temperature is used by the canopy model both as the ambient and surface temperature (this assumption is invalid since the vertical temperature profile from the surface to above the canopy is not normally isothermal). This modeling assumption is also inconsistent with another assumption applied in the leaf energy balance model; temperature lapse rate in the canopy of 0.06°C/m in the night and -0.06°C/m in the day.

In a further review of the leaf temperature model, we also discovered some physically unusual results. For example, after running the test case for North Carolina provided with PC-BEIS, we found the leaf model predicted a leaf temperature in the layer closest to the ground that was 8 to 11°C cooler than ambient air (above the canopy). This finding disagrees with the PC-BEIS documentation, which states the lower portion of the canopy tends to be only a couple of degrees cooler than ambient. Because the canopy height has been preset to 15 m and 20 m for deciduous and coniferous forests, the leaf temperature lapse rate in the canopy for this test case is about 0.5°C/m, regardless of day or night. This finding is inconsistent with the leaf energy balance assumption of a temperature lapse rate in the canopy of 0.06°C/m in the night and -0.06°C/m in the day. This leaf energy balance model also uses a logarithmic profile to reduce the wind speed in the top one-third of the canopy relative to ambient, and the wind speed below two-thirds of the canopy height is set to 0.1 m/s. This wind modeling assumption is inconsistent with wind profiles measured inside an oak hickory forest, which were observed to be fairly constant (independent of height) (Gay, 1987). Because there are a number of modeling assumptions applied in the leaf energy model that are incorrect, we recommend this sub-model undergo further evaluation and modifications as needed.

6.3.3.1.3 BEIS-2 Environmental Adjustments

Perhaps in recognition of problems with PC-BEIS and UAM-BEIS environmental adjustment algorithms, BEIS-2 environmental adjustments have been developed from entirely new procedures. BEIS-2 does not use the leaf energy balance model described above, and does not apply the Tingey formulas to correct isoprene and monoterpene emissions for temperature and solar radiation effects. The environmental formulas applied in BEIS-2 were derived from data collected by Guenther and co-workers (Geron *et al.*, 1994) primarily in the eastern United States. Thus, it is not clear whether they can be applied directly for California. The BEIS-2 environmental formulas are reported in Guenther *et al.* (1993) as shown below:

$$
\begin{aligned}
&\textit{Isoprene} && F_i(S,T) = f(S)\, f(T) \\
&\quad\textit{where:} && \\
& && f(T) = \frac{e^{\left[\frac{37.7(T-30)}{(T+273)}\right]}}{1 + e^{\left[\frac{41.3\,(T-41)}{(T+273)}\right]}} \\
&\quad\textit{and,} && \\
&\qquad\textit{Non-Forests:} && \\
& && f(S) = \frac{1.066\ g\ PAR}{(1+g^2\,PAR^2)^{1/2}} \qquad\qquad (6\text{-}5) \\
&\qquad\textit{Forests:} && \\
& && f(S) = \frac{1.066\ g\ PAR}{(1+g^2\,PAR^2)^{1/2}} \\
&\qquad\quad\textit{where:} && \\
& && PAR_i = PAR_o\, e^{\left[\frac{-0.42\,LAI\,(2i-1)}{10}\right]} \\
&\textit{Monoterpenes} && F_i(S,T) = e^{[0.09(T-30^\circ C)]} \\
&\textit{OVOC} && F_i(S,T) = e^{[0.09(T-30^\circ C)]}
\end{aligned}
$$

where g equals 0.0027, S denotes solar radiation, T defines the air temperature (°C), and PAR (umol/m^2/s) is the photosynthetic active part of the solar radiation. Notice this model applies a different solar radiation adjustment factor for forest and non-forest vegetation. For non-forests the model requires the PAR value while for forests the model requires not only the PAR value but also the leaf area index, LAI. LAI is assumed to equal 3 for pine, 5 for deciduous, and 7 for Abies, Pices, and Pseduotsuga stands, which are reported to be appropriate values for mature (closed canopy) stands. Lower values, resulting in higher emissions, would be more appropriate for young (unclosed canopy) stands.

In a review of the BEIS-2 code, we found several modifications to the equations given above as reported by Guenther *et al.* (1993). These modifications were made to the solar radiation environmental factor for isoprene. The changes were only applied when estimating the environmental correction factor to pine, coniferous forests, and deciduous forests. For these forest types, f(S) is computed in BEIS-2 as follows:

Pine and Coniferous Forests:

$$f(S) = \frac{0.2\ E\ g\ PAR\ pc_i}{(1 + (g\ PAR\ pc_i)^2)^{1/2}} \qquad \textbf{(6-6)}$$

Deciduous Forests:

$$f(S) = \frac{0.2\ E\ g\ PAR\ dc_i}{(1 + (g\ PAR\ dc_i)^2)^{1/2}} \qquad \textbf{(6-7)}$$

where pc_i and dc_i are attenuation factors specific for pine, coniferous, and deciduous forests. The values of pc_i and dc_i are less than 1 and decrease as i increases. i denotes the canopy level (i ranges from 1 to 5, with 1 representing the upper layer)."

A coding error was also found in the PC-BEIS-2 model, and it involves the estimate of f(S) for canopies which are not pine, coniferous, or deciduous forests. The code bug was found on line 1677 of the computer file BIOGEN.ASC within the SUBROUTINE CORRECT. The line of code in question appears as follows:

$$PAR_i = PAR_o\ e^{[-0.0042\ LAI\ (2i-1)]} \qquad \textbf{(6-8)}$$

The value of -0.0042 in the above equation should be corrected to -0.042. This coding error will lead PC-BEIS-2 to predict higher values of PAR_i than with the correct formula. Geron *et al.* (1994) report that experimental data will support values from -0.028 to -0.084. However, most canopies yielded values between -0.04 and -0.05.

To investigate the degree of error introduced by applying the PC-BEIS-2 coded equation, we computed normalized PAR_{ni} (PAR_i/PAR_o) values for a leaf area index of 5 for i equal 1 to 5. As shown in Table 6-5, the normalized PAR values applying the correct formula are as much as a factor of 2 to 5 lower than values obtained with the formula coded in PC-BEIS-2. We notified EPA (Pierce, 1994) of this coding error, and they concurred with our finding.

Table 6-5. Normalized PAR_{ni} estimates for a LAI of 5 with formula coded in BEIS-2 and correction to code.

Canopy Level	Normalized PAR_{ni} (error)	Normalized PAR_{ni} (correct formula)
1	0.98	0.81
2	0.94	0.53
3	0.90	0.35
4	0.86	0.23
5	0.83	0.15

6.3.3.1.4 Uncertainty of Hydrocarbon Environmental Factors

Some of the uncertainty associated with the Tingey (PC-BEIS, UAM-BEIS, GEMAP, VEGIES) and Guenther (BEIS-2) environmental factors can be estimated from a review by Sudol and Winer (1994). These authors report α-pinene (a monoterpene) emission rate changes from a dozen plant species to be as high as about 18 percent and as low as about 7 percent per degree Celsius. The rate of change applied by the Tingey algorithm (6.5 percent) is equivalent to the lowest reported measurement, and the rate of change applied by the Guenther algorithm (9.5 percent) is near the mean of the reported values. As a result, the Guenther algorithm provides a better description of the average change in monoterpene emissions with a change in temperature. The uncertainty associated with applying the Guenther algorithm can be estimated from the upper range of reported α-pinene emission rate changes per degree Celsius (18 percent). This uncertainty would be minimized at 30°C and about a factor of 2 at 20°C and 40°C, i.e.,

$$\textit{Uncertainty Factor } (T) = \frac{e^{[0.095(T-30)]}}{e^{[0.18(T-30)]}} \qquad \textbf{(6-9)}$$

Sudol and Winer (1994) plotted the Tingey and Guenther isoprene environmental factor values for light intensity values of 100, 200, 400, and 800 μE/m²/s for a range of temperatures from 10 to 50°C (see Figures 6-3 through 6-6). By reviewing these figures, we found the Guenther model (used in BEIS-2) predicted higher environmental correction factors for isoprene than Tingey (PC-BEIS, UAM-BEIS, GEMAP, VEGIES) for the temperature range of 20 to 35°C for light intensities from 0 to 400 μE/m²/s. The difference between these models was largest at the lowest light intensity plotted (100 μE/m²/s), in which the Guenther model (BEIS-2) was a factor of 5 larger than Tingey. For light intensities from 200 to 400 μE/m²/s, the Guenther model was about a factor of 2 higher than Tingey from 25 to 35°C. At a light intensity of 800 μE/m²/s, the Guenther and Tingey models are similar over the temperature range of 10 to 35°C. At temperatures above about 35°C, emissions are reduced in the Guenther model from their peak, while the Tingey model predicts continued high emission rates. The Guenther model (Guenther *et al.*, 1991, 1993) behavior at temperatures above 35°C has been shown to accurately model actual plant behavior whereas the Tingey model does not.

Based on this information, it seems that using the Guenther model will increase isoprene emissions over using the Tingey model by a factor of 2 to 5 for the temperature range of 25 to 35°C and for light intensities of 0 to 400 μE/m²/s. However, the differences between the models for low light intensities is not as important since the light intensities expected during peak ozone generating conditions are generally greater than 800 μE/m²/s.

In view of this information, we would expect the Guenther model to predict higher emissions than the Tingey isoprene model in the summer when the temperature is relatively high (25 to 35°C). We would also expect the difference in the daily-averaged environmental-correction factors from these two models in such situations to be no greater than a factor of 2. A larger difference is not expected because the highest isoprene

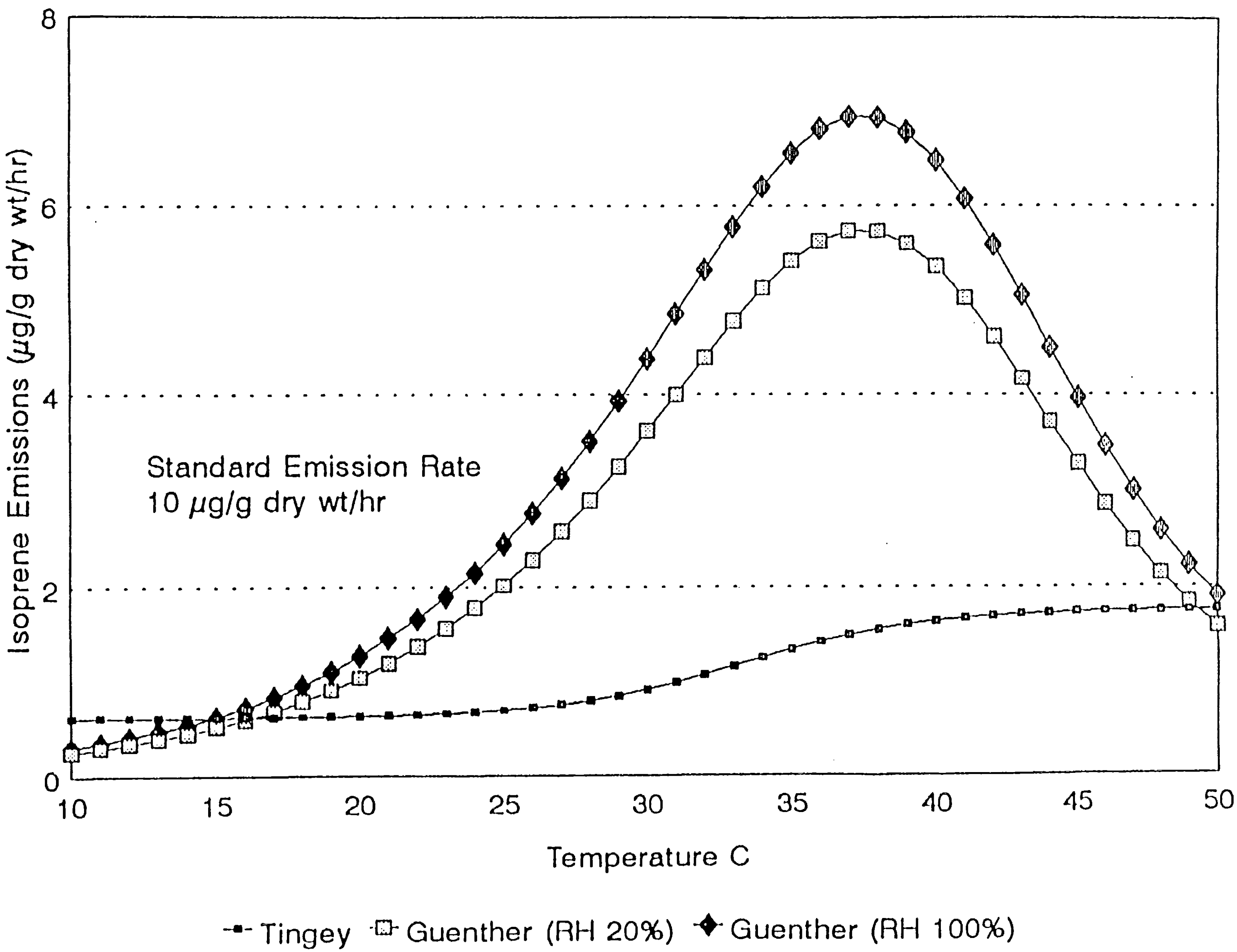


Figure 6-3. Effect of temperature on isoprene emission rate: comparison of Tingey algorithm versus Guenther algorithm. Output is based on light intensity of 100 $\mu E/m^2/s$ (Sudol and Winer, 1994).

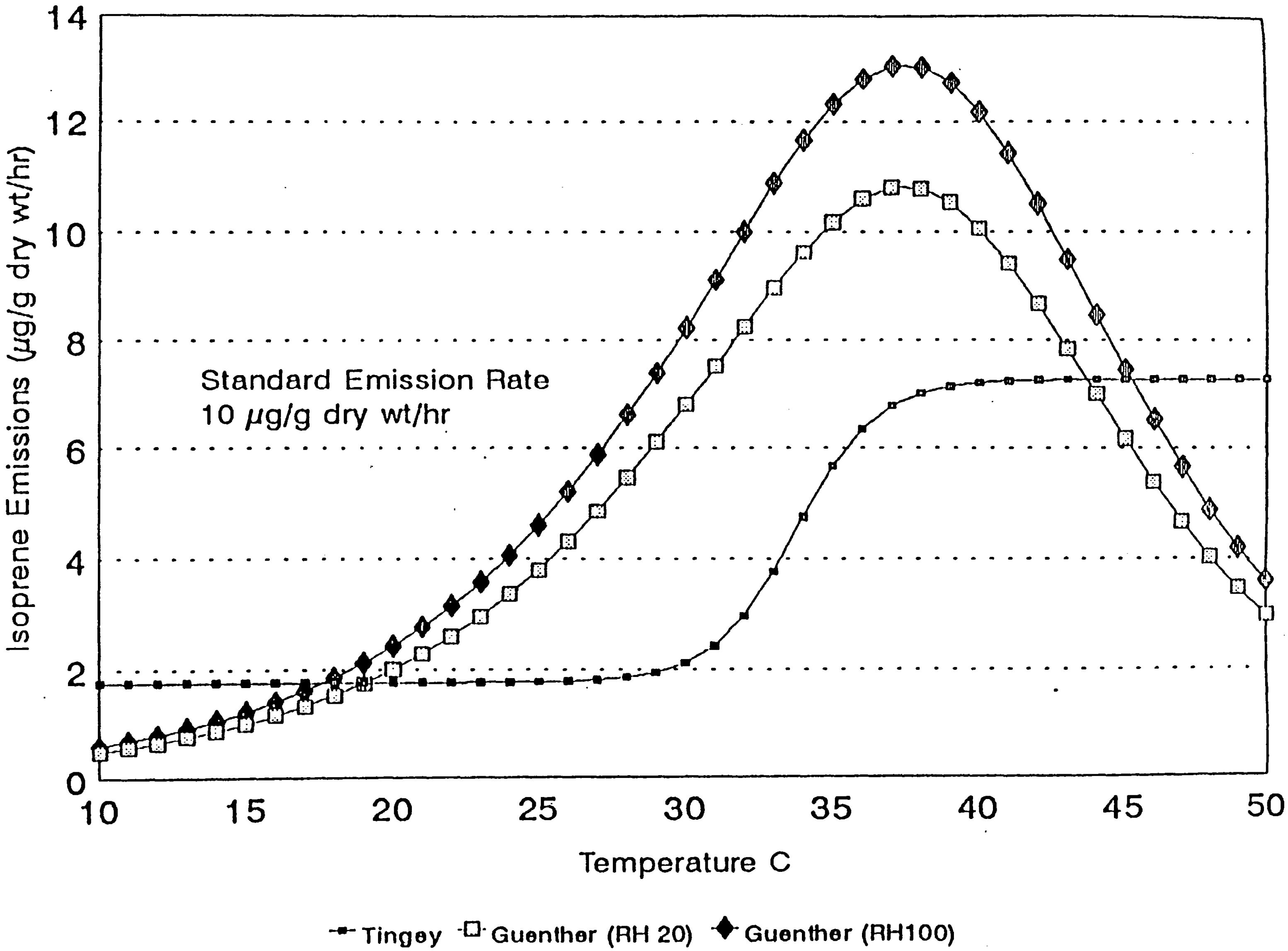


Figure 6-4. Effect of temperature on isoprene emission rate: comparison of Tingey algorithm versus Guenther algorithm. Output is based on light intensity of 200µE/m^2/s (Sudol and Winer, 1994).

