



# Improved Biogenic Emission Inventories across the West

## Technical Analysis Report

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## Executive Summary

The Western Regional Air Partnership (WRAP) requires geo-gridded (model-ready) biogenic VOC and NO emission estimates for air quality modeling projects in the Western U.S. The objective of this project is to assess and improve biogenic emissions model procedures and input variables. The biogenic emissions model used for this task is MEGAN version 2.10 which includes several enhancements over the previous MEGAN versions, including an explicit canopy environment and updated emission algorithms. MEGAN uses the best available emission algorithms and input variables and has a structure that facilitates the use of improved input data and parameters. As part of this project, several additional improvements were incorporated into MEGANv2.1 including a soil NO<sub>x</sub> emission model that accounts for fertilizer application and precipitation and the ability to use a more frequent 8-day average Leaf Area Index (LAI) rather than monthly average LAI. This project has also improved the ability of MEGAN to accurately estimate biogenic emissions in the Western U.S. by improving Western U.S. land-use and landcover data with 1) plant functional type fractional (PFT<sub>f</sub>) coverage data based on 30 meter Landsat TM data, 2) emission factors based on recent emission measurements and improved U.S. species composition data, and 3) LAI based on improved satellite data products that are for a specific year and with higher (8-day) temporal resolution.

To provide continuity from historic biogenic emissions modeling methods used in Ozone, PM, and Regional Haze modeling and source apportionment studies and to assess the planned MEGAN 2.1 improvements, comparative analyses of BEIS3 and earlier MEGAN versions were conducted. Uncertainties and areas of potential improvement are discussed.

## 1.0 Introduction

A stroll in nature presents us with many familiar odors that we can identify, especially those associated with vegetation and soils. The scents of flowers and fruits are particularly well known along with odors that are representative of pine trees, sagebrush, and other iconic plants of the western U.S. Some of these odors are blends of hundreds of different chemicals while others are associated with a specific compound. For example, leaf aldehyde (hexenal) is characteristic of the smell of freshly cut grass while limonene contributes to the smell of citrus. Many of these scents are composed of volatile organic compounds (VOC) that have important purposes for biological organisms and also have a surprisingly large impact on the chemistry of the atmosphere.

Emissions from vegetation, mostly from the leaves of plants, are the largest source of VOC in the global atmosphere although VOC emissions from cars, factories and fires dominate in urban and industrial areas. In the atmosphere, the oxidation of VOC can influence aerosol particles, precipitation acidity, and regional ozone distributions (Guenther et al., 2006). Accurate predictions of biogenic VOC emissions are important for developing regulatory ozone and aerosol control strategies for at least some rural and urban areas (Karl et al. 2001). These organic carbon emissions are also a minor but potentially significant pathway for the flow of carbon between an ecosystem and the atmosphere (Guenther, 2002).

One of the great challenges associated with characterizing biogenic VOC (BVOC) is the large variety of compounds. Isoprene is the single most important BVOC with an emission that is about half of the global BVOC emission (Guenther et al., 2006). Many monoterpenes have been observed in the atmosphere but only a few, such as  $\alpha$ -pinene, make a significant contribution to the global total emissions. The dominant sesquiterpenes, such as  $\beta$ -caryophyllene, have lifetimes of only minutes in the atmosphere and so are present at very low levels but their reaction products may be an important source of secondary organic aerosol. Oxygenated BVOC include a wide range of alcohols, aldehydes, ketones, acids, ethers, and esters but are dominated by relatively low molecular weight compounds such as methanol, acetaldehyde and acetone. Other BVOC include alkanes (e.g., heptane), alkenes (e.g., ethene), aromatic hydrocarbons (e.g., toluene), sulfur compounds (e.g., dimethyl sulfide), and nitrogen compounds (e.g., hydrogen cyanide). Observations of land-atmosphere interactions must include not only primary emissions but also the larger number of reaction products that impact atmospheric oxidants and particle formation and growth.

The production of BVOC requires a significant allocation of resources, which leads to the question of why plants would produce these compounds if they merely end up being lost into the atmosphere. We know that at least some BVOC emissions have an important biological role although there are other cases where the purpose remains a mystery. One of the best known biological roles is the use of BVOC by plants to attract pollinators and seed dispersers. Insects and animals are also known to use BVOC for a variety of other signaling activities. Some VOC are emitted from a limited number of plants or for only a limited time but emissions can be high for certain conditions and locations. Examples of this include large emission of linalool from stands of flowering plants and large emissions of methyl salicylate from stressed vegetation. Emission variations are driven by environmental conditions (light and temperature) and land-cover characteristics (foliar biomass and plant species composition) that result in

variations of more than an order of magnitude for different ecosystems and for different seasons at the same location. The large variety of compounds, biological roles, and complex controlling variables make quantitative predictions of BVOC emissions a challenging task. The lack of long-term observations is a major limitation for parameterizing and evaluating existing models.

Investigations of NO emission from soils began in the 1960s with agronomists that were interested in the fate of fertilizer applied to soil (Smith and Chalk 1980) but the amount lost to the atmosphere was a relatively small part (a few percent) of the total fertilizer applied. NO emissions were later observed from unfertilized landscapes and it was recognized that this could be an important source of atmospheric NO in some regions (Galbally and Roy 1978). Early studies of the microbial and ecological processes and environmental controls over NO emissions led to what has been called the “hole-in-the-pipe” model (Firestone and Davidson 1989). This model conceptualizes NO emission regulation at two levels: 1) the rate of nitrogen cycling (the amount of nitrogen flowing through the pipe) and 2) factors influencing the ability of NO to escape from the soil into the atmosphere (the hole in the pipe). The nitrogen cycling includes two components: 1) nitrification (converting  $\text{NH}_4$  to  $\text{NO}_3$ ) and denitrification (converting  $\text{NO}_3$  to  $\text{N}_2$ ). Nitrification is considered the main source of NO emission. Fertilizer, atmospheric nitrogen deposition, leaf litter, soil temperature and perhaps other factors can influence the rate of nitrogen cycling in the soil while soil properties and water content and perhaps other factors influence the amount that can leak into the atmosphere.

Although NO emissions have been observed from a wide range of landscapes under various conditions, the implementation in regional to global models has been relatively simple due to the lack of suitable databases for scaling observations to regional scales. The model of Williams et al. (1992) is a simple approach with emissions based on landcover type and soil temperature. Yienger and Levy (1995) improved on this approach by including the two factors (fertilizer rates and soil moisture) responsible for much of the observed variability.

The Western Regional Air Partnership (WRAP) is seeking to understand current and evolving regional air quality issues in the West. Among the issues of interest to WRAP include regional haze, ozone, particulate matter, and the effects of climate change on regional air quality. Biogenic emissions play a significant role in all of these issues and accurate estimates are needed for quantitative assessments. The original BEIS model was developed by Pierce and Waldruff (1991) in response to this need. Considerable advancements have been made in the following two decades with most of the initial effort focused on the forests of the eastern U.S. In particular, studies in recent years have added considerably to our knowledge of biogenic emissions from western U.S. landscapes. The major focus of this study is improving data that drive biogenic emission inventories in the West to account for important factors such as inter-annual variability in vegetation due to drought, land cover change due to progressive urbanization, the biogenic VOC emission potential of Western plants and ecosystems, and the importance of correctly characterizing biogenic NO<sub>x</sub> emissions in sparsely populated Western regions.

Quantitative biogenic emissions were first estimated almost 50 years ago by Rasmussen and Went (1965). They extrapolated a few biogenic VOC enclosure observations to the global scale by simply multiplying a typical emission rate by the global area covered by vegetation and the fraction of the year that plants are growing. The resulting annual total (isoprene plus all other

non-methane biogenic VOC) flux estimate of 438 Tg ( $10^{12}$  g) is about a factor of 3 lower than the global estimate of Guenther et al. (1995). The next advance in biogenic VOC emission modeling was the U.S. emission inventory generated by Zimmerman (1979) that used gridded landcover and weather data. In addition, Zimmerman made over 600 measurements of isoprene, monoterpene and other VOC emissions from vegetation at field sites in southeastern, southwestern, and northwestern United States. Additional biogenic VOC emission studies were conducted in the 1980s (Winer, 1982; Lamb et al., 1985, 1986) and incorporated into a U.S. national inventory (Lamb et al., 1987) with much higher resolution than the Zimmerman (1979) inventory. The Zimmerman and Lamb et al. procedures were adapted by USEPA for use in the Regional Oxidant Model (ROM) beginning in 1986. The first model, Biogenic Emissions Software System (BESS), was replaced in 1988 by the Biogenic Emissions Inventory System (BEIS). Second (BEIS2) and third (BEIS3) generation biogenic emission models have also been released by USEPA.

Due primarily to the limited capabilities for introducing location-specific information into BEIS, U.S. regional organizations, especially in the western U.S., have developed alternative models. The models include BIOME (developed for LADCO), GLOBEIS (developed for TNRC), BEIGIS (developed for CARB) and MAGBEIS (developed for MAG). All of these models use the same general approach (emission factors, emission algorithms, source distributions) as the BEIS models. Table 1 provides a summary comparison of seven models that have been used to estimate emissions in at least some portion of the western U.S. Three of these models are currently used to estimate biogenic emission across the entire WRAP modeling domain: the third generation BEIS model (BEIS3), the second generation MEGAN model (MEGAN2), and the third generation GloBEIS model (GloBEIS3). Other models are designed for specific areas within these regions (MAGBEIS for Arizona and BEIGIS for California). All of these models use the same general framework established for BEIS in the late 1980s (Lamb et al., 1987; Pierce and Waldruff, 1991) and a detailed comparison of the differences and similarities is given in section 3.

There are considerable differences which often lead to emission estimates that differ by a factor of two or more. Much of these differences are due to the emission factors and landcover inputs used for the models so that by using similar inputs it is often possible to bring these models into agreement of better than 30%. Most of the observations available for evaluating the accuracy of these models are concentrations measurements. Since ambient concentrations are dependent on emissions, chemical loss and transport, they are reliable for evaluating emission estimates only if we have an accurate understanding of chemical loss rates and transport. Presently, our limited understanding of OH distributions, the dominant sink for most BVOC, means that ambient concentrations are only useful for constraining emissions to within about a factor of two which is the same magnitude as the difference between model estimates and so these observations are of limited value for identifying which model provides the better estimates. Recent advances in direct BVOC flux measurements, including airborne eddy covariance systems and low cost tower-based relaxed eddy accumulation system, are beginning to provide a substantial database that can be used to constrain emission estimates to within ~30% which will improve our ability to evaluate BVOC emission models. A more detailed description of BVOC emission measurements is given in section 3. While the improved landcover and emission factors could be incorporated into any BVOC emission model, we have used the MEGAN model primarily because 1) it is easier to incorporate new landcover and

emission factors, and 2) it is the only model that already includes recent (i.e., past 5 years) advances in BVOC emission process understanding.

The Williams et al. (1992) model, used in MEGANv2.04, provides only a rough estimate of soil NO emissions in a region. The Yienger and Levy (1995) approach used in BEISv3.14, provides estimates that can differ substantially from MEGANv2.04 in regions of active fertilizer application and during periods after rain events. As part of this project, we have implemented the Yienger and Levy approach into MEGANv2.1 so that this model can provide the best available approach for both VOC and NO.

MEGAN is widely used by the global research and earth system modeling community and was identified by ISI Thomason Reuters as a “fast moving research front” by ISI Sciencewatch (see <http://sciencewatch.com/dr/fmf/2009/09novfmf/09novfmfGuen/>). MEGAN is increasingly being used by the U.S. regulatory modeling community and was recently used in the Denver Colorado SIP that was approved in 2010.

An important consideration for interpreting the impact of biogenic VOC emissions is the wide range of reactivities and production capacities for secondary products. Biogenic VOCs influence both oxidants (ozone, hydroxyl) and secondary organic aerosol (SOA). Isoprene strongly influences oxidants but weakly influences SOA. However, although isoprene SOA yields are relatively low, isoprene can make substantial contributions to SOA in some regions due to the relatively high emission rates. Monoterpenes and sesquiterpenes strongly influence SOA and weakly influence oxidants. Other VOCs is a broad category that includes compounds that influence both oxidants (e.g., methylbutenol and methanol) and SOA (e.g., toluene and methyl chavicol). This qualitative guidance is intended to assist in the interpretation of emission summaries that will categorize emissions as isoprene, terpenes, other VOCs.

**Table 1. Overview of biogenic emission models used for estimating U.S. biogenic emissions.**

Model	BIEGIS	BEIS2	BEIS3	BIOME3	GLOBEIS3	MAG-BEIS2	MEGAN2.1
Sponsors/ developers	CARB	EPA	EPA	LADCO/ Alpine Geophysics	TNRCC/Envir on	MAG/STI	EPA/NSF/NCAR
Programming Language	ARCGIS	FORTRAN	FORTRAN	SAS	Microsoft Access	FORTRAN	FORTRAN
Website	None	<a href="http://www.epa.gov/asmdnerl">www.epa.gov/asmdnerl</a>	<a href="http://www.epa.gov/asmdnerl">www.epa.gov/asmdnerl</a>	None	<a href="http://www.globeis.com">www.globeis.com</a>	None	<a href="http://bai.acd.ucar.edu/Megan">http://bai.acd.ucar.edu/Megan</a>
Canopy Model	None	BEIS2	BEIS2	BEIS2 or GLOBEIS3	GLOBEIS3	BEIS2	MEGAN
PPFD	Input	Calculated	Calculated	Input	Input	Calculated	Input
Emission factor type	Canopy	Average leaf	Average leaf	Average or sun leaf	Average or sun leaf	Average leaf	Canopy
Emission factor database	BIEGIS	BEIS2	BEIS2	BEIS2 or GLOBEIS3	BEIS2 or GLOBEIS3	MAGBEIS2	MEGAN
Landcover data	CARB	BELD3	BELD3	BELD3	user developed database	MAG- LAND2	MEGAN
Emission activity algorithms	BEIS2	BEIS2	BEIS2	BEIS2 or GLOBEIS	GLOBEIS	BEIS2	MEGAN
Canopy production and loss	None	none	none	None	None	none	Yes
Chemical species	4	4	34	34	34	4	150

## 2.0 Landcover and emission data

Improved landcover and emission factor data for the western U.S. have been assembled and are described in this section. Table 2 summarizes these data and indicates the best available data for each component. These data are described in more detail in sections 2.1 to 2.3.