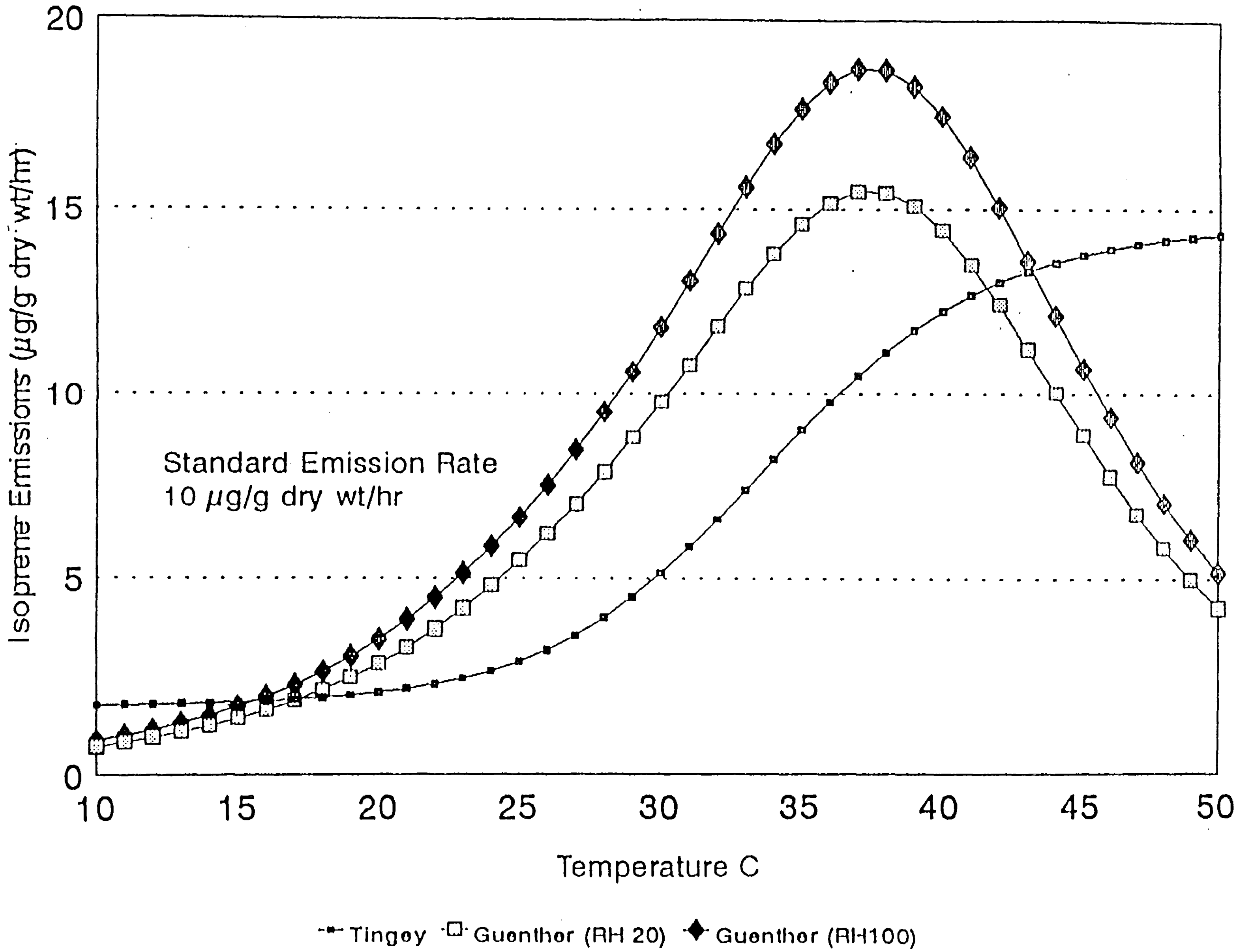


Figure 6-5. Effect of temperature on isoprene emission rate: comparison of Tingey algorithm versus Guenther algorithm. Output is based on light intensity of 400µE/m^2/s (Sudol and Winer, 1994).

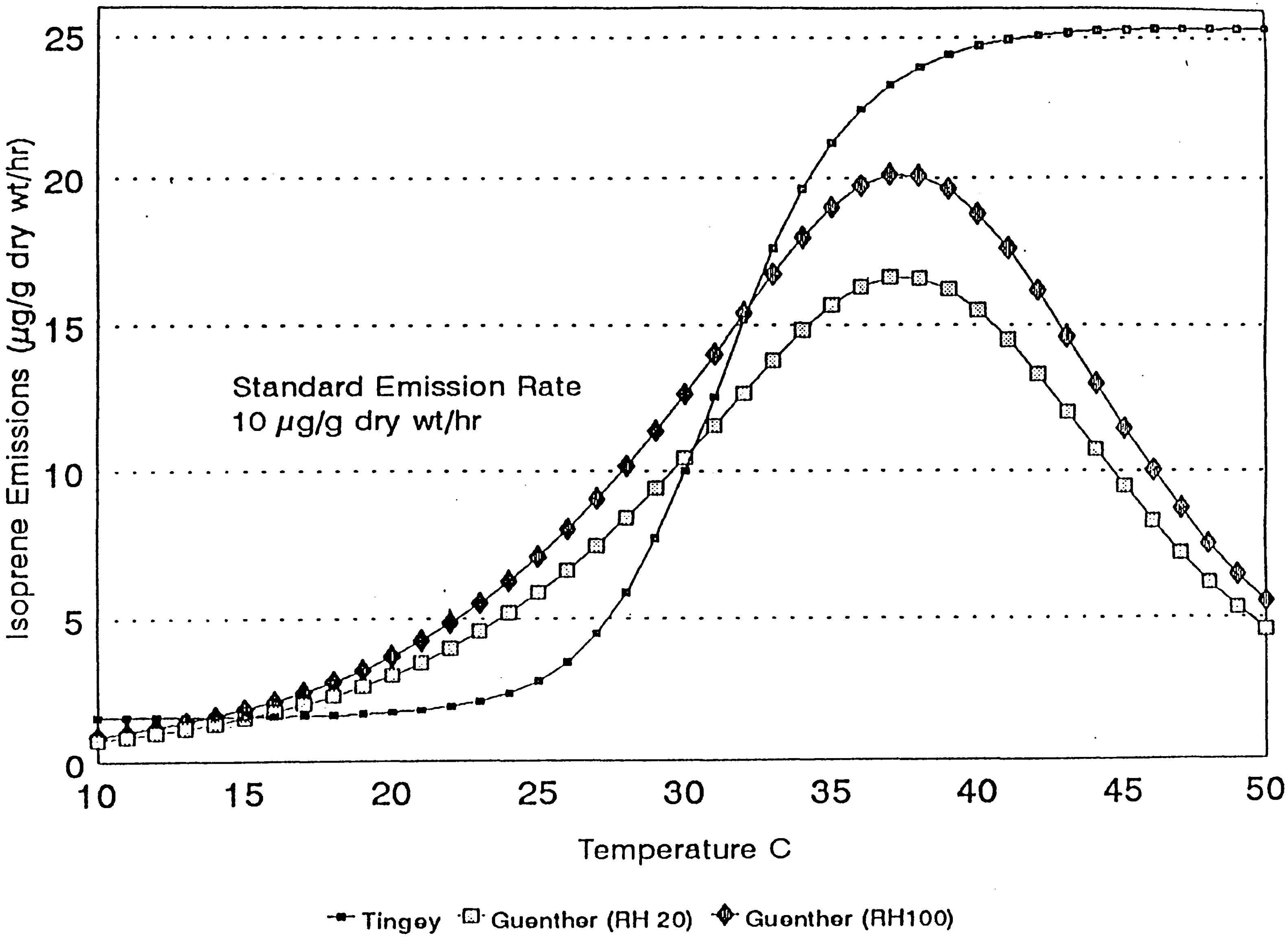


Figure 6-6. Effect of temperature on isoprene emission rate: comparison of Tingey algorithm versus Guenther algorithm. Output is based on light intensity of 800µE/m^2/s (Sudol and Winer, 1994).

emission rates occur when the light intensity is high (> 400 $\mu E/m^2/s$); both models perform similarly in such conditions except for extremely high temperatures (> 40°C), where the Guenther model predicts lower emissions. In addition, although significant differences exist between these models at lower light intensities, on a daily-average basis these effects will be dampened by the similar maximum isoprene emission rates predicted by both models at midday. Nevertheless, emission rate differences at non-midday hours could be important for photochemical model performance. Additional detailed discussion of emission rate factor temperature dependance is provided in preceding chapters.

6.3.3.1.5 <u>Other Environmental Factors</u>

Guenther *et al.* (1991) recommend including ambient relative humidity and the CO_2 concentration as additional isoprene environmental factors. The environmental adjustment algorithms reported by Guenther *et al.* (1991) for the relative humidity and CO_2 isoprene factors are as follows:

$$H = RH\,H_1 + H_2 \qquad \textbf{(6-10)}$$
$$C = [CO_2]\,C_1 + C_2$$

where H is the correction factor for humidity, RH is the relative humidity (%), H_1 equals 0.00236 and H_2 equals 0.8495. C is the correction factor for CO_2, and $[CO_2]$ is the CO_2 mixing ratio (ppm). C_1 and C_2 equal 0.00195 and 0.805 for $[CO_2]$ below 100; they are equal to 0 and 1 for $[CO_2]$ values between 100 and 600 ppm; and they are equal to -0.00041 and 1.28 for $[CO_2]$ values greater than 600 ppm. By reviewing these formulas, we estimate that these effects could change the isoprene emission rate by up to 16 percent due to relative humidity and 20 percent due to the CO_2 concentration.

As will be further discussed later, gridded meteorological inputs (including RH, temperatures, winds) are prepared for UAM simulations as part of the UAM meteorological input preparation process. CO_2 is generally not considered as a reactant in photochemistry and is not generally estimated for use in UAM simulations and thus will not be readily available for use in estimating biogenic emissions. It should be emphasized that both RH and CO_2 were deleted from the most recent algorithms developed by Guenther *et al.* (1993) as contributing only second-order effects. For a more detailed discussion, see Section 4.8.

6.3.4 Soil NO_x Emission Estimates

6.3.4.1 Background

Although soil NO_x emissions were not a focus of this study, we have conducted a brief review of the literature on this subject and of the soil NO_x model codes in the biogenic models reviewed in this study, and briefly summarize our findings in this section. Additional discussion and data are presented in Section 4.9.

NO_x is produced in soils by microbial processes of nitrification and denitrification and by several chemical mechanisms that involve nitrite. NO is the principal nitrogen species emitted (NO_2 accounts for less than 10 percent of the total emissions). It has long been known that soil nitrogen emissions also include N_2O (see Anderson and Levine, 1987), which is not an ozone precursor. However, the key issue involved in assessing the impact of soil emissions on ozone production is the quantity of biogenic NO_x relative to anthropogenic NO_x emitted in any given area.

Table 6-6 (Anderson and Levine, 1987) summarizes the global NO budget as estimated by several researchers. The estimates for the contribution of biogenic production (emission from soils) range from negligible to as much as 25 percent. The large uncertainty is caused by the vast number of species involved and the paucity of measurements. There are particularly few measurements in the western U.S. Nonetheless, Williams *et al.* (1992) estimated the biogenic emissions of NO for the month of July throughout the United States by combining emission information with land-use type, and their results are shown in Figure 6-7 (Williams *et al.*, 1992). Figure 6-8 (Williams *et al.*, 1992) shows their estimates for anthropogenic NO_x emissions. A comparison of these figures suggests that in some portions of the Central Valley of California, the biogenic NO_x emissions are commensurate to the anthropogenic NO_x emissions. The high biogenic NO_x emission estimates in the Central Valley may be a

Table 6-6. Global tropospheric sources of NO (Anderson and Levine, 1987).

	Baulch et al. (1982)	Ehhalt and Drummond (1982)	Logan (1983)	Stedman and Shetter (1983)	National Academy of Sciences (1984)
Surface sources					
Fossil fuel combustion	8.2-18.5	13.5(8.2-18.5)	21(14-28)	20(18-22)	15-25
Biomass burning	10-40	11.2(5.6-16.4)	12(4-24)	5(1.7-15)	1-10
Biogenic production	0-15	5.5(1-10)	8(4-16)	10(5-20)	1-10
Atmospheric sources					
Lightning	3-4	5(2-8)	8(2-20)	3(1.5-6)	2-20
NH_3 oxidation	---	3.1(1.2-4.9)	1-10	1(0.5-2)	≤5
From stratosphere	0.5-1.5	0.6(0.3-0.9)	0.5	1(0.5-2)	0.5-1.5
High-flying aircraft	0.25	0.3(0.2-0.4)			0.15-0.3
Total	22-80	39(19-59)	50(25-99)	40(27.2-67)	20-70

Units are Mt(N) yr^{-1}.