**Table 2. Comparison of MEGAN and BEIS3.14 landcover and emission factors.**

Model used (if any)	Approach	Advantages
<b>LAI</b>		
MEGANv2.1	MODIS observations	This is the best available option because it provides a means to represent 1) interannual variations due to climate, insects and other factors, 2) seasonal variations of deciduous vegetation, and 3) spatial variations in canopy density.
BEISv3.14	Constant maximum LAI for individual species	Minimal effort is required to use this approach.
<b>PFT</b>		
MEGANv2.1	30-m LANDSAT-TM NLCD and 56-m AWiFS CDL satellite data.	This is the best available option because the high resolution data are a considerable in heterogeneous landscapes found in much of the western U.S. The approach is also arguably easier to apply.
BEISv3.14	1000-m MODIS based landcover data for western U.S.	None
<b>Species Composition Data and Averaging</b>		
MEGANv2.1	Average over ecoregions. FIA tree data and NRCS grass and shrub data. CDL for crops.	This is the best available option because ecoregions provide an area with more consistent species composition in comparison to a county-based approach. The addition of NRCS shrub and grass species composition and CDL crop distributions provides a substantial improvement for these plant functional types.
BEISv3.14	Average over counties. FIA tree data. No shrub and grass data.	None
<b>Emission factors</b>		
MEGANv2.1	Emission factor database updated in 2011	This is the best available option because it includes recent measurements including field campaigns in the western U.S.
BEISv3.14	Emission factor database has not been updated recently	None

## 2.1 SATELLITE LANDCOVER DATA

### 2.1.1 MODIS LAI product

MEGAN uses Leaf Area Index to quantify the amount of foliage at a given location and the age of the foliage. The LAI estimate is based on 1-km resolution NASA MODIS satellite observations. Alternative global LAI estimates are available from the European SPOT/VEGETATION satellite observations. Garrigues et al. (2008) compared these two products with ground observations and found that each product performed better in some ways (e.g. SPOT generally agreed better with observations but MODIS was better at getting the high LAI values in forests). MODIS is available globally for 2003 to present while the SPOT LAI is currently only available from October 2009 to present (although earlier data were collected and may be available in the future). The MODIS instrument operates on both the NASA Terra and Aqua spacecraft. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every one to two days. Its detectors measure 36 spectral bands and it acquires data at three spatial resolutions: 250-m (bands 1 and 2), 500-m (bands 3 to 7), and 1,000-m (bands 8 to 36). The level-4 MODIS global LAI product used for MEGAN is MCD15A2 and is available from the [USGS LP DAAC](https://lpdaac.usgs.gov/)<sup>1</sup>. The satellite observed radiances at several wavelengths are related to chlorophyll activity and leaf area. The LAI variable defines the number of equivalent layers of leaves relative to a unit of ground area. The data is composited every 8 days at 1-kilometer resolution on a Sinusoidal grid.

MEGAN previously used monthly averaged LAI data for year 2003 that was based on an earlier version of the MODIS satellite data product. This section will present an analysis of the impact of the following three changes to the LAI product used for MEGAN:

- 8-day average LAI instead of monthly average.
- Specific year (2008) rather than generic year.
- New MODIS LAI product (version 5).

#### *LAI processing*

The MODIS 8-day combined (using data from both Terra and Aqua spacecraft) data is available in 10 degree by 10 degree tiles that can be downloaded from the USGS LP DAAC. The tile system is illustrated in Figure 2.1a. 32 tiles were selected to cover all of North America in order to cover the entire WRAP modeling domain. A total of 46 sets of 32 files were used to obtain an annual data set of 8-day averages resulting a total of 1472 tiles downloaded for the year 2008 North American LAI dataset. An additional 46 sets of 8-day periods were processed to obtain results for months in years 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010 in order to compare with the MEGANv2.04 LAI and to examine inter-annual variations.

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<sup>1</sup>[https://lpdaac.usgs.gov/lpdaac/products/modis\\_products\\_table/leaf\\_area\\_index\\_fraction\\_of\\_photosynthetically\\_active\\_radiation/8\\_day\\_l4\\_global\\_1km/mcd15a2](https://lpdaac.usgs.gov/lpdaac/products/modis_products_table/leaf_area_index_fraction_of_photosynthetically_active_radiation/8_day_l4_global_1km/mcd15a2).

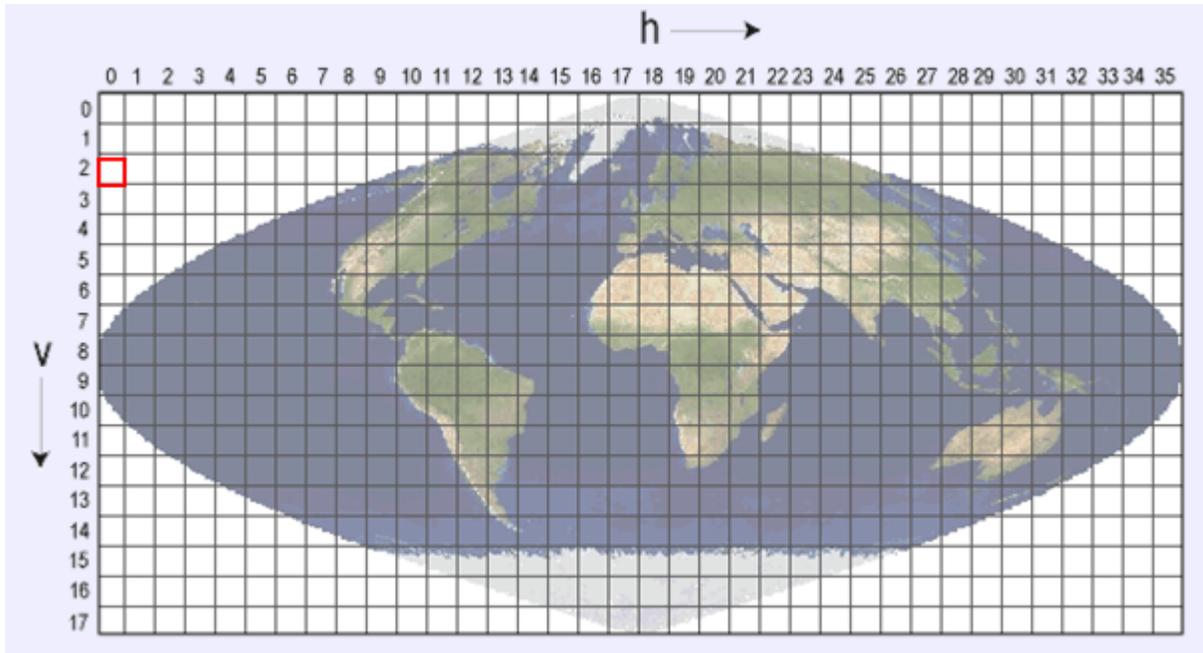


Figure 2.1a. MODIS tiles.