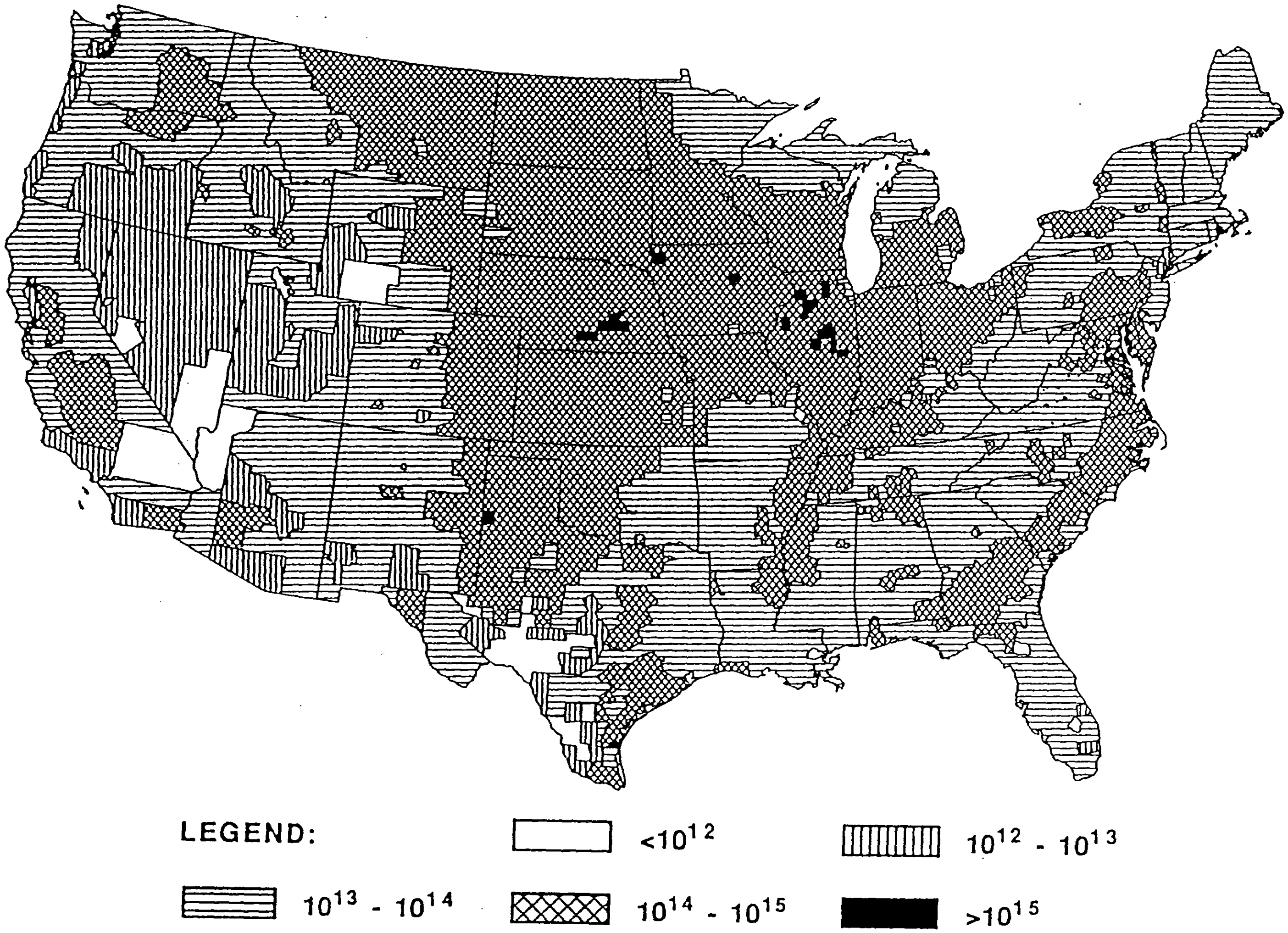


Figure 6-7. July-averaged emissions of nitric oxide from U.S. soils in molecules of NO per square meter per second. The different emission levels are shown in the legend below the figure (Williams *et al.*, 1992).

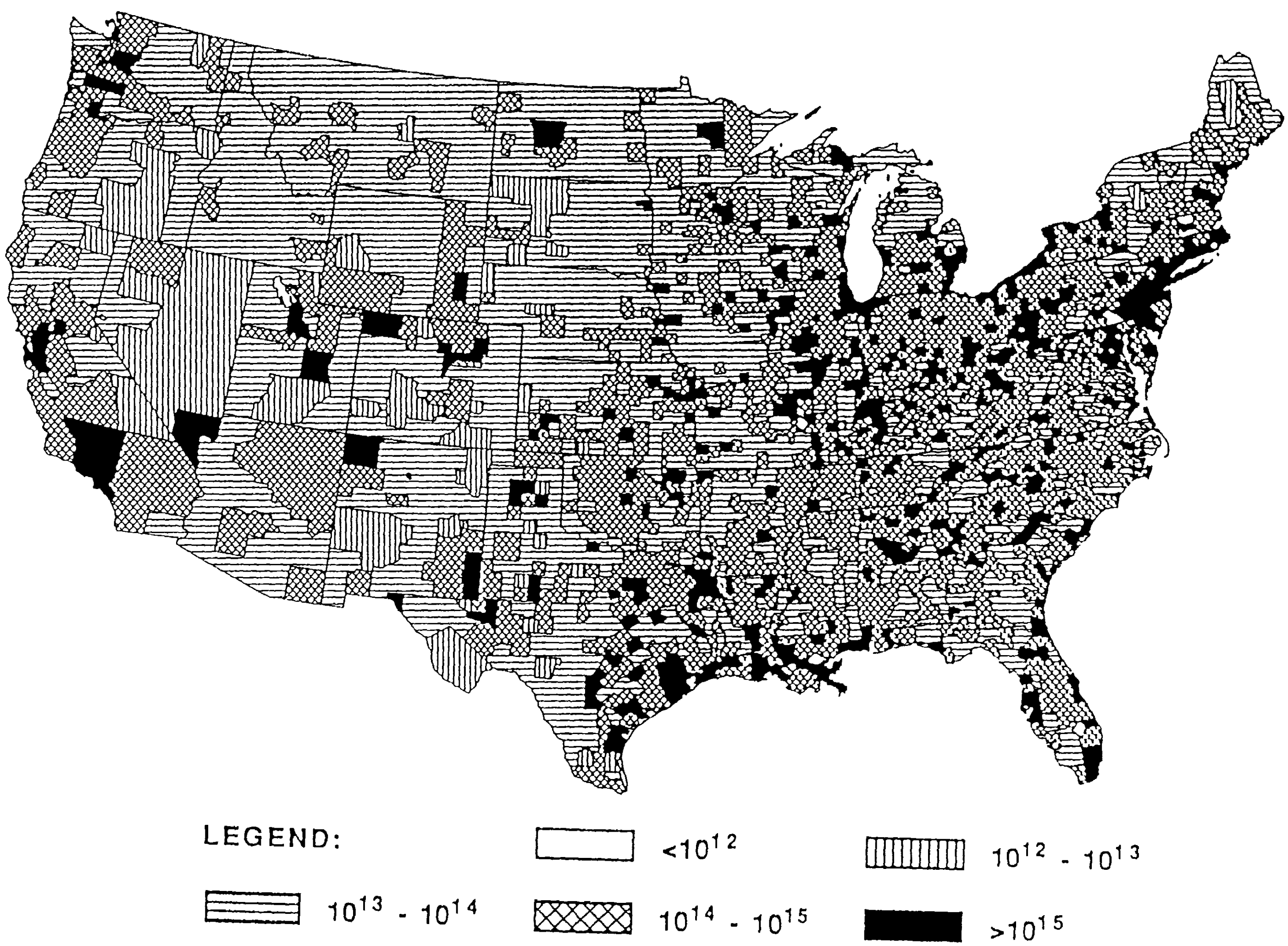


Figure 6-8. Anthropogenic point and area source emissions of NO for an average day in July in molecules of NO per square meter per second. The different emission levels are shown in the legend below the figure (Williams *et al.*, 1992).

result of the large amount of agriculture in this area, which is one of the highest categories of biogenic NO_x emissions.

We also examined materials from a recent presentation by EPA for a Regional Oxidant Model (ROM) application in the eastern United States (Pierce, 1994). In that study domain, emission estimates of soil NO_x using BEIS-2 accounted for 20 percent of the overall NO_x (e.g., anthropogenic and biogenic), in spite of the fact that 40 percent of the modeling domain in the study area was covered with water (where no NO_x emissions are produced). The next two largest land-use types are agriculture and forest, which cover 24 and 23 percent, respectively, of the model domain.

Pierce (1994) also reports the need to be concerned with NO_x emissions in the Central Valley of California because of the large amounts of fertilizer being applied. Existing data on this subject is sparse. Pierce (1994) states chamber studies need to be coupled with atmospheric measurements to obtain a reliable picture of the NO_x flux over agriculture fields. He intends to work on such an experiment in North Carolina next year. We recommend ARB sponsor similar research in California. Given the importance of biogenic NO_x emissions in that study domain and because the Central Valley of California is primarily covered with agriculture, it seems likely that biogenic NO_x emissions need to be included for photochemical modeling in that airshed.

The finding that biogenic NO_x emissions cannot be ignored in California agrees with a previous study sponsored by ARB that focused on explaining SO_x and NO_x deposition data in California using a Long Range Transport (LRT) model. It is our understanding the sulfate data were explained fairly well by the LRT model, while the NO_x data were consistently underpredicted by the model, especially in the San Joaquin Valley. Those results re-enforce our belief that biogenic NO_x emissions may be important in California's agricultural regions. Although it is not clear what role soil NO_x plays in the urbanized portions of California, we recommend ARB sponsor a study to resolve the NO_x deposition data using a long-range transport model with both anthropogenic and biogenic NO_x emissions. This could help determine whether existing soil NO_x models can help explain NO_x deposition data collected in California.

6.3.4.2 Model Formulations

The biogenic emissions model for soil NO_x is denoted by the following equation:

$$Q_{NO} = \sum_{J=1}^{n} A_j \, BF_j \, F_{NO} \, (S,T) \qquad \textbf{(6-11)}$$

where Q_{NO} (μg/hr) defines the biogenic NO_x emission rate. In this formula, one inputs a standardized flux for NO_x denoted by BF_j (μg NO_x/m^2 hr), applicable to 30°C. The value of BF_j varies with land-use type. A_j is the area (m^2) occupied by land-use type j, and $F_{NO}(S,T)$ is the NO_x environmental adjustment factor. Of the biogenic models reviewed in this study, only the UAM-BEIS and BEIS-2 models estimate biogenic soil NO_x emissions.

UAM-BEIS and BEIS-2 calculate soil NO_x emissions and their environmental adjustment factors in different manners. BEIS-2 calculates the environmental adjustment factor in a separate step, while UAM-BEIS calculates an emission flux (which includes an environmental adjustment factor) and multiplies the flux by the area of vegetation type in a separate step. Both models rely on the approach developed by Williams *et al.* (1992), who proposed the following equations:

Grass:

$$s = 0.66\,(T_{air} - 273) + 8.8 \qquad \textbf{(6-12)}$$

$$BF_j\,F_{NO}(S,T) = 0.9\ (\mathrm{ng\ N/m^2/s})\ \ e^{[0.071\ s]}$$

Forest:

$$s = 0.84\,(T_{air} - 273) + 3.6 \qquad \textbf{(6-13)}$$

$$BF_j\,F_{NO}(S,T) = 0.07\ (\mathrm{ng\ N/m^2/s})\ \ e^{[0.071\ s]}$$

Agriculture (Cotton, Wheat, Soybeans):

$$s = 1.03\ (T_{air} - 273) + 2.9 \qquad \textbf{(6-14)}$$

$$BF_j\ F_{NO}(S,T) = A\ (ng\ N/m^2/s)\ \ e^{[0.071\ s]}$$

Wetlands:

$$s = 0.92\ (T_{air} - 273) + 4.4 \qquad \textbf{(6-15)}$$

$$BF_j\ F_{NO}(S,T) = 0.003\ (ng\ N/m^2/s)\ \ e^{[0.071\ s]}$$

where A is the pre-exponential coefficient and equals 4 ($ng/m^2/s$) for cotton, 3 ($ng/m^2/s$) for wheat, and 0.2 ($ng/m^2/s$) for soybeans. In reviewing the UAM-BEIS code and Williams *et al.* (1992) formulas, the most important differences between these are their treatment of the pre-exponential coefficient for agricultural crops. UAM-BEIS applies a pre-exponential coefficient of 0.2 ($ng\ N/m^2/s$) for all agriculture crops. Williams *et al.* (1992) recommends varying the pre-exponential coefficient between 0.2 and 9 $ng\ N/m^2/s$, depending upon the crop. BEIS-2 treats species within the same land-use type in this manner. This is done in BEIS-2 by reading a data file containing more than 200 pre-exponential coefficients to distinguish between more than 200 plant species. This allows BEIS-2 to be more accurate than UAM-BEIS, because it has the capability to differentiate between NO emissions from different tree species (e.g., spruce, oak, fir) and agricultural crops (oats, peanuts, corn, cotton, soybeans, etc.). For example, use of the BEIS-2 pre-exponential coefficients results in soil NO_x emissions about 15 to 20 times larger than those predicted in UAM-BEIS for cotton and wheat, and from corn by a factor of 45.

BEIS-2 uses similar environmental adjustment factors to those of UAM-BEIS. After some mathematical manipulations of the BEIS-2 source code, it can be shown that the BEIS-2 environmental factors are as follows:

Grass:

$$s = 0.66\ (T_{air} - 273) + 8.8 \qquad \textbf{(6-16)}$$

$$F_{NO}(S,T) = 0.118\ e^{[0.071\ s]}$$

Forest:

$$s = 0.84\,(T_{air} - 273) + 3.6 \qquad \textbf{(6-17)}$$

$$F_{NO}(S,T) = 0.118\, e^{[0.071\, s]}$$

Agriculture (Corn):

$$s = 0.72\,(T_{air} - 273) + 5.8 \qquad \textbf{(6-18)}$$

$$F_{NO}(S,T) = 0.118\, e^{[0.071\, s]}$$

Wetlands:

$$s = 0.92\,(T_{air} - 273) + 4.4 \qquad \textbf{(6-19)}$$

$$F_{NO}(S,T) = 0.118\, e^{[0.071\, s]}$$

BEIS-2 normalizes the environmental adjustment factor for soil NO_x to 30°C using a factor of 0.118 (see above). Also note that BEIS-2 uses a different exponential factor for agricultural crops than UAM-BEIS. BEIS-2 uses the factor from Williams *et al.* (1992) for corn, while UAM-BEIS uses the factor from soybean.

6.4 Comparison of Model Predictions to Observations

One approach for evaluating the current generation of biogenic emission models is to compare model predictions with observations. Geron *et al.* (1994) compared model predictions to observation of isoprene and monoterpene emissions at selected sites in the United States. Their study used the emission factors and environmental adjustment algorithms of Guenther *et al.* (1991)(used in BEIS-2). Sites were located in Alabama, Georgia, and Washington. A site measuring isoprene emissions was located in Pennsylvania and a site measuring monoterpene emissions was located in North Carolina.