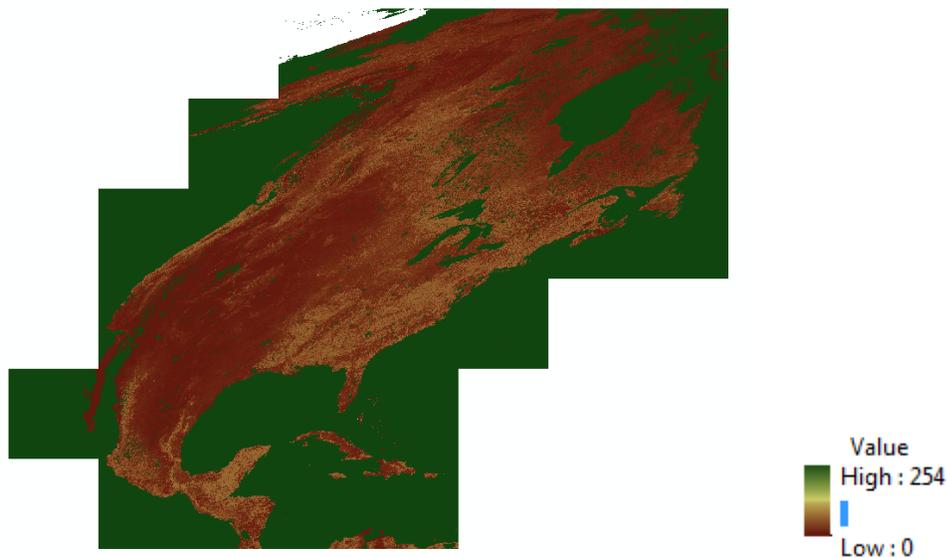
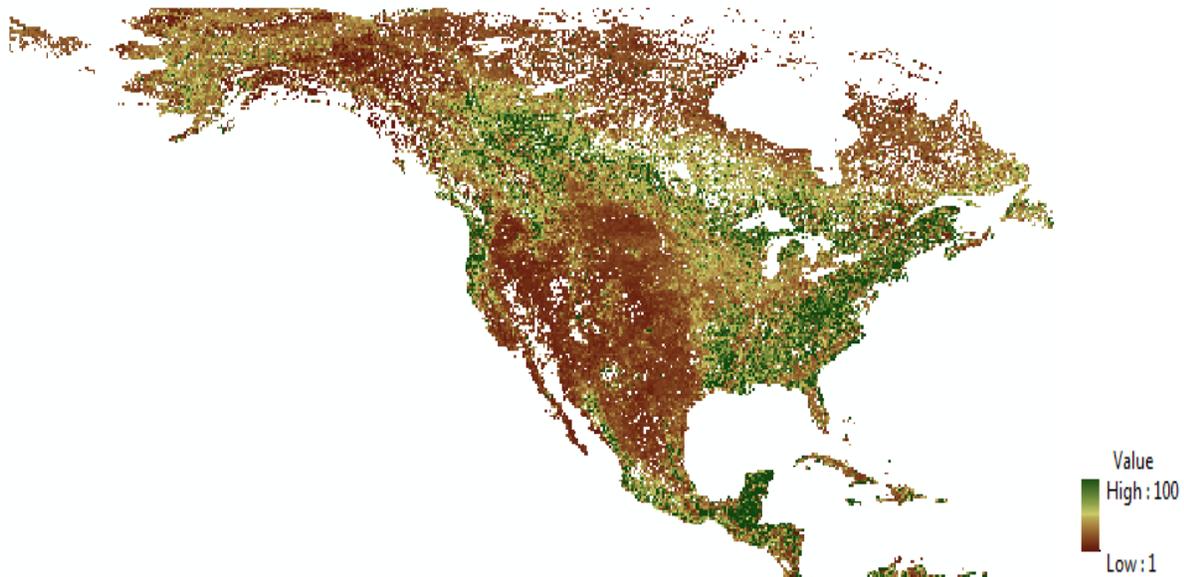


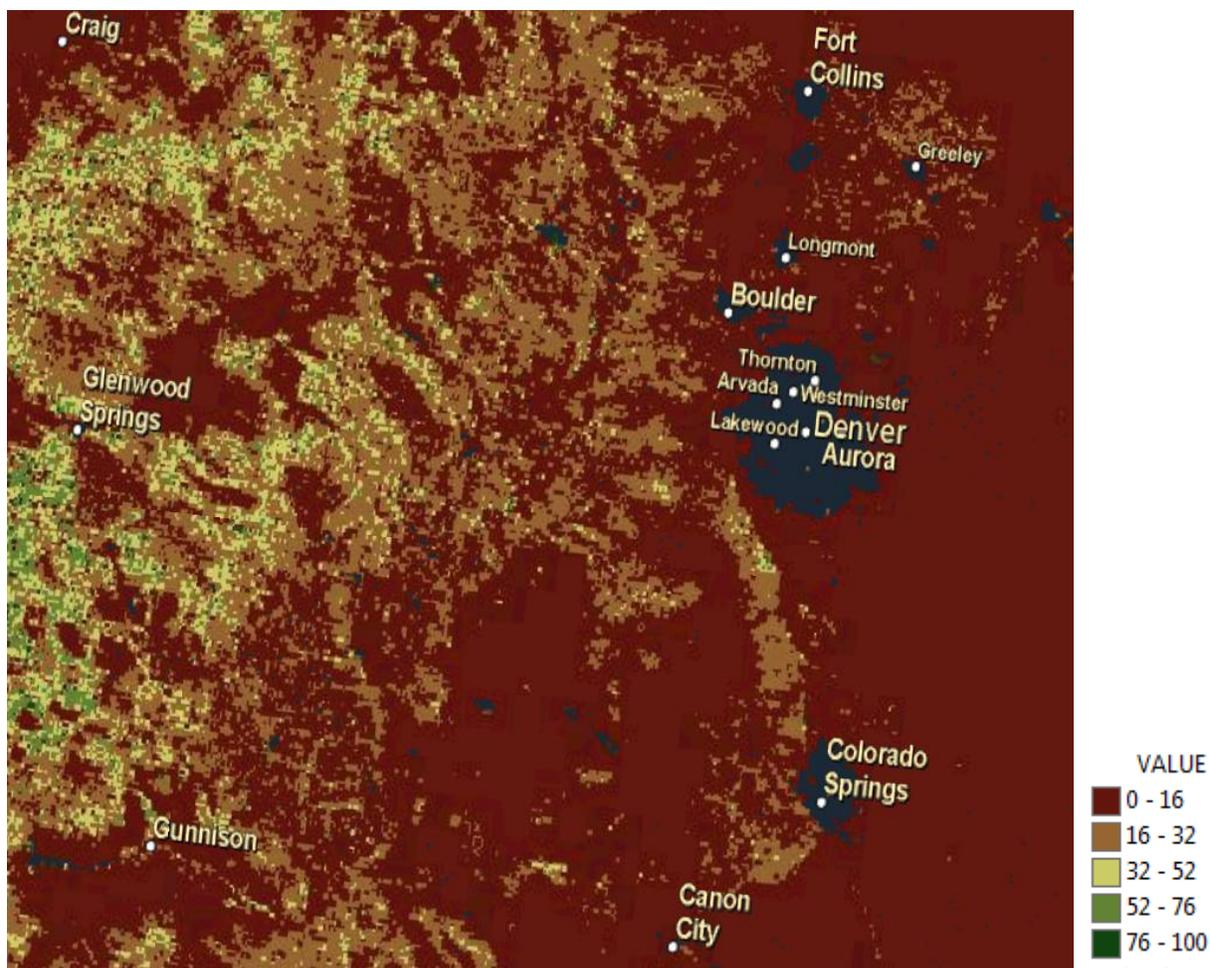
Figure 2.1b. North American Distribution of MODIS MCD15A2 for day 201-208 of year 2008.