Figure 6-9 shows the relationship between observed and Guenther *et al.* (1991) predicted isoprene and monoterpene emission rates. Geron *et al.* (1994) report that for both isoprene and monoterpenes, two-thirds of Guenther predictions fall within 50 percent

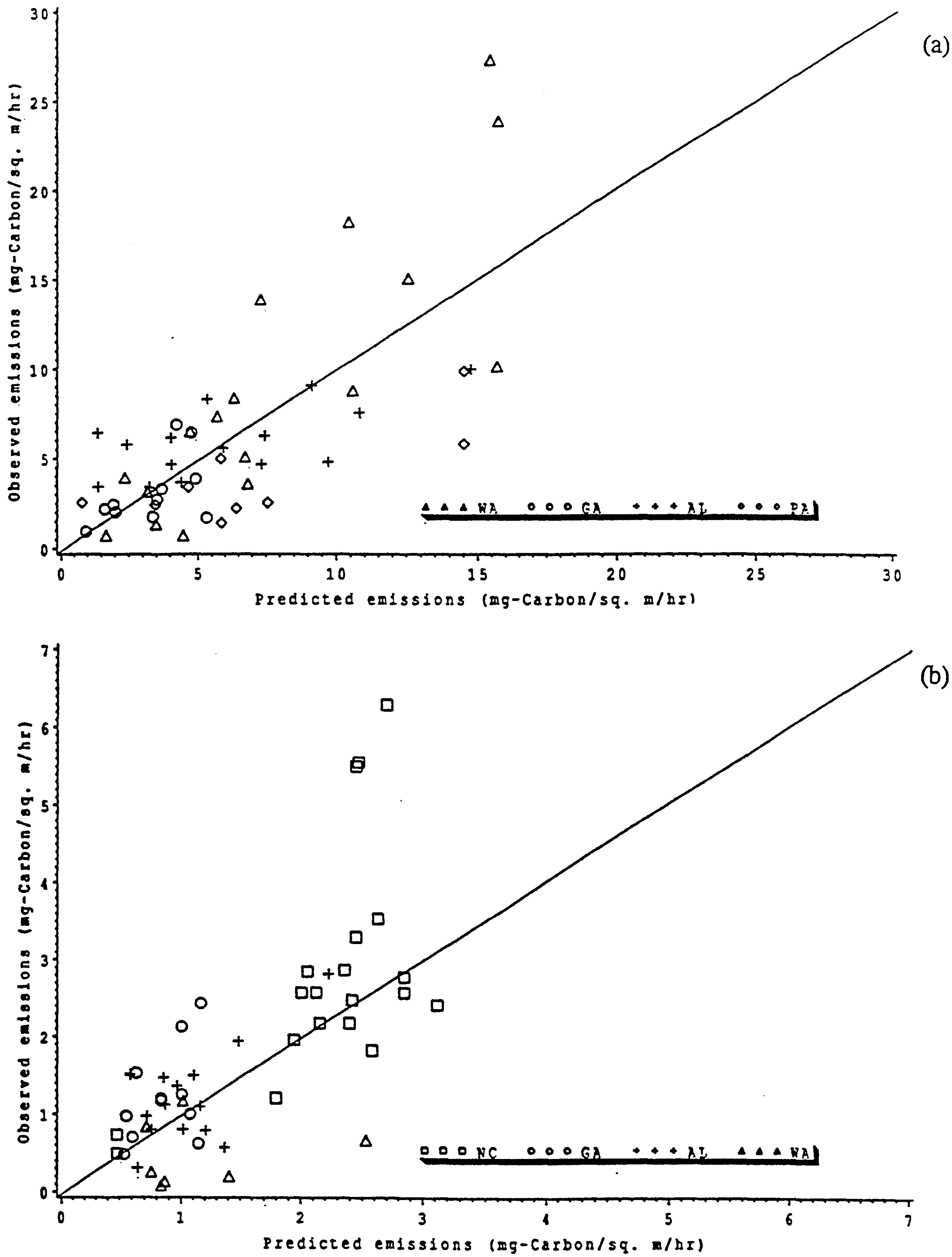


Figure 6-9. Predicted versus observed (a) isoprene and (b) monoterpene emission rates (mg-C m-2 h-1) for four forested sites. Diagonal lines represent perfect agreement between the observed values and model estimates. The codes in the legends refer to the state where the measurements were made (Geron et al., 1994).

of the measured rates. The highest observed isoprene emissions were measured at the Washington site, where the forest canopy composition was almost 100-percent oak. On average, predicted emission rates at the Washington site agree reasonably well with observations, although predictions deviated by as much as a factor of 2 when compared to individual observations. At the Alabama site, isoprene emissions measured at temperatures less than 30°C were consistently overestimated by the model, but underestimated at higher temperatures. The model also consistently overpredicted isoprene emissions at the Pennsylvania site, with the average error about a factor of 2. The lowest isoprene emission rates were recorded at the Georgia site.

Comparisons of measured and predicted monoterpene emissions showed similar patterns to those found for isoprene emissions. The highest concentrations were observed at the North Carolina lobolly pine stand. Although the model underpredicted the highest observations reported at the North Carolina site by a factor of 3, the model was reported (Geron *et al*., 1994) to overpredict emissions from another lobolly pine stand by a factor of 2 to 4 (data not shown). At the Washington site, monoterpene emissions were consistently overpredicted by factors as high as 2 to 8. Average predicted monoterpene emissions at the Alabama site agreed with observations, although predictions deviated by as much as a factor of 2 when compared to individual observations. There were consistent model underpredictions of monoterpene emissions at the Georgia site, in general, by about a factor of 2.

It is important to note that the uncertainty typically attributed to micrometeorological emission rate measurement techniques at sites like the ones discussed above are on the order of 50 percent. This uncertainty is carried into the model predictions and to some extent contributes to poor model performance. It should be noted the emission factors used by Geron *et al.* (1994) to calculate emissions involve a reference PAR flux of 800 uE/m2/s. However, Lamb *et al.* (1993), the source of these data, reported that the data better fit a model based on 400 $uE/m^2/s$. The response to temperature is much less at lower light levels and should significantly affect these results.

In another study, Fujita *et al.*(1994) discussed the predictive capability of GEMAP. Using the Chemical Mass Balance (CMB) receptor model to estimate emissions in the

SJVAQS/AUSPEX region, CMB predicted that the Yosemite and Giant Forest (located in Sequoia National Park) sites were the only ones showing significant contributions (about 10 to 15 percent of total non-methane organic gas) from biogenic emissions. However, the relative contributions of biogenic emissions calculated using the biogenic processor of GEMAP were significantly higher than CMB estimates at these sites (58 and 50 percent for Yosemite and Giant Forest, respectively). GEMAP also predicted substantial emissions at other sites, while CMB only predicted significant emissions at the Yosemite and Giant Forest site. Fujita *et al.* (1994) noted several explanations for the lower relative contributions of biogenic emissions, such as the transport of anthropogenic emissions from other areas into Yosemite and Giant Forest, and the reaction of some biogenic emissions in the atmosphere. As a result of these limitations, the true contributions of biogenic emissions could not be assessed. Nevertheless, Fujita *et al.* (1994) concluded that biogenic emissions are probably overestimated by GEMAP because CMB did not detect significant contributions from biogenic emissions at other sites in the SJV, where GEMAP predicted biogenic emission estimates in excess of those in the vicinity of the Yosemite and Giant Forest sites.

6.5 Model Intercomparison

Another approach to quantifying differences in these biogenic models is through model intercomparisons. Although there were no model comparisons with VEGIES available for our review, UAM-BEIS, BEIS-2, and GEMAP comparisons were available in the literature. UAM-BEIS and GEMAP were applied in the Midwest (Mayenkar, 1993) as part of the Lake Michigan Ozone Study (LMOS). It should be noted that the LMOS version of GEMAP is not the same as that applied to the AUSPEX region. In fact, we did not have nearly as detailed information on the inputs to this application of GEMAP as with AUSPEX. In the LMOS, emission predictions were found to be comparable for isoprene and higher aldehydes for the two models. Paraffin and olefin predictions differed by a factor of 3, with BEIS giving the higher emission rate. It is believed that the olefin and paraffin differences between the two models were due to revisions to GEMAP species-specific emission factors for corn based on more recent data than was available at the time BEIS was run. Note that the version of PC-BEIS reviewed in this project contains the revised emission factors for corn. Recall that BEIS and GEMAP also apply the same Tingey environmental factors and the same canopy model. As a consequence, it appears that BEIS and GEMAP are now comparable models.

EPA is currently comparing BEIS-2 and BEIS. Pierce (1994) showed BEIS-2 predicts substantially higher biogenic isoprene and monoterpene emissions during the summer months compared to BEIS. For example, in one study cited by Pierce, BEIS-2 predicted 47-percent higher monoterpene emissions when compared to BEIS. However, there was no obvious reason for the large increase. One might speculate the increase was due to the differences in biomass factors between the models; the biomass factors in BEIS-2 are about double those used in BEIS for Abies, Picea, Tsuga, and Pseudotsuga genera. However, these species did not appear to be prevalent in the study domain. Changes in the environmental factor algorithms for monoterpenes from BEIS to BEIS-2 lead to both increases and decreases in emissions for monoterpenes depending on temperature and light intensity. Another possible explanation is the cumulative effect of changes in individual emission factors between the two models.

At the same site, BEIS-2 also predicted approximately 400-percent higher isoprene emissions than BEIS. Again, it is not likely the increase in the isoprene emissions is due to the doubling of the biomass factors for Albies, Picea, Tsuga, and Pseudotsuga, because these species did not appear to be prevalent in the study domain. A factor of 2 increase in the isoprene emission rate was expected from BEIS-2 relative to BEIS because of differences in the Tingey and Guenther environmental factor algorithms. Because the study domain contained a large area of oak trees, it can also be argued BEIS-2 would include an additional factor of 2.5 increase in the isoprene emission rate relative to BEIS. This is possible if BEIS-2 applied an isoprene emission factor of 7350 $\mu g/m^2/hr$, which is reported for oak savannah, while BEIS applied an isoprene emission factor of 3108 $\mu g/m^2/hr$ for oak. It is also important to recall that a coding error was found in BEIS-2 that would also lead to a higher BEIS-2 isoprene emission rate than would be predicted by BEIS.

6.6 Application of Biogenic Emission Models in a UAM Framework

Biogenic emissions have been used in photochemical models such as the UAM along with anthropogenic emissions for about the last decade. The first routine use came with the release of the EPA's UAM-BEIS in the late 1980s. The EPA has released specific guidance for regulatory applications of the UAM (EPA, 1991). Input preparation guidelines for the UAM include specific requirements for gridding surface temperature, winds, relative humidity, pressure, and cloud cover. The guidelines permit either interpolation of meteorological observations or prognostic meteorological modeling to prepare the gridded meteorological inputs for use in the UAM. In addition, the UAM requires gridded land-use data to estimate surface roughness factors used in calculating air pollutant deposition velocities.

UAM-BEIS, GEMAP, VEGIES, and BEIS-2 are designed to accept gridded meteorological inputs for use in calculating environmental adjustment factors and emission rates, it is only natural that one would recommend the use of the UAM gridded inputs as a likely source of the gridded inputs for the biogenic emission models. The use of the same gridded inputs ensure consistency of meteorological conditions for emission estimation and air quality modeling and consistency between the land-use data for surface roughness and vegetation types used in the emission rate calculations.

The user's guide for UAM-BEIS (EPA, 1992) describes the use of default input values for county land use and corresponding biomass factors. The biomass factors are adjusted within UAM-BEIS by time of year of the modeling episode. The UAM-BEIS also permits the use of alternative user-supplied inputs for land use. In its default mode, the UAM-BEIS allocates county-wide emissions to individual grid cells by apportioning the county total to the portion of the county in a given grid cell. Alternatively, a gridded land-use file may be used to develop more highly resolved allocations of the county total biogenic emissions. UAM-BEIS-2 does not allow the user to input their own gridded land-use. The only option is the UAM-BEIS default mode. This method may result in significant spatial misallocation of emissions when the modeling domain is a heterogeneous land area. Thus, UAM-BEIS-2 needs to be modified to allow the input of user-supplied gridded land-use. The UAM-BEIS and UAM-BEIS-2 models also require hourly surface meteorological data on relative humidity and cloud cover for at least one site in the modeling domain and expects to have a gridded temperature and wind field produced by the UAM temperature and winds preprocessors.

Historically, the inputs needed for biogenic emission models have been developed from data available at sub-county resolution and then aggregated to county totals. While this approach may be adequate for large regional scale photochemical modeling such as the Regional Oxidant Model (ROM), a better approach would maintain the resolution of the raw data at the highest level possible.

6.7 Summary and Conclusions

Four biogenic emission modeling systems were reviewed: BEIS (PC-BEIS and UAM-BEIS), BEIS-2 (PC-BEIS-2 and UAM-BEIS-2), VEGIES, and GEMAP. These models all predict biogenic hydrocarbon emissions by multiplying the following four parameters for each species and summing the species emissions:

Area covered by specific species

- Leaf biomass factor for specific species
- Emission factor for specific species
- Species-specific environmental adjustment factor

Table 6-7 summarizes the methods used by each of these models for parameter estimation. The table also lists the minimum estimated uncertainty factor for each parameter based on qualitative assessments for each parameter. The estimated minimum uncertainties are as much as a factor of 2 in the formulas applied by the emission models to predict VOC leaf biomass, plant specific VOC emission factors, VOC environmental factors, and soil NO_x emissions.

Our analysis of the appropriateness of each of the models for use in modeling biogenic hydrocarbon emissions in California has yielded the following observations for each of the models:

Table 6-7. Features of the biogenic models reviewed.

Model	Land-Use Coverage	Leaf Biomass	Vegetation Specific Emission Factors	Environmental Factor	Biogenic NO_x Model
BEIS	Geocology	Lamb et al., 1987	Lamb et al., 1987	Tingey et al., 1979, 1980	NO
UAM-BEIS	Geocology	Lamb et al., 1987	Lamb et al., 1987	Tingey et al., 1979, 1980	YES
GEMAP	Satellite imagery, USGS land use	Sidawi and Horie, 1992	Sidawi and Horie, 1992	Tingey et al., 1979, 1980	NO
VEGIES	N/A	N/A	Causley and Wilson, 1994	Tingey et al., 1979, 1980[a]	NO
BEIS-2	U.S. Forest Service, AVHRR	Guenther et al., 1995	Guenther et al., 1995	Guenther et al., 1991, 1993	YES
Estimated minimum uncertainty factor	No estimate	2	2	2.4	2[b]

[a] Includes a physically incorrect diurnal adjustment factor for monoterpenes.
[b] Based on differences in UAM-BEIS and BEIS-2 NO_x environmental factors.
N/A = Not available.

BEIS and BEIS-2

- BEIS and BEIS-2 do not adequately represent land-use type in California.

- BEIS and BEIS-2 emission factors are based on measurements made in the eastern United States and may not be representative of emissions of similar species in California.

- BEIS-2 is the only model to use the most recently developed environmental correction algorithm, which has been shown to be more accurate than the algorithm used in the other models. However, a small coding error in the application of these formulas was found and needs to be corrected.

- PC-BEIS and UAM-BEIS leaf models produce some unusual results.

- PC-BEIS-2 and UAM-BEIS-2 were the most robust and easily followed codes.

- UAM-BEIS-2 does not accept gridded land-use, which may result in spatial misallocation of biogenic emissions in modeling domains with heterogeneous land areas

GEMAP

- Applies emissions and biomass factors that are specific to the AUSPEX region.

- Applies the most extensive land-use coverage.

- Uses an outdated environmental correction factor algorithm.

- Does not have a soil NO_x module.

VEGIES

- Applies emission and biomass factors that are specific to the SCAQMD.

- Applies a physically incorrect solar radiation adjustment to monoterpene emissions.

- Does not adjust leaf temperature for canopy effects.

- Uses an outdated environmental correction factor algorithm.

- Does not have a soil NO_x module.

Given these observations, we can make several recommendations on what aspects of each model can be used to develop a state-of-the-art model that is optimized for use in California.

Land-use data are best represented by satellite imagery or areal photography. For example, Tanner *et al.* (1992) divided the SJVAQS/AUSPEX region into 39 vegetation types by satellite imagery. However, adequate "ground-truth" validation of the interpolated land-use distribution is needed, and the analysis needs to be extended to the remainder of California. The work of Tanner *et al.* (1992) provides a good starting point. For a more detailed discussion of imagery application, see Section 5.7.

Leaf biomass factors and species-specific emission factors are best represented by the GEMAP model for the AUSPEX region and the VEGIES model in the SoCAB. The BEIS-2 model has significantly fewer leaf biomass and species-specific emission factors, and the emphasis in BEIS-2 is on the eastern United States where emission factors may be different than in California. Thus, GEMAP and VEGIES provide both the most comprehensive data base of leaf biomass factors and species-specific emission factors that are most applicable in California.

The environmental correction model proposed by Guenther *et al.* (1991) has been shown to agree better with existing observation than the earlier models of Tingey *et al.* (1979, 1980). At the time of this report, the Guenther algorithm is presently only incorporated into the BEIS-2 model, while the others still use the Tingey algorithm. None use the most recent algorithms by Guenther *et al.* (1993).

Although it was not the focus of this study, we have briefly reviewed the literature on biogenic soil NO_x, and have determined that while there are currently large uncertainties in soil NO_x emission estimates, present estimates suggest the need for their inclusion into UAM, and for further chamber and laboratory study. Only BEIS-2 and UAM-BEIS contain soil NO_x models. The estimation methods in both models are similar except that BEIS-2 used more crop-specific data on agriculture for its emission estimates. As agriculture is particularly important in California, the BEIS-2 model is likely to produce better estimates of soil NO_x.

6.8 Recommendations

BEIS-2 incorporates the most recent advances in environmental adjustments and it has a soil NO_x module. It is also the most robust and easily followed code. However, UAM-BEIS-2 must be modified to allow the input of user-supplied gridded land-use before it can be adequately used to provide biogenic emission inputs to UAM. GEMAP and VEGIES use input parameters that are more detailed and more specific to California than those used in BEIS-2. Fortunately, BEIS-2 can be modified to account for California-specific leaf biomass factors and species-specific emission factors, or GEMAP could be modified to incorporate the improvements of BEIS-2, including the addition of a biogenic soil NO_x module. If BEIS-2 is selected as the platform for California's biogenic model, we recommend that the area of vegetation types, the leaf biomass factors, and the species-specific emission factors used in GEMAP and VEGIES, plus supplements for the remainder of California, be incorporated.

In addition, since each of the models reviewed has desirable attributes, we believe a more quantitative comparison would be helpful in identifying model differences. This would involve running each model for a common set of inputs and comparing the results. Also a sensitivity analysis could be performed on input parameters such as leaf biomass factors and species-specific emission rates using the ranges of values reported in the literature for these parameters.

We also recommend that any California biogenic emission modeling system include an uncertainty module. The uncertainty module would allow the model to generate a range of reasonable (best estimate, high, low) biogenic emissions as input to an air quality model. In this way, optimal anthropogenic emission reduction scenarios for a range of biogenic emissions could be developed.

Although the environmental adjustment algorithms in BEIS-2 are generally superior to the algorithms in BEIS, it is important to note that BEIS-2 does not currently use a leaf energy model. In BEIS and GEMAP, Gay's leaf energy model was used to estimate the leaf temperature. As noted in our review of Gay's model, we found that the model was physically inconsistent and needed improvement. We believe ARB needs to consider adding a replacement leaf energy model, since it seems likely that leaf temperature will deviate significantly from ambient air temperature under conditions of direct sunlight. Furthermore, Gay's model lacked a leaf shading component, which is needed to reduce the modeled temperature of leaves in the shade relative to those in the direct sunlight. Given that a majority of leaves are expected to be in the shade for fully stocked stands of deciduous, coniferous or oak trees, this seems to be an important modeling component overlooked to date. We recommend ARB sponsor an experimental study to develop an adequate leaf canopy model to account for leaf shading effects.

Another item not addressed in any of the biogenic models reviewed in this study is the potential effect of plant stress (water shortage) or the presence of dew on leaves on emission rates from plants. Theoretically, plant stress or the presence of dew on leaves should reduce the emission rate from certain plants because they limit the mass transfer process. Little research is available on this subject, however. The effects of changes in plant physiology is included in some air quality models. For example, the dry deposition algorithm in UAM-V contains factors to reduce plant response as the result of stress or the presence of dew. We recommend ARB consider sponsoring laboratory research to investigate the magnitude of effect that plant stress or the presence of dew could have on emissions. In the interim, biogenic emission rates could be adjusted to account for plant response for stress or the presence of dew by using the existing responses assumed in the UAM-V dry deposition algorithm. At a later time, improved algorithms could be developed from experimental data.

Lastly, although biogenic soil NO_x emissions are very uncertain in magnitude, recent research indicates they may be as important as anthropogenic NO_x emissions in some rural parts of California. BEIS-2 and UAM-BEIS contain a biogenic soil NO_x emission model; PC-BEIS, VEGIES, and GEMAP do not have such a model. We recommend BEIS-2 be run and evaluated along with soil NO_x deposition data in the Central Valley of California to assess the accuracy of soil NO_x emission rates in the Central Valley. In addition, as noted earlier, Pierce (1994) states chamber studies need to be coupled with atmospheric measurements to obtain a true picture of the NO_x flux over agriculture fields. We recommend ARB sponsor research of this kind in California.

7.0 DATA DEFICIENCIES AND FUTURE RESEARCH NEEDS

As discussed in detail in this report, assessing the relative effectiveness of VOC vs. NO_x control, or simultaneous control of both precursors, in reducing photochemical smog in California's airsheds depends, in part, upon obtaining accurate biogenic emissions inventories for those airsheds. To date, biogenic emission inventory development in California has been based on a summation, or bottoms-up approach, which we believe is most likely to yield accurate results. However, while considerable progress has been made in quantifying the contribution of vegetation emissions of reactive organic gases in terms of identity, quantity, and reactivity, it is also apparent that many uncertainties remain which must be addressed by further research. The focus of this section is to identify research most likely to resolve key uncertainties in a cost-effective manner, and to suggest priorities among current significant deficiencies in needed data, methodologies, or models.

7.1 Emission Rate Measurements

A systematic experimental programs of emission rate measurements is needed for selected plant species which have not yet been investigated, with an emphasis on the most important species in California. Of the more than 500 plant species identified in the SoCAB and in other California airsheds, to date the biogenic hydrocarbon emissions of only about 125 have been measured. Fortunately, it may not be necessary to conduct measurements for all remaining species. Rather, taxonomic relationships and biomass considerations can be exploited to prioritize plant species for study cost-effectiveness.

For example, plant species which have been assigned either high emission rates or zero emission rates, based on taxonomic relationships, should be given highest priority, both in order to reduce the current level of uncertainty in emissions inventories, and to further test and validate taxonomic predictions. Similarly, plant species which comprise a large fraction of biomass or occupy extensive ground area should be given priority attention. The taxonomic methods developed by Benjamin *et al.* (1995) provide a basis for developing cost-effective criteria for choosing which plant species should be selected for future experimental studies. Generation of additional emission rate data for the most critical plant species in California's airsheds remains the most urgent research priority.

Ideally, emission rate measurements should be performed on a range of leaves, branches, and whole plants for a given plant species in order to develop a better understanding of the range of rates from that plant species. If possible, emission rate measurements should also be performed at various times of the year, or at least from early spring to late fall, to characterize any seasonal variations in emissions. Although a number of plant species have been shown to exhibit seasonal variation in emissions, to date most reported emission rates were obtained over a very limited time period (e.g. one day). For example, emission rates obtained in mid-summer do not account for either emissions from blooms in Spring or senescence and death in late summer of spring-growing annual species. It should be recognized that these more extensive investigations may be beyond current research resources, and should be assigned a secondary priority.

However, additional comparisons should be made between emission rate measurements using the enclosure method and measurements made with leaf cuvettes, a technique which could expedite gathering of emission rate data with accurate light intensity data.

7.2 Atmospheric Transformations

Rate constants are available for the reaction of isoprene and most of the important monoterpenes with OH and NO_3 radicals and ozone. Rate data are available for OH, NO_3, and O_3 with sesquiterpenes (Shu and Atkinson, 1994, 1995) and with *cis*-3-hexen-1-ol, *cis*-3-hexenylacetate, *trans*-2-hexenal, and linalool (Atkinson *et al.*, 1995, in press). However, additional kinetic data are required for the sesquiterpenes and other compounds identified as emissions from vegetation.

While the mechanism of reaction of isoprene with the hydroxyl radical has been well established, this is not true for mono- and sesquiterpenes. Further investigation concerning the mechanisms of reaction of such compounds needs to be performed, especially for α- and β-pinene, d-limonene, myrcene, and sabinene which are prominent emissions from a variety of plant species. Such studies of reaction mechanisms are required not only for OH radical reactions but also for reaction with NO_3 radicals and ozone. In addition to further investigations of the reaction mechanisms of parent compounds, the atmospheric fate of the secondary products produced by their reactions needs to be established, including not only chemical reaction pathways, but also wet and dry deposition rates and gas-to-particle formation processes.

To date, maximum incremental reactivities have been reported only for isoprene and α- and β-pinene. Further investigation is needed of the ozone-forming potential of additional important monoterpenes and other biogenic hydrocarbons.

7.3 Effects of Plant Stresses and Dew on Emission Rates

A factor not addressed in any of the biogenic emissions models reviewed in this study is the potential effects of plant stress (e.g. water shortage), or the presence of dew on leaves, on emission rates from plants. Laboratory research is needed to investigate the magnitude of these potential influences on emissions. In principle, plant stress or the presence of dew on leaves should reduce biogenic emission rates from certain plants because they limit the mass transfer process. However, there are few reports in the literature concerning this subject.

There is also a lack of information concerning the effect of ambient oxidants such as ozone and PAN on biogenic emission rates. It is well established these air pollutants cause plant injury and thus their corresponding effects (if any) on emission rates need to be established. While studies of this kind are desirable, they also must be assigned a secondary priority and would most properly be supported in programs of basic plant physiology research.

7.4 Improved Emission Algorithms

Further investigation is needed to improve existing emission rate algorithms in order to develop better estimates of emission fluxes under a variety of environmental conditions. At the present time, the most accurate emission rate algorithm is based on experimental data from only four plant species. An assessment of the environmental influences on emission rates is needed for additional plant species in order to improve the reliability of the present algorithms. These studies would most properly be conducted by those research groups which have specialized in the development of emission rate algorithms, and be supported by agencies other than the ARB.

7.5 Improved Canopy Correction Algorithms

Further investigation is required to develop improved canopy correction, or leaf shading, factors suitable for California's air basins. In particular, new canopy correction algorithms need to be developed, or existing algorithms validated, for the SoCAB and SJVAB. Specifically, the canopy correction algorithms developed by Gay (1987) and Lamb *et al.* (1993) are based on dense homogenous forest types and therefore may not be appropriate for the SoCAB and SJVAB, which contain quite dissimilar vegetative communities. The isolated or widely separated urban trees in these airsheds are not likely to be well modeled by current canopy correction algorithms. Similarly, the canopy correction factor developed by the SCAQMD, a blanket 23% reduction in emissions, is simplistic and may not represent actual emission reductions due to shading effects. Given the linear impact of such canopy correction factors on total emission inventories, the development of more applicable and reliable canopy algorithms is a high priority.

7.6 Validation of Compiled Biogenic Emission Inventories

Validation of compiled biogenic emission inventories for a variety of vegetative communities needs to be performed. One approach would involve comparing ambient air biogenic hydrocarbon measurements, utilizing grab sample, gradient, or tracer methodologies, with predictions from airshed models incorporating biogenic emissions inventories and models appropriate to a given airshed. Clearly, this is a difficult challenge given the complexity of the vegetative communities present, for example, in the SoCAB and SJVAB, and given the high photochemical reactivity of isoprene and the monoterpenes. The air quality study scheduled for the SoCAB in 1997 offers an opportunity to collect ambient air data for biogenic hydrocarbons which might be used to conduct such a validation. In addition to making ambient measurements of isoprene and monoterpenes (and other biogenic emissions), measurements, whenever possible, should be made of the reaction products which are less reactive than the parent biogenics (for example, methacrolein and methyl vinyl ketone from isoprene, and nopinone from β-pinene). This would enable the extent of transformations of the biogenic emissions to be taken into account, at least partially.

Emissions inventories of NO_x compounds from soils need to be compiled in order to determine their contribution to the total NO_x budget, especially in the SJVAB with its extensive agricultural activities. As discussed in more detail below, in section 7.7, knowledge of the NO_x emission flux from soil could have important implications for emission control strategies in those California air basins dominated by agricultural activities. Chamber studies should be coupled with atmospheric measurements to obtain a reliable data concerning NO_x fluxes from agricultural fields. We recommend such research be supported in California.

7.7 Quantitative Comparison of Emissions Models

Overall, BEIS-2 is currently the best biogenic emissions model available. It incorporates the most recent advances in environmental adjustments and has a soil NO_x module. It is also has the most robust and easily followed code. However, GEMAP and VEGIES use input parameters that are more detailed and more specific to California than those used in BEIS-2. Fortunately, BEIS-2 can be modified to account for California-specific leaf biomass factors and species-specific emission factors, or GEMAP could be modified to incorporate the improvements of BEIS-2, including the addition of a biogenic soil NO_x module. If BEIS-2 is selected as the platform for California's biogenic model, we recommend that the area of vegetation types, the leaf biomass factors, and the species-specific emission factors used in GEMAP and VEGIES, plus supplements for the remainder of California, be incorporated. Some features of UAM-BEIS should also be added into BEIS-2 to allow for direct use in UAM.

In addition, since each of the models reviewed has desirable attributes, we believe a more quantitative comparison would be helpful in identifying model differences. This would involve running each model for a common set of inputs and comparing the results. Also a sensitivity analysis could be performed on input parameters such as leaf biomass factors and species-specific emission rates using the ranges of values reported in the literature for these parameters.

We also recommend that any California biogenic emission modeling system include an uncertainty module which would allow the model to generate a range (e.g. best estimate, high, low) of biogenic emissions as inputs to an air quality model. In this way, optimal anthropogenic emission reduction scenarios for a range of biogenic emissions could be developed.

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As discussed in Section 7.3, another item not addressed in any of the biogenic models reviewed in this study is the potential effect of plant stress (water shortage) or the presence of dew on leaves on emission rates from plants. Theoretically, plant stress or the presence of dew on leaves should reduce the emission rate from certain plants because they limit the mass transfer process. Little research is available on this subject, however. The effects of changes in plant physiology is included in some air quality models. For example, the dry deposition algorithm in UAM-V contains factors to reduce plant response as the result of stress or the presence of dew. We recommend ARB consider sponsoring laboratory research to investigate the magnitude of effect that plant stress or the presence of dew could have on emissions. In the interim, biogenic emission rates could be adjusted to account for plant response for stress or the presence of dew by using the existing responses assumed in the UAM-V dry deposition algorithm. At a later time, improved algorithms could be developed from experimental data.

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7.8 Linkage of Remote Sensing to Emission Rates

Plant biophysical properties as inferred from chlorophyll content and water content are amenable to remote sensing. Unfortunately, no direct link shared among many plant species has been discovered between a measurable biophysical property and emission rate. Because of the enormous potential value of such a link, research is needed to explore whether such a link exists. However, no obvious experimental approach appears available at this time, and this is not judged appropriate research for support by ARB relative to other priorities identified in this study.