After downloading 32 tiles covering North America, a mosaic of these files was created using ARCGIS-10.0. An example, July 17-25 of year 2008, is shown in Figure 2.1b. The MCD15A2 data includes flags (e.g., 253, 254) for landscapes where MODIS is unable to estimate LAI including urban areas and wetlands. These flags were filled with the average value for a 30 km region

surrounding each flagged landscape. The LAI was then divided by the vegetation cover fraction to obtain the LAI of vegetation covered surface (referred to as LAI<sub>v</sub>) which is used for input to MEGAN. If, for example, the LAI is 3 m<sup>2</sup>/m<sup>2</sup> and vegetation fraction is 0.5 (i.e., vegetation covers half of the surface) then the LAI<sub>v</sub> is 6 m<sup>2</sup>/m<sup>2</sup> indicating that this is the value of LAI for that area that is covered by vegetation. There are two main reasons that MEGAN uses LAI<sub>v</sub>: 1) LAI<sub>v</sub> is the more appropriate input for a canopy environment model since this is the actual LAI of the canopy, 2) minimum and maximum bounds can be placed on LAI<sub>v</sub> since vegetation covered surfaces rarely have a maximum LAI of less than 0.1 or more than 10. Examples of LAI<sub>v</sub> distributions are shown in Figures 2.1c and 2.1d.



**Figure 2.1c. North American Distribution of MEGAN LAI<sub>v</sub> for July 17-25 of year 2008. Values range from 1= 0.1 m<sup>2</sup>/m<sup>2</sup> to 100= 10 m<sup>2</sup>/m<sup>2</sup>.**



**Figure 2.1d. North American Distribution of MEGAN LAI<sub>v</sub> for July 17-25 of year 2008. Values range from 1= 0.1 m<sup>2</sup>/m<sup>2</sup> to 100= 10 m<sup>2</sup>/m<sup>2</sup>. Dark blue indicates urban areas where LAI is determined by averaging surrounding region.**

#### *8-day average LAI data*

MEGANv2.04 used monthly average LAI data to represent seasonal variations in LAI and leaf age. We have introduced an 8-day LAI product for MEGANv2.1 in order to account for LAI variations that occur on a time scale of less than one month. Figure 2.1e shows that this is important for landscapes that are dominated by deciduous vegetation.

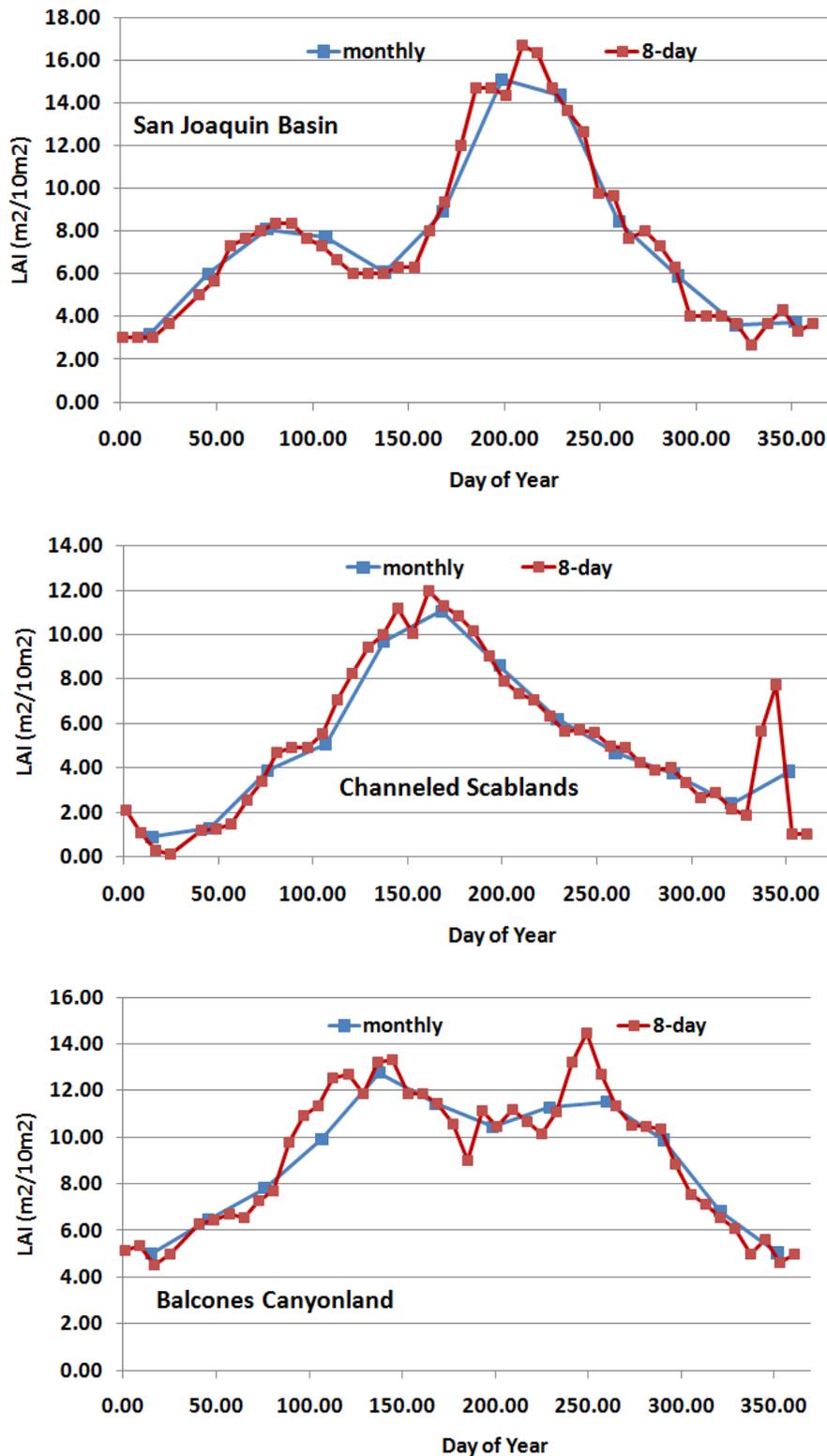


Figure 2.1e. Comparison of MEGAN LAI monthly and 8-day time series averaged over level 4 ecoregions: San Joaquin Valley in California (upper) and Channeled Scablands in Washington State, Balcones Canyonland in Texas.