7.9 Validation of Plant Maps or Databases

For natural communities, further characterization of plant species distribution and/or community distribution and composition is needed. In particular, either California state cooperative vegetation type maps or CALVEG could be validated, for example through selective ground survey. Because CALVEG appears to be the only current GIS database for the SJVAB, validation through field studies is recommended. Given the direct importance of plant species and biomass distribution in compiling emission inventories, this is judged to be a high priority.

7.10 Biomass Constants

At present, there is a paucity of experimentally determined leaf mass constants for California plant species. Biomass constants should be determined in the field for key agricultural crops and for plants commonly found within the natural communities of the SoCAB and SJVAB. The highest priority plants in the SJVAB include agricultural crops occupying large acreages, such as cotton, almonds, and table grapes. Biomass constants are relatively easy to determine experimentally, and actual measurement is preferred rather than extrapolation or interpolation from plant data in the literature. Acquisition of these data for key plant species is a high priority relative to other data deficiencies identified here.

8.0 RECOMMENDED PROCEDURES FOR VERIFYING BIOGENIC EMISSION ESTIMATES USED IN PHOTOCHEMICAL MODELS

The intent of this section is to provide guidance to the ARB and ARB-supported researchers in assembling more reliable biogenic emission inventories for California's airsheds, and in the use of such inventories in photochemical models. The protocol recommendations given here arise from the critical review conducted in this report of past and present practices in each step necessary in generating such inventories and in applying them in airshed models. In certain cases, where current practices are still deemed insufficient to achieve a higher level of reliability in biogenic emission inventories, we recommend enhanced procedures which will require a commensurate commitment of resources.

8.1 Emission Rate Measurements

Emission rate measurements should be performed using a flow-through plant enclosure apparatus as described by Arey *et al.* (1991a,b,c, 1995) and Winer *et al.* (1992). In this method, a Teflon bag supported on a PVC-pipe frame is placed over a whole plant or a portion of the plant and medical breathing air containing ambient humidity and CO_2 levels is flowed through the chamber at a rate of approximately 40 L min^{-1}. Air flow should be continued for at least three air exchanges prior to sampling to ensure that steady-state NMOC concentrations in the chamber are achieved. Chamber air sampling should then be performed using adsorbent cartridges for hydrocarbon analysis by GC-FID and/or GC-MS analysis. This methodology is preferred over the static chamber enclosure method as described by Zimmerman (1979) because of fewer problems associated with rough handling, and the larger chamber volumes which avoid sharp increases in temperature and humidity levels. However, it should be emphasized that even with a rigid enclosure apparatus great care must be taken to minimize plant specimen disturbance. Further research may indicate that a leaf cuvette technique can be used effectively for isoprene emission rate measurements.

Emission rate measurements should be performed under conditions which approximate prevailing environmental conditions found in the airshed of interest. All relevant physical parameters, including temperature, light intensity levels, CO_2 and humidity levels, should be reported with the observed emission rates, not only to permit future evaluation of the effects these factors have on emission rates, but to permit normalization to standard environmental conditions as improved emission rate algorithms are developed. This is especially true for agricultural species where the dependencies on environmental effects have not yet been fully established. In addition, the calculations used in deriving emission rates from these measurement data should be explicitly given.

The apparent water status of a plant (e.g. well-irrigated vs. summer drought conditions) and its nutrient status should be noted based on visual observation. If future research finds a strong correlation between emission rate and water status or specific nutrient levels, these factors will need to be measured and reported more precisely.

Ideally, emission rate measurements should attempt to include analysis for all significant compounds emitted from each individual plant and these should be reported individually. Furthermore, the emission rates at the measurement temperature should be reported in addition to any corrected emissions at (for example) 30 °C. This allows future emission rate algorithms to be correctly applied to the data. Emitted compounds should not be compiled into broad classification types (e.g. monoterpenes) for reporting purposes. If classification of hydrocarbon species into groups is needed, this should be done according to reactivity and/or ozone-forming potential rather than compound structural class.

Based on difficulties we encountered in attempting to critically evaluate reported emission rate data, it is essential in the future that researchers report, or make available on request, the underlying emission rate data obtained in experimental programs, as well as the data on the corresponding environmental conditions. This would permit future retroactive correction for environmental conditions such as light intensity and temperature as new correction algorithms become available. At the same time, investigators should make explicit in reports and journal articles how emission factors they report are derived from present algorithms. Finally, whenever possible, data concerning leaf-to-leaf and plant-to-plant variability in emission rates should be reported, in order to further characterize the range of uncertainties in the reported measurements.

8.2 Models

Overall, BEIS-2 is currently the most appropriate biogenic emissions model., since it incorporates the most recent advances in environmental adjustment factors and contains a soil NO_x module. It also contains the most well documented and easily followed code. However, GEMAP and VEGIES use input parameters that are more detailed and more specific to California than those used in BEIS-2. Fortunately, BEIS-2 can be modified to account for California-specific leaf biomass factors and species-specific emission factors. Alternatively, GEMAP could be modified to incorporate the improvements of BEIS-2, including the addition of a biogenic soil NO_x module. If BEIS-2 is selected as the platform for California's biogenic model, we recommend the area of vegetation types, the leaf biomass factors, and the species-specific emission factors used in GEMAP and VEGIES, plus supplements for other California airsheds, be incorporated. Some features of UAM-BEIS should also be added to BEIS-2 to allow for direct use in UAM.

We also recommend that any California biogenic emission modeling system include an uncertainty module which would allow the model to generate a range (e.g. best estimate, high, low) of biogenic emissions as inputs to an air quality model. In this way, optimal anthropogenic emission reduction scenarios for a range of biogenic emissions could be developed.

8.3 Biomass Inventories

The stratified random sampling approach for inventory development in urban areas appears to be a reasonably sound and practical. The data developed by Horie *et al.* (1991) and Winer *et al.* (1983) for the SoCAB appear to adequately represent urban vegetation in that airshed. Similarly, the inventory developed by Sidawi and Horie (1992) for the urban areas within the SJVAB appear to be adequate and may be used in emissions calculations. However, the importance of conducting adequate ground surveys to validate imagery-based assessments cannot be overemphasized.

For agricultural areas within the SJVAB, a census approach based on recent CDFA data is recommended rather than an approach based on remote sensing. It is doubtful that in the near future remote sensing of agricultural areas can provide a better estimate than the actual inventories available of crops and acreage. Movement within CDFA toward listing of crops on a geographical grid system further supports the choice of this data source for possible compatibility with GIS databases.

For the natural areas, it should be noted there is progress toward a standardized classification scheme for plant communities (Keeler-Wolf, 1995). The Ecological Society of America has a subcommittee addressing vegetation standards and classification and a standardized classification scheme for California is expected to be published in late 1995, and distributed by the California Native Plant Society. This standardized scheme should be used to define and discuss plant communities. Biomass inventory development for the natural plant communities should include ground validation. Preference should be given to experimental determination of biomass constants rather than extrapolation from the literature.

8.4 GIS Databases

GIS maps or databases should contain a clear history of development, including criteria for classification and method of classification. The procedure for selecting training sites should be noted. GIS databases with a component of field validation are preferred over those generated from remote sensing data alone. Quantitative error estimation is possible, and recommended.

8.5 Use of Remote Sensing Data

At the present time, remote sensing from satellite platforms offers the capability of determining land cover classes where spectral characteristics are well-defined and distinct. However, establishment of plant identity at the species level goes beyond the normal capabilities of even advanced instrumentation, although color infrared aerial photography remains a useful technology where fine resolution is required.

Remote sensing is useful for identifying individual plant species where differences are obvious in terms of spectral characteristics or phenology. Because of the similarity of plant components, species identification in ecosystems is limited to situations where choice can be made among plant types, implying *a priori* knowledge exists. Biomass may be adjusted using remote sensing and the NDVI, but quantitative baseline values for biomass are needed from some other source.

California airsheds pose problems for remote sensing because of the variety of plant communities and the breadth of transition zones. Therefore, remote sensing should be coupled with field validation or comparison to maps or GIS databases where field validation has occurred. If the existing maps or database are found to be reasonably accurate, remote sensing could be used to identify and quantify future changes.

8.6 Ambient Air Measurements

Ambient air measurements of isoprene and monoterpenes, and other biogenic emissions, need to be carried out in such a manner that losses due to reactions with O_3 during the sampling and analysis procedures are avoided or minimized. This applies to both measurements using samples collected in canisters (where reactions of O_3 with the biogenics can occur) and to samples collected onto solid adsorbents, where reactions with O_3 have been observed (Strömvall and Peterson, 1992). This will require either measurement methods such as those used by Fehsenfeld and co-workers (Montzka *et al.*,1995), or the use of denuders or scrubbers to remove O_3 prior to storage of the biogenics in canisters or on solid adsorbents.

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APPENDIX A

Recommended Emission Rate Factors

Trees and shrubs ranked by sum of hourly emission rate of isoprene and monoterpenes. Emission rate expressed as ug(g dry leaf wt.)$^{-1}$ hr^{-1} corrected to ambient temperature of 30 °C. "Assign" column indicates method for assigning emission rates to each species: '1' = direct measurement; '2' = assigned based on genus average; '3' = assigned based on family average; '4' = no emission rate assigned.

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Arbutus menziesii	Madrone	0.0	0.0	0.0	3
Arbutus unedo	Strawberry Madrone	0.0	0.0	0.0	3
Arctostaphylos glandulosa	Peninsular Manzanita	0.0	0.0	0.0	1
Arctostaphylos glauca	Bigberry Manzanita	0.0	0.0	0.0	1
Arctostaphylos manzanita	Dr. Hurd Manzanita	0.0	0.0	0.0	2
Carissa macrocarpa	Natal Plum	0.0	0.0	0.0	1
Ceanothus crassifolius	Hoaryleaf Ceanothus	0.0	0.0	0.0	1
Celtis sinensis	Chinese Hackberry	0.0	0.0	0.0	3
Cercocarpus betuloides	Mountain Mahogany	0.0	0.0	0.0	1
Cercocarpus ledifolius	Curly-Leaf Mountain Mahogany	0.0	0.0	0.0	2
Citrus limon 'Meyer'	Meyer Lemon	0.0	0.0	0.0	1
Comarostaphylis diversifolia	Summer Holly	0.0	0.0	0.0	3
Cotoneaster pannosus	Cotoneaster	0.0	0.0	0.0	1
Eriogonum fasciculatum	California Buckwheat	0.0	0.0	0.0	1
Fraxinus caroliniana	Carolina Ash	0.0	0.0	0.0	1
Fraxinus dipetala	Foothill Ash	0.0	0.0	0.0	2
Fraxinus latifolia	Oregon Ash	0.0	0.0	0.0	2
Fraxinus pennsylvanica	Green Ash	0.0	0.0	0.0	2
Fraxinus uhdei	Evergreen Ash	0.0	0.0	0.0	1
Fraxinus velutina	Arizona Ash	0.0	0.0	0.0	2
Fraxinus velutina 'Modesto'	Modesto Ash	0.0	0.0	0.0	2
Fraxinus velutina coriacea	Montebello Ash	0.0	0.0	0.0	2
Hymenosporum flavum	Sweetshade	0.0	0.0	0.0	3
Ilex aquifolium	English Holly	0.0	0.0	0.0	2
Ilex cassine	Dahoon Holly	0.0	0.0	0.0	1
Ilex comuta	Chinese Holly	0.0	0.0	0.0	2
Jacaranda mimosifolia	Jacaranda	0.0	0.0	0.0	1
Lagerstroemia indica	Crape Myrtle	0.0	0.0	0.0	1
Ligustrum lucidum	Glossy Privet	0.0	0.0	0.0	1
Nerium oleander	Oleander	0.0	0.0	0.0	1
Persea americana	Avocado	0.0	0.0	0.0	1
Pittosporum rhombifolium	Queensland Pittosporum	0.0	0.0	0.0	2
Pittosporum tobira	Japanese Pittosporum	0.0	0.0	0.0	1
Pittosporum undulatum	Victorian Box	0.0	0.0	0.0	1
Podarcarpus macrophyllus	Yew Pine	0.0	0.0	0.0	3
Podocarpus gracilior	Fern Pine	0.0	0.0	0.0	1
Pyrus calleryana 'Aristocrat'	Aristocrat Flowering Pear	0.0	0.0	0.0	2
Pyrus calleryana 'Bradford'	Bradford Pear	0.0	0.0	0.0	2
Pyrus kawakamii	Evergreen Pear	0.0	0.0	0.0	1
Pyrus sp.	Pear	0.0	0.0	0.0	2
Rhaphiolepis excelsa	Lady Palm	0.0	0.0	0.0	2
Rhaphiolepis indica	India Hawthorne	0.0	0.0	0.0	1
Rhaphiolepis Majestic Beauty'	Majestic Beauty Indian Hawthor	0.0	0.0	0.0	2
Rhododendron spp.	Azalea/Rhododendron	0.0	0.0	0.0	3
Rhus glabra	Smooth Sumac	0.0	0.0	0.0	2
Rhus lancea	African Sumac	0.0	0.0	0.0	2
Rhus ovata	Sugarbush	0.0	0.0	0.0	1
Sambucus callicarpa	Red Coastal Elderberry	0.0	0.0	0.0	2
Sambucus glauca	Blue Elderberry	0.0	0.0	0.0	2
Sambucus mexicana	Hairy Blue Elderberry	0.0	0.0	0.0	2
Sambucus simponii	Elderberry	0.0	0.0	0.0	1
Tecomaria capensis	Cape-Honeysuckle	0.0	0.0	0.0	1
Ulmus americana	American Elm	0.0	0.0	0.0	1
Ulmus parvifolia	Chinese Elm	0.0	0.0	0.0	1
Zelkova serrata	Sawleaf Zelkova	0.0	0.0	0.0	3
Prunus dulcis	Nonpareil Almond	0.0	0.0	0.0	1
Cercis canadensis	Redbud	0.0	0.0	0.0	1
Cercis occidentalis	Western Redbud	0.0	0.0	0.0	2
Cinnamomum camphora	Camphor	0.0	0.0	0.0	1
Cinnamomum pedunculatum	Camphor	0.0	0.0	0.0	2