### *LAI data for 2008*

MEGANv2.04 allows users to provide data for other years but in practice most users take advantage of the LAI data available on the MEGAN website which is only for the year 2003. The impact of using data from a specific year was assessed by processing and examining LAI for selected summer months from a 9-year period from 2003 to 2011. When averaged over a month and for all ecoregions in entire western U.S., there were fairly small (6% increase for June 2005 and 4% or less for other cases) differences between values in 2003 compared to other years. Differences were as much as 30% greater when 8-day values were compared. Figure 2.1f shows LAI<sub>v</sub> for the same 8-day period in 2003 and 2005. LAI<sub>v</sub> in 2005 is more than 30% higher in much of the Pacific Northwest but is lower in Colorado. This is not surprising given the regional differences in climate variability. Year-to-year differences for individual ecoregions differed by as much as a factor of 6 for monthly averages and a factor of 15 for 8-day averages. However, the ecosystems with large differences tended to be desert landscapes with very low average LAI.

Figure 2.1g provides a closer look at LAI changes in the northern Colorado and southern Wyoming front range of the Rocky mountains with an estimate of the change in LAI in forested regions for the first week of July averaged over years 2003 to 2005 and compared to the average for 2010 and 2011. An LAI decrease of >10% is estimated for most of the forested regions west of the continental divide and a decrease of more than 30% in the northern part of this region. This is presumably due to pine beetle outbreaks in this region which are illustrated at <http://csfs.colostate.edu/pdfs/aerial-mpb96-2010-progression-web.pdf>. Many areas east of the continental divide, where pine beetles have only recently been impacting the forest, have no change or an increase in LAI. Some of these areas were burned in 2002 and earlier (e.g. the Hayman fire) and the increased LAI could indicate a post-burn recovery from 2003 to 2011. This Figure suggests that the use of year-specific LAI in MEGAN can capture at least some of the variation in emissions associated with changing LAI following beetle outbreaks and wildfires. In addition to the decreased emission associated with LAI decreases after ecosystem stress, there may be increased emissions due to ecosystem stress but these processes have not been incorporated into biogenic emission models (see section 3.2.4).

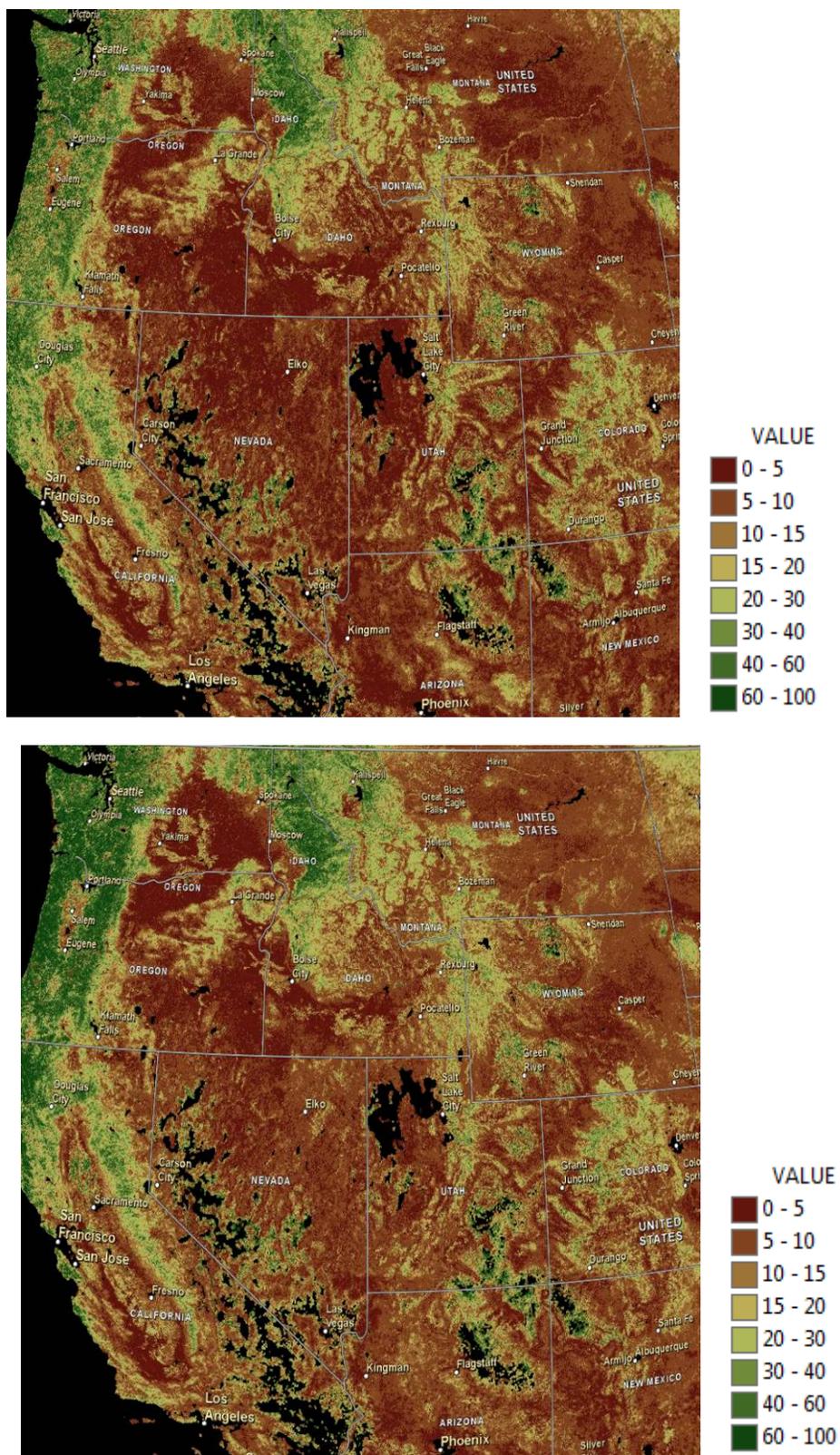


Figure 2.1f. MEGAN LAIv for August 5-12 in 2003 (upper) and 2005 (lower)

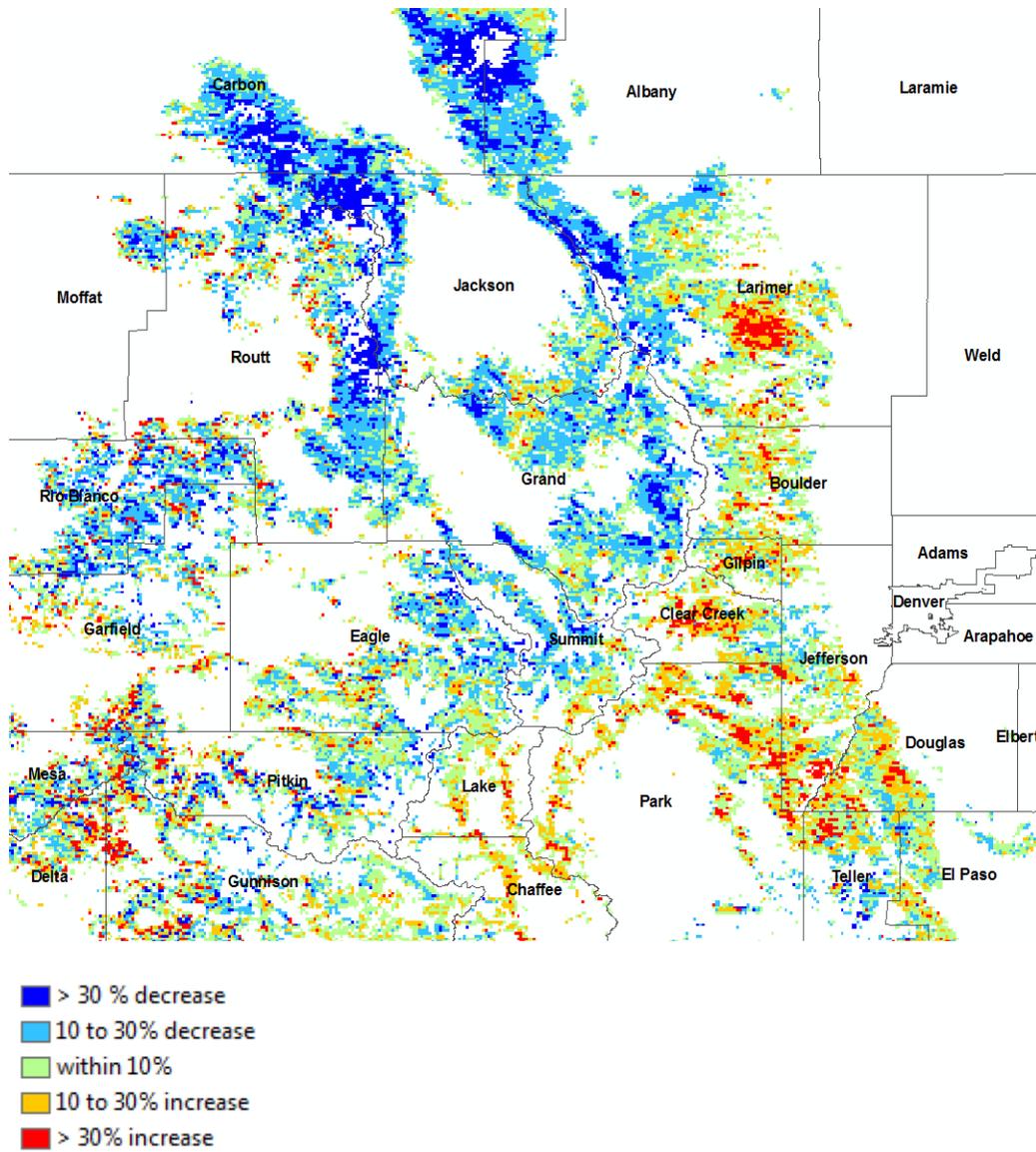


Figure 2.1g. Change in average MEGAN LAIv for the first week in July in 2003- 2005 compared to 2010-2011. Only values for forested areas (tree cover > 50%) are shown.

### *MODIS LAI product version 5*

The NASA MODIS team has an active effort to improve the MODIS LAI product. Based on the documentation on the NASA MODIS website (see above link), the latest version of the MODIS LAI product (Version 5) is an improvement over the earlier version that was used for input for MEGANv2.04. The MODIS LAI version 5 algorithms improved the quality of all LAI but in particular for woody biomes for estimating LAI were refined for the version currently available in June 2011. This included splitting broadleaf and needleleaf forest classes into deciduous and evergreen subclasses. The NASA document shows improved performance, by comparison to ground observations in a range of landscapes including savanna, broadleaf forest, and needleleaf forest.

A comparison of LAIv based on version 5 to that of the version used for MEGAN v2.04 indicates that average values ranged from about 20% higher in June, July and August to 1% lower in March. The differences varied considerably for various regions. The increase was greatest in the conifer dominated forests of the Rocky Mountains and Pacific Northwest and less in grasslands and shrublands. LAIv was about a factor of 2 lower outside the main growing season in at least some croplands and slightly higher during the growing season. LAIv is considerably (20 to 40%) lower in some, but not all, of the oak woodlands in California.

#### **2.1.2 LANDSAT-TM NLCD tree cover and impervious fraction products**

The National Land Cover Dataset (NLCD) is a LANDSAT-TM based landcover dataset developed by the Multi-Resolution Land Characteristics (MRLC) Consortium is a group of federal agencies who first joined together in 1993 (see [www.mrlc.gov](http://www.mrlc.gov)) to coordinate the production of a comprehensive land cover database. The NLCD includes 3 products that are used in the development of the MEGAN landcover: tree-cover fraction (see figure 2.1h), impervious cover fraction, and a landcover dataset. The impervious cover and landcover are available for 2001 and 2006 while the tree cover data are available only for 2001. Tree-cover fraction represents the fraction of the land surface covered by tree canopy. Impervious fraction can be used to represent the area covered by roads, pavement and buildings. The procedures used are described in detail by Homer et al. (2004). LANDSAT-TM data used for this product provides a very high spatial resolution (30 m).