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Glycine max		0.0	0.0	0.0	1
Prunus domestica	Santa Rosa Plum	0.0	0.0	0.0	1
Amelanchier alnifolia	Mountain Serviceberry	0.0	0.1	0.1	3
Eriobotrya deflexa	Bronze Loquat	0.0	0.1	0.1	3
Eriobotrya japonica	Loquat	0.0	0.1	0.1	3
Heteromeles arbutifolia	Toyon	0.0	0.1	0.1	3
Lyonothamnus floribundus aspenifolia	Catalina Ironwood	0.0	0.1	0.1	3
Malus sp.	Apple	0.0	0.1	0.1	3
Photinia fraseri	Common Photinia	0.0	0.1	0.1	3
Pyracantha coccinea	Firethorn	0.0	0.1	0.1	3
Rosa sp.	Rose	0.0	0.1	0.1	3
Jasminum sp.	Jasmine	0.0	0.1	0.1	3
Osmanthus fragrans	Sweet Olive	0.0	0.1	0.1	3
Prunus caroliniana	Carolina Laurel Cherry	0.0	0.1	0.1	2
Prunus cerasifera	Cherry Plum	0.0	0.1	0.1	2
Prunus ilicifolia	Hollyleaf Cherry	0.0	0.1	0.1	2
Prunus lusitanica	Portugal Laurel	0.0	0.1	0.1	2
Prunus lyonii	Catalina Cherry	0.0	0.1	0.1	2
Prunus serotina	Black Cherry	0.0	0.1	0.1	2
Prunus subcordata	Sierra Plum	0.0	0.1	0.1	2
Prunus virginiana	Choke Cherry	0.0	0.1	0.1	2
Prunus avium	Bing Cherry	0.0	0.1	0.1	1
Cupressus sempervirens	Italian Cypress	0.0	0.1	0.1	1
Abelia grandiflora	Glossy Abelia	0.0	0.1	0.1	3
Adenostoma fasciculatum	Chamise	0.0	0.1	0.1	1
Prunus armeniaca	Blenheim Apricot	0.0	0.1	0.1	1
Prunus persica	Halford Peach	0.0	0.1	0.1	1
Prunus persica	Halford Peach	0.0	0.1	0.1	1
Pinus densiflora	Red Pine	0.0	0.2	0.2	1
Viburnum rufidulum	Viburnum	0.0	0.2	0.2	1
Pinus pinea	Italian Stone Pine	0.0	0.2	0.2	1
Olea europaea	Olive	0.0	0.3	0.3	1
Pinus halepensis	Aleppo Pine	0.0	0.3	0.3	1
Laurus nobilis	Grecian Laurel	0.0	0.4	0.4	3
Sassafras albidum	Sassafras	0.0	0.4	0.4	3
Cedrus atlantica	Atlas Cedar	0.0	0.6	0.6	2
Cedrus deodara	Deodar Cedar	0.0	0.6	0.6	1
Juniperus californica	California Juniper	0.0	0.6	0.6	2
Juniperus chinensis	Chinese Juniper	0.0	0.6	0.6	1
Juniperus occidentalis	Western Juniper	0.0	0.6	0.6	2
Pinus sabiniana	Foothill Pine	0.0	0.6	0.6	1
Carya aquatica	Water Hickory	0.0	0.7	0.7	1
Carya sp.	Red Hickory	0.0	0.7	0.7	2
Calocedrus decurrens	Incense Cedar	0.0	0.8	0.8	3
Chamaecyparis lawsoniana	Port Orford Cedar	0.0	0.8	0.8	3
Chamaecyparis nootkatensis	Nootka Cypress	0.0	0.8	0.8	3
Cupressocyparis leylandii	Leylandi Cypress	0.0	0.8	0.8	3
Cycas revoluta	Sago Palm	0.0	0.8	0.8	3
Platycladus orientalis	Oriental Arborvitae	0.0	0.8	0.8	3
Thuja plicata	Western Red Cedar	0.0	0.8	0.8	3
Pinus radiata	Monterey Pine	0.0	0.8	0.8	1
Cupressus glabra	Smooth Arizona Cypress	0.0	0.9	0.9	2
Cupressus macnabiana	Macnab Cypress	0.0	0.9	0.9	2
Cupressus macrocarpo	Monterey Cypress	0.0	0.9	0.9	2
Citrus sinensis 'Valencia'	Valencia Orange	0.0	0.9	0.9	1
Myrtica cerifera	Wax Myrtle	0.0	1.1	1.1	1
Pseudotsuga macrocarpa	Bigcone Douglas Fir	0.0	1.1	1.1	1
Persea borbonia	Red Bay	0.0	1.2	1.2	1
Calodendrum capense	Cape Chestnut	0.0	1.5	1.5	3
Casimiroa edulis	White Sapote	0.0	1.5	1.5	3

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Citrus limonia burm.	Meyer Lemon	0.0	1.5	1.5	2
Citrus orangoma	Orange	0.0	1.5	1.5	2
Citrus paradisi	Grapefruit	0.0	1.5	1.5	2
Geijera parvifolia	Australian Willow	0.0	1.5	1.5	3
Morus alba 'Fruitless'	Fruitless Mulberry	0.0	1.6	1.6	2
Morus rubra	Red Mulberry	0.0	1.6	1.6	1
Cupressus forbesii	Tecate Cypress	0.0	1.7	1.7	1
Juglans californica	California Walnut	0.0	1.8	1.8	2
Juglans hindsii	California Black Walnut	0.0	1.8	1.8	2
Juglans nigra	Black Walnut	0.0	1.8	1.8	2
Juglans regia	English Walnut	0.0	1.8	1.8	1
Citrus sinensis	Navel Orange	0.0	1.8	1.8	1
Citrus sinensis	Valencia Orange	0.0	1.8	1.8	1
Ceanothus spinosus	Greenbark	0.0	1.8	1.8	1
Schinus molle	California Pepper	0.0	1.9	1.9	1
Acer floridanum	Silver Maple	0.0	2.0	2.0	1
Pinus canariensis	Canary Island Pine	0.0	2.1	2.1	1
Ceanothus thyrsiflorus	Blue Blossom	0.0	2.4	2.4	2
Acer circinatum	Vine Maple	0.0	2.8	2.8	2
Acer glabrum	Rocky Mountain Maple	0.0	2.8	2.8	2
Acer macrophyllum	Bigleaf Maple	0.0	2.8	2.8	2
Acer negundo	Box Elder	0.0	2.8	2.8	2
Acer palmatum	Japanese Maple	0.0	2.8	2.8	2
Acer saccharinum	Silver Maple	0.0	2.8	2.8	1
Ginkgo biloba	Ginkgo	0.0	3.0	3.0	1
Citrus limon	Lisbon Lemon	0.0	3.2	3.2	1
Quercus lobata	Valley Oak	3.4	0.0	3.5	1
Acer rubrum	Red Maple	0.0	3.5	3.5	1
Pinus albicaulis	Whitebark Pine	0.0	3.5	3.5	2
Pinus aristata	Bristlecone Pine	0.0	3.5	3.5	2
Pinus attenuata	Knobcone Pine	0.0	3.5	3.5	2
Pinus balfouriana	Foxtail Pine	0.0	3.5	3.5	2
Pinus contorta	Beach Pine	0.0	3.5	3.5	2
Pinus coulteri	Coulter Pine	0.0	3.5	3.5	2
Pinus edulis	Pinyon Pine	0.0	3.5	3.5	2
Pinus flexilis	Limber Pine	0.0	3.5	3.5	2
Pinus jeffreyi	Jeffery Pine	0.0	3.5	3.5	2
Pinus lambertiana	Sugar Pine	0.0	3.5	3.5	2
Pinus monophylla	Singleleaf Pinyon Pine	0.0	3.5	3.5	2
Pinus monticola	Western White Pine	0.0	3.5	3.5	2
Pinus muricata	Bishop Pine	0.0	3.5	3.5	2
Pinus pinaster	Cluster Pine	0.0	3.5	3.5	2
Pinus ponderosa	Ponderosa Pine	0.0	3.5	3.5	2
Pinus quadrifolia	Four Needle Pinyon Pine	0.0	3.5	3.5	2
Pinus thunbergiana	Japanese Black Pine	0.0	3.5	3.5	2
Pinus torreyana	Torrey Pine	0.0	3.5	3.5	2
Harpephyllum caffrum	Kaffir Plum	0.0	4.2	4.2	3
Mangifera indica	Mango	0.0	4.2	4.2	3
Abies bracteata	Santa Lucia Fir	1.4	2.9	4.3	3
Abies concolor	White Fir	1.4	2.9	4.3	3
Abies grandis	Lowland Fir	1.4	2.9	4.3	3
Abies magnifica	Red Fir	1.4	2.9	4.3	3
Abies procera	Noble Fir	1.4	2.9	4.3	3
Pseudotsuga menziesii	Douglas Fir	1.4	2.9	4.3	3
Tsuga heterophylla	Western Hemlock	1.4	2.9	4.3	3
Tsuga mertensiana	Mountain Hemlock	1.4	2.9	4.3	3
Acacia baileyana	Bailey Acacia	0.0	4.7	4.7	2
Acacia farnesiana	Sweet Acacia	0.0	4.7	4.7	1
Acacia melanoxylon	Blackwood Acacia	0.0	4.7	4.7	2
Acacia subporosa	River Wattle	0.0	4.7	4.7	2

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Sabel palmetto	Sabel Palmetto	4.7	0.4	5.1	1
Pinus taeda	Loblolly Pine	0.0	5.1	5.1	2
Picea sitchensis	Sitka Spruce	4.0	1.1	5.1	1
Pinus ellotii	Slash Pine	0.0	5.3	5.3	1
Ceanothus leucodermis	Chaparral Whitehorn	0.0	5.4	5.4	1
Albizia julibrissin	Silk Tree	4.3	1.4	5.7	3
Bauhinia variegata	Purple Orchid Tree	4.3	1.4	5.7	3
Calliandra haematocephela	Pink Powder Puff	4.3	1.4	5.7	3
Ceratonia siliqua	Carob	4.3	1.4	5.7	3
Cercidium floridum	Blue Palo Verde	4.3	1.4	5.7	3
Cercidium microphyllum	Foothills Palo Verde	4.3	1.4	5.7	3
Dalea spinosa	Smoke Tree	4.3	1.4	5.7	3
Erythrina caffra	Kaffirboom Coral Tree	4.3	1.4	5.7	3
Olneya tesota	Desert Ironwood	4.3	1.4	5.7	3
Parkinsonia aculeata	Jerusalem Thorn	4.3	1.4	5.7	3
Sophora japonica	Japanese Pagoda Tree	4.3	1.4	5.7	3
Tipuana tipu	Tipu Tree	4.3	1.4	5.7	3
Umbellularia californica	California Laurel	4.3	1.4	5.7	3
Schinus terebinthifolius	Brazilian Pepper	0.0	5.9	5.9	1
Chilopsis linearis	Desert Willow	0.0	5.9	5.9	3
Tabebuia chrysotricha	Golden Trumpet Tree	0.0	5.9	5.9	3
Pinus palustris	Longleaf Pine	0.0	5.9	5.9	1
Magnolia grandiflora	Magnolia	0.0	5.9	5.9	1
Magnolia soulangiana	Saucer Magnolia	0.0	5.9	5.9	2
Pinus sylvestris	Scots Pine	0.0	6.4	6.4	1
Xylosma congestum	Shiny Xylosma	6.8	0.0	6.8	1
Hevea brasiliensis	Rubber Tree	7.5	0.5	8.0	1
Quercus prinus	Chestnut Oak	6.5	1.5	8.0	1
Eucalyptus viminalis	Ribbon Gum	8.0	0.0	8.0	1
Salvia mellifera	Black Sage	0.0	8.3	8.3	1
Sequoia sempervirens	Coast Redwood	0.0	8.5	8.5	3
Sequoiadendron giganteum	Giant Sequoia	0.0	8.5	8.5	3
Taxodium sp.	Cypress	0.0	8.5	8.5	1
Quercus douglasii	Blue Oak	8.7	0.0	8.7	1
Serenoa repens	Saw Palmetto	8.9	0.0	8.9	1
Pistacia chinensis	Chinese Pistache	0.0	9.0	9.0	2
Pistacia vera	Kerman Pistachio	0.0	9.0	9.0	1
Quercus alba	White Oak	7.8	1.5	9.3	1
Pueraria lobata		9.6	0.0	9.6	1
Washingtonia filifera	California Fan Palm	9.9	0.0	9.9	1
Washingtonia robusta	Mexican Fan Palm	9.9	0.0	9.9	2
Liriodendron tulipifera	Tulip Tree	4.1	5.9	10.0	3
Quercus laurifolia	Diamond Leaf Oak	10.4	0.2	10.6	1
Platanus racemosa	Western Sycamore	10.9	0.0	10.9	1
Picea abies	Norwegian Spruce	10.1	1.2	11.4	2
Pinus clausa	Sand Pine	0.0	11.5	11.5	1
Picea breweriana	Brewer's Weeping Spruce	10.1	1.9	12.1	2
Quercus wislizenii	Interior Live Oak	12.5	0.0	12.5	1
Salix caroliniana	Coast Plain Willow	12.5	0.0	12.5	1
Eugenia grandis	Eugenia	12.1	2.1	14.1	3
Robinia pseudoacacia	Black Locust	11.8	2.3	14.1	1
Quercus myrtifolia	Myrtle Oak	15.2	0.2	15.4	1
Phoenix canariensis	Canary Island Date Palm	15.8	0.0	15.8	2
Phoenix dactylifera	Date Palm	15.8	0.0	15.8	1
Phoenix recliinata	Senegal Data Palm	15.8	0.0	15.8	2
Callistemon citrinus	Bottlebrush	16.0	0.0	16.0	1
Callistemon viminalis	Weeping Bottlebrush	16.0	0.0	16.0	2
Quercus rubra	Northern Red Oak	14.8	1.8	16.7	1
Trichostema lanatum	Woolly Blue Curls	0.0	17.7	17.7	1
Platanus acerifolia	London Plane Tree	19.2	0.0	19.2	2

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Picea engelmannii	Engelmann Spruce	16.3	3.4	19.7	1
Quercus velutina	Black Oak	18.9	1.0	19.9	1
Quercus virginiana	Virginia Live Oak	20.2	0.3	20.5	1
Agonis flexuosa	Willow Myrtle	21.2	2.1	23.2	3
Feijoa sellowiana	Pineapple Guava	21.2	2.1	23.2	3
Melaleuca ericifolia	Heath Melaleuca	21.2	2.1	23.2	3
Melaleuca linariifolia	Flaxleaf Paperbark	21.2	2.1	23.2	3
Melaleuca quinquenervia	Cajeput Tree	21.2	2.1	23.2	3
Metrosideros excelsus	New Zealand Christmas Tree	21.2	2.1	23.2	3
Myrica californica	Pacific Wax-Myrtle	21.2	2.1	23.2	3
Psidium guajava	Guava	21.2	2.1	23.2	3
Syzygium paniculatum	Brush Cherry	21.2	2.1	23.2	3
Tristania conferta	Brisbane Box	21.2	2.1	23.2	3
Quercus coccinea	Scarlet Oak	20.1	3.2	23.3	1
Thelypteris decursive-pinnata		24.5	0.0	24.5	1
Quercus nigra	Water Oak	24.6	0.0	24.6	1
Quercus laevis	Scrub Oak	24.3	0.8	25.1	1
Nandina domestica	Heavenly Bamboo	25.1	0.0	25.1	1
Salix nigra	Black Willow	25.2	0.0	25.2	1
Fagus sp.	Beech	24.8	0.6	25.4	3
Quercus chrysolepis	Canyon Live Oak	24.8	0.6	25.4	2
Quercus durata	Leather Oak	24.8	0.6	25.4	2
Quercus engelmanii	Mesa Oak	24.8	0.6	25.4	2
Quercus falcata	Southern Red Oak	24.8	0.6	25.4	2
Quercus ilex	Holly Oak	24.8	0.6	25.4	2
Quercus kelloggii	California Black Oak	24.8	0.6	25.4	2
Quercus suber	Cork Oak	24.8	0.6	25.4	2
Ficus benjamina	Weeping Chinese Banyan	27.0	0.2	27.1	2
Ficus carica	Edible Fig	27.0	0.2	27.1	2
Ficus elastica	Rubber Plant	27.0	0.2	27.1	2
Ficus fistulosa	Fig	27.0	0.2	27.1	1
Ficus lyrata	Fiddleleaf Fig	27.0	0.2	27.1	2
Ficus macrocarpa	Indian Laurel Fig	27.0	0.2	27.1	2
Ficus macrophylla	Moreton Bay Fig	27.0	0.2	27.1	2
Ficus rubiginosa	Rustyleaf Fig	27.0	0.2	27.1	2
Mallotus paniculatis	Mallotus	26.4	0.8	27.2	3
Platanus occidentalis	American Sycamore	27.5	0.0	27.5	1
Artemisia californica	California Sagebrush	0.0	28.3	28.3	1
Baccharis pilularis	Coyote Brush	0.0	28.3	28.3	3
Euryops pectinatus	Euryops Daisy	0.0	28.3	28.3	3
Rhamnus californica	Coffeeberry	29.3	0.0	29.3	1
Quercus dumosa	California Scrub Oak	29.8	0.0	29.8	1
Quercus borealis	Red Oak	30.1	0.0	30.1	1
Quercus phellos	Willow Oak	32.2	0.0	32.2	1
Myrtus communis	Common Myrtle	34.0	0.0	34.0	1
Quercus agrifolia	Coast Live Oak	35.3	0.0	35.3	1
Populus deltoides	Eastern Cottonwood	37.0	0.0	37.0	1
Eucalyptus camaldulensis	Red Gum	32.5	4.6	37.1	2
Eucalyptus citriodora	Lemon-Scented Gum	32.5	4.6	37.1	2
Eucalyptus erythrocorys	Red-Cap Gum	32.5	4.6	37.1	2
Eucalyptus gunnii	Cider Gum	32.5	4.6	37.1	2
Eucalyptus maculata	Spotted Eucalyptus	32.5	4.6	37.1	2
Eucalyptus polyanthemos	Silver Dollar Gum	32.5	4.6	37.1	2
Eucalyptus rudis	Flooded Gum	32.5	4.6	37.1	2
Eucalyptus sideroxylon	Red Ironbark	32.5	4.6	37.1	2
Liquidambar formosana	Chinese Sweet Gum	18.9	19.1	38.0	2
Liquidambar styraciflua	Liquidambar	18.9	19.1	38.0	1
Rhamnus crocea ilicifolia	Hollyleaf Redberry	41.9	0.0	41.9	2
Populus angustifolia	Narrowleaf Cottonwood	43.6	0.0	43.6	2
Populus fremontii	Fremont Cottonwood	43.6	0.0	43.6	2

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Populus trichocarpa	Black Cottonwood	43.6	0.0	43.6	2
Quercus incana	Bluejack Oak	45.6	0.2	45.8	1
Macaraunga triloba	Macauranga	45.3	0.7	46.0	1
Populus tremuloides	Quaking Aspen	50.2	0.0	50.2	1
Salix lasiandra	Western Black Willow	50.9	0.0	50.9	2
Salix lasiolepis	Arroyo Willow	50.9	0.0	50.9	2
Salix scouleriana	Scouler Willow	50.9	0.0	50.9	2
Cupaniopsis anacardioides	Carrotwood	50.9	0.0	50.9	1
Koelreuteria bipinnata	Chinese Flametree	50.9	0.0	50.9	3
Koelreuteria paniculata	Goldenrain Tree	50.9	0.0	50.9	3
Rhamnus crocea	Redberry	54.4	0.0	54.4	1
Quercus garryana	Oregon White Oak	59.2	0.6	59.8	2
Eucalyptus globulus	Blue Gum Eucalyptus	57.0	9.2	66.2	1
Quercus robur	European Oak	76.6	0.6	77.2	2
Salix babylonica	Weeping Willow	115.0	0.0	115.0	1
Elaeis guineensis	Palm Oil Tree	172.9	0.1	173.0	3
Aesculus californica	California Buckeye	***	***	***	4
Ailanthus altissima	Tree-of-Heaven	***	***	***	4
Alnus cordata	Italian Alder	***	***	***	4
Alnus oregona	Red Alder	***	***	***	4
Alnus rhombifolia	White Alder	***	***	***	4
Alnus tenuifolia	Mountain Alder	***	***	***	4
Araucaria bidwilli	Bunya-Bunya	***	***	***	4
Araucaria spp.	Araucaria	***	***	***	4
Archontophoenix cunninghamiana	King Palm	***	***	***	4
Arecastrum romanzoffianum	Queen Palm	***	***	***	4
Betula lenta	Sweet Birch	***	***	***	4
Betula nigra	River Birch	***	***	***	4
Betula occidentalis	Streamside Birch	***	***	***	4
Betula pendula	European White Birch	***	***	***	4
Bougainvillea spp.	Bougainvillea	***	***	***	4
Brachychiton acerifolius	Flame Tree	***	***	***	4
Brachychiton populneus	Bottle Tree	***	***	***	4
Brahea edulis	Guadalupe Palm	***	***	***	4
Brahea spp.	Brahea Palm	***	***	***	4
Camellia japonica	Common Camellia	***	***	***	4
Carica papaya	Papaya	***	***	***	4
Cedrella fissilis	Cedrela	***	***	***	4
Cephalanthus occidentalis	Buttonbush	***	***	***	4
Chamaerops humilis	Mediterranean Palm	***	***	***	4
Chorisia speciosa	Silk-Floss Tree	***	***	***	4
Coprosma repens	Mirror Plant	***	***	***	4
Cordyline australis	Bronze Dracaena	***	***	***	4
Cornus nutalli	Pacific Dogwood	***	***	***	4
Cornus sp.	Dogwood	***	***	***	4
Cornus stolonifera	Redstem Dogwood	***	***	***	4
Crassula argentea	Jade Plant	***	***	***	4
Davidia involucrata	Dove Tree	***	***	***	4
Dendromecon harfordii	Island Bushpoppy	***	***	***	4
Diospyros virginiana	American Persimmon	***	***	***	4
Escallonia exoniensis	Escallonia	***	***	***	4
Euonymus japonica	Evergreen Euonymus	***	***	***	4
Fremontodendron Californicum	Common Flannel Bush	***	***	***	4
Fremontodendron Mexicanum	Southern Flannel Bush	***	***	***	4
Garrya elliptica	Coast Silktassel	***	***	***	4
Grevillea robusta	Silk Oak	***	***	***	4
Grevillea rosmarinifolia	Rosemary Grevillea	***	***	***	4
Hebe buxifolia	Boxleaf Hebe	***	***	***	4
Hibiscus rosa-sinensis	Chinese Hibiscus	***	***	***	4
Justicia brandegeana	Shrimp Plant	***	***	***	4

Botanical Name	Common Name	Iso.	Mono.	Iso.+Mono.	Assign
		ug./g. dry leaf wt./hr.			
Maytenus boaria	Mayten Tree	***	***	***	4
Melia azedarach	Chinaberry	***	***	***	4
Musa paradisiaca	Banana	***	***	***	4
Myoporum laetum	Myoporum	***	***	***	4
Nicotiana glauca	Tree Tobacco	***	***	***	4
Nyssa sylvatica	Black Gum	***	***	***	4
Plumbago auriculata	Cape Plumbago	***	***	***	4
Punica granatum	Pomegranate	***	***	***	4
Sapium sebiferum	Chinese Tallow Tree	***	***	***	4
Schefflera actinophylla	Octopus Tree	***	***	***	4
Stenocarpus sinuatus	Firewheel Tree	***	***	***	4
Strelitzia nicolai	Giant Bird of Paradise	***	***	***	4
Taxus brevifolia	Western/Oregon Yew	***	***	***	4
Torreya californica	California Nutmeg	***	***	***	4
Trachycarpus fortunei	Windmill Palm	***	***	***	4
Yucca brevifolia	Joshua Tree	***	***	***	4
Yucca elephantipes	Giant Yucca	***	***	***	4

APPENDIX B

Subroutine CORFAC.F of VEGIES

APPENDIX B - SUBROUTINE CORFAC.F OF VEGIES

```
cdeck corfac
c
      subroutine corfac (ipidx,ih,temp,sol,efac,efcor,ierr)
      implicit integer*4 (i-n)
      implicit real*4    (a-h,o-z)
c
c------------------------------------------------------------------
c
c  ---- Computes emissions correction factors for emiitted compunds
c       Emission factor data was received from VRC as different
c       emissions for monoterpenes dependent on day/night time
c       so this code has been setup to accept emission factors based
c       on solar radiation ranges.  Currently we only have information
c       for night (sol=0) and day (sol > 0 or <=9999.)
c
c NOTES:
c   efac   -  *ug/g/hr) retrieved emissions factors from data base
c             = 1  isoprene
c             = 2  monoterpenes
c   efcor  -  (g/g/hr) corrected emissions factors from data
c             in efspecs.
c             = 1  isoprene
c             = 2  other terpenes
c             = 3  a-pinenes
c             = 4  b-pinenes
c             = 5  d-limonene
c             = 6  myrcene
c             = 7  d3-carene
c             = 8,9,10  (not used)
c   cnvfac - convert micrograms (ug) to grams (g)
c
c   dterp  - standard diurnal profile for monoterpenes for a
c            summer day
c   solstd  - average summer day solar intensity in langleys
c
c------------------------------------------------------------------
c LOG:
c
c------------------------------------------------------------------
c  Subroutines called:  <<NONE>>
c------------------------------------------------------------------
c  Include files:
c------------------------------------------------------------------
c
```

```
      include "vegies.inc"
c
c-----------------------------------------------------------------------
c   Argument declarations:
c-----------------------------------------------------------------------
c
      character*6 ipcod
      real*4      efac(mxefin), efcor(mxef)
c
c-----------------------------------------------------------------------
c   Local Variables:
c-----------------------------------------------------------------------
c
      save cnvfac,dterp,solstd
c
      character*8 cmpin(mxef)
      real*4      cnvfac,dterp(mxhr),solstd(mxhr)
c
c-----------------------------------------------------------------------
c   Data Statements:
c-----------------------------------------------------------------------
c
      data cmpin / 'isoprene','mterp   ','a-pinene','b-pinene',
     &             'd-limone','myrcene ','carene  ',3*'        ' /
      data dterp /0.036,0.034,0.032,0.028,0.025,0.025,0.026,0.028,
     &            0.030,0.038,0.046,0.056,0.058,0.059,0.058,0.056,
     &            0.055,0.052,0.048,0.047,0.044,0.042,0.040,0.036/
      data solstd / 0,0,0,0,3, 8, 21, 35, 50, 62, 76, 76, 72,
     &              60, 45, 27, 4, 1, 0, 0, 0, 0, 0, 0 /
      data cnvfac / 1.0e-6 /
c
c-----------------------------------------------------------------
c   Entry Point:
c-----------------------------------------------------------------
c
      ierr = -1
c
c   ----- initialize corrected ef's to zero ----
c
      do 10 iz = 1, mxef
        efcor(iz) = 0.
 10   continue
c
c   ----- find index for plant class and solar rad range ----
c
      index = -1
      ipcod = vcode(ipidx)
```

```
      read (ipcod,8000) ipclas
      do 20 is = 1, nsol
        if (ipclas.ne.ipcls(is)) go to 20
        if (ipclas.eq.ipcls(is) .and. sol.le.solrng(is)) then
          index = is
          go to 111
        endif
 20   continue
c
      ierr = 0
      go to 999
 111  continue
c
c  ----- isoprene emission factor calculations ----
c
      sol1=solrin(ih)*26.564
      eftmp = 0.
      tcor = 0.
c     if (efac(1).gt.0.0 .and. sol.gt.0.) then
      if (sol1.ge.800.) then
        cisop= 10.**(1.200/(1.+exp(-0.400*(temp-28.30)))-.796)
      else if (sol1.ge.400.) then
        f800= 10.**(1.200/(1.+exp(-0.400*(temp-28.30)))-.796)
        f400= 10.**(0.916/(1.+exp(-0.239*(temp-29.93)))-.462)
        cisop= f400/1.95 + (f800 - f400/1.95) * (sol1-400.)/400.
      else if (sol1.ge.200.) then
        f400= 10.**(0.916/(1.+exp(-0.239*(temp-29.93)))-.462)
        f200= 10.**(0.615/(1.+exp(-0.696*(temp-32.79)))-.077)
        cisop= f200/4.75 + (f400/1.95 - f200/4.75) * (sol1-200.)/200.
      else if (sol1.ge.100.) then
        f200= 10.**(0.615/(1.+exp(-0.696*(temp-32.79)))-.077)
        f100= 10.**(0.437/(1.+exp(-0.312*(temp-31.75)))-.160)
        cisop= f100/10.73 + (f200/4.75 - f100/10.73)*(sol1-100.)/100.
      else if (sol1.gt.0.) then
        f100= 10.**(0.437/(1.+exp(-0.312*(temp-31.75)))-.160)
        cisop= (f100/10.73) * sol1/100.
      else
        cisop=0.
      endif
c
c       cisop = -0.019 + 0.0416*temp
c       eftmp = 10.**(cisop)
        eftmp = cisop
        efcor(1) = (efac(1)*eftmp) * cnvfac * efsplt(1,index)
c       efcor(1) = (efac(1)*eftmp) * cnvfac * efsplt(1,index) * sol
        tcor = efcor(1)
c     endif
```

```
c
c  ----- generic monoterpenes -----
c
c  >> adjust monoterpene diurnal profile given for an average summer
c     day by ratio of solrin/solstd, that is input solar in langleys
c     divided by solar radiation for an average summer day.  All night
c     hours are 1 no matter what season
c
c  NOTE: Monoterpenes emissions factors are not sensitive to solar
c        intensity.  The adjustment here & may be incorrect.
c                                 (Causley, SAI)
c
c
      solfac = 1.
      if (solstd(ih).gt.0.0001 .and. solrin(ih).gt.0.0001)
     &       solfac = solrin(ih)/solstd(ih)

      efsav1 = 0.
      if (efac(2).gt.0.0) then
c        cmtrps = -1.577 + 0.0568*temp
c        eftmp = 10.**(cmtrps)
         cmtrps = exp(0.0739*(temp-30.0))
         eftmp = cmtrps
c
c  &  (Causley, SAI)
c
c    efsav1 = (efac(2)*eftmp) * cnvfac * 24. * dterp(ih)*solfac
c    efsav1 = (efac(2)*eftmp) * cnvfac
c
         efsav1 = (efac(2)*eftmp) * cnvfac * 24. * dterp(ih)*solfac
      endif
c
c  ----- alpha-pinenes -----
c
c  >> adjust alpha-pinene diurnal profile given for an average summer
c     day by ratio of solrin/solstd, that is input solar in langleys
c     divided by solar radiation for an average summer day.  All night
c     hours are 1 no matter what season
c
      solfac = 1.
      if (solstd(ih).gt.0.0001 .and. solrin(ih).gt.0.0001)
     &       solfac = solrin(ih)/solstd(ih)

      efsav2 = 0.
      if (efac(2).gt.0.0) then
c        cmtrps = -1.577 + 0.0568*temp
c        eftmp = 10.**(cmtrps)
```

```
        cmtrps = exp(0.0670*(temp-30.0))
        eftmp = cmtrps
        efsav2 = (efac(2)*eftmp) * cnvfac * 24. * dterp(ih)*solfac
      endif
c
c
      if (efsav2.le.0.) then
        if (efcor(1).le.0.) then
          ierr = 2
        else
          ierr = 0
        endif
        go to 999
      endif
c
      lps = nscod
      do 30 ic = 2, nscod
        efsav = efsav1
        if (ic.eq.3) efsav = efsav2
         efcor(ic) = efsav * efsplt(ic,index)
         tcor = tcor + efcor(ic)
 30   continue
c
c  ----- If no total correction factor is zero, skip plant ----
c
      if (tcor.le.0.) then
        ierr = 2
        go to 999
      endif
      ierr = 0
c
c---------------------------------------------------------------------
c  Format Statements:
c---------------------------------------------------------------------
c
 8000 format (i1)
c
 999  return
      end
```