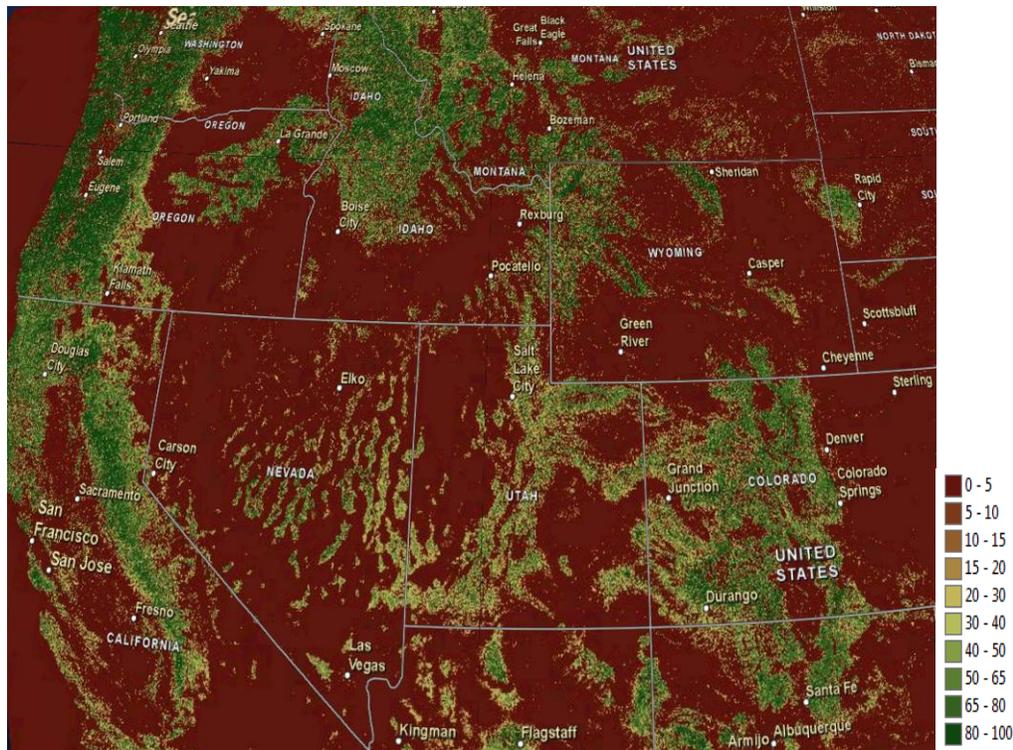


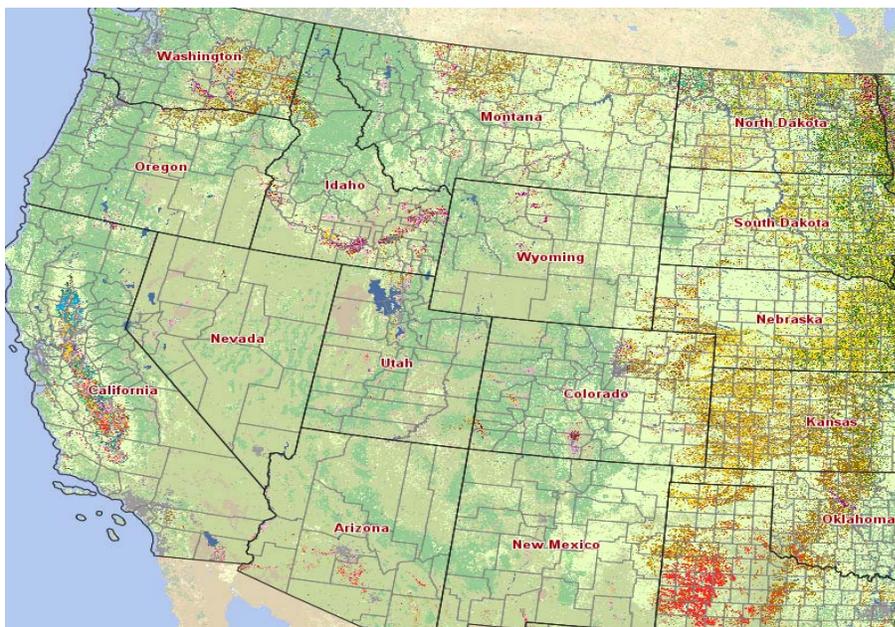
Figure 2.1h. NLCD tree cover (%) distribution for western U.S.

### 2.1.3 AWiFS CDL landuse and landcover product

The Cropland Data Layer (CDL) is a landcover product developed by the USDA/NASS (see <http://www.nass.usda.gov/research/Cropland/SARS1a.htm>). The goal of the CDL effort is to produce an annual census of geo-located crop inventory in the U.S. It uses The NLCD 30-m landcover data product for non-crop landcover and adds information on crop distributions (over 100 crop types listed in Table 3) for specific years using observations from AWiFS satellite and county level crop reporting statistics (see figure 2.1i). Each crop is identified by a unique code in the database. The CDL is available for the entire contiguous U.S. annually beginning in 2009 and for selected states for earlier years. Coverage for most of the U.S. is available for 2008, except for a few states which are available for 2007. The 2007 and 2008 data were combined to generate the MEGAN 2008 landcover data. An assessment of multi-year CDL data for Maricopa county, Arizona shown in Table 4 and 5 indicates that there is considerable change within individual categories but the change within land-use categories (e.g. urban, cropland and wildland) is relatively small and probably within the uncertainties of these data given that the expected pattern of increasing urban land was not evident. Changes in Clark county, which has a relatively small percentage of urban and cropland, were smaller with no significant trends. A longer time series is needed to assess the ability of the CDL product to capture landuse trends. However, the CDL currently only provides data starting in 2008 for most western states. The expected continuation of these data in the future will enable further evaluation.

**Table 3. Crops included in the CDL 56-m landcover product.**

Alfalfa	Dbl. Crop Barley/Corn	Misc. Vegs. & Fruits	Pumpkins
Almonds	Dbl. Crop Barley/Sorghum	Mustard	Radishes
Apples	Dbl. Crop Barley/Soybeans	Nectarines	Rape Seed
Apricots	Dbl. Crop Corn/Soybeans	Oats	Rice
Aquaculture	Dbl. Crop Durum Wht/Sorghum	Olives	Rye
Asparagus	Dbl. Crop Lettuce/Barley	Onions	Safflower
Barley	Dbl. Crop Lettuce/Cantaloupe	Oranges	Sod/Grass Seed
Blueberries	Dbl. Crop Lettuce/Durum Wht	Other Crops	Sorghum
Broccoli	Dbl. Crop Lettuce/Upland Cotton	Other Hay	Soybeans
Cabbage	Dbl. Crop Oats/Corn	Other Non-Tree Fruit	Speltz
Camelina	Dbl. Crop Soybeans/Cotton	Other Small Grains	Spring Wheat
Caneberries	Dbl. Crop Soybeans/Oats	Other Tree Fruits	Squash
Canola	Dbl. Crop WinWht/Corn	Other Tree Nuts	Strawberries
Cantaloupes	Dbl. Crop WinWht/Cotton	Pasture/Grass	Sugarbeets
Carrots	Dbl. Crop WinWht/Sorghum	Pasture/Hay	Sugarcane
Cauliflower	Dbl. Crop WinWht/Soy	Peaches	Sunflower
Celery	Fallow/Idle Cropland	Peanuts	Sweet Corn
Cherries	Flaxseed	Pears	Sweet Potatoes
Chick Peas	Garlic	Peas	Switchgrass
Christmas Trees	Gourds	Pecans	Tobacco
Citrus	Grapes	Peppers	Tomatoes
Clover/Wildflowers	Greens	Perennial Ice/Snow	Triticale
Corn	Herbs	Pickles	Turnips
Cotton	Honeydew Melons	Pistachios	Vetch
Cranberries	Hops	Plums	Walnuts
Cucumbers	Lentils	Pomegranates	Watermelons
Dry Beans	Lettuce	Pop. or Orn. Corn	Winter Wheat
Durum Wheat	Millet	Potatoes	
Eggplants	Mint	Prunes	



**Figure 2.1i. CDL western U.S. landcover distribution for 2010**

**Table 4. Maricopa county AZ landcover acreage for years 2008 to 2010 estimated from the CDL 56-m landcover product.**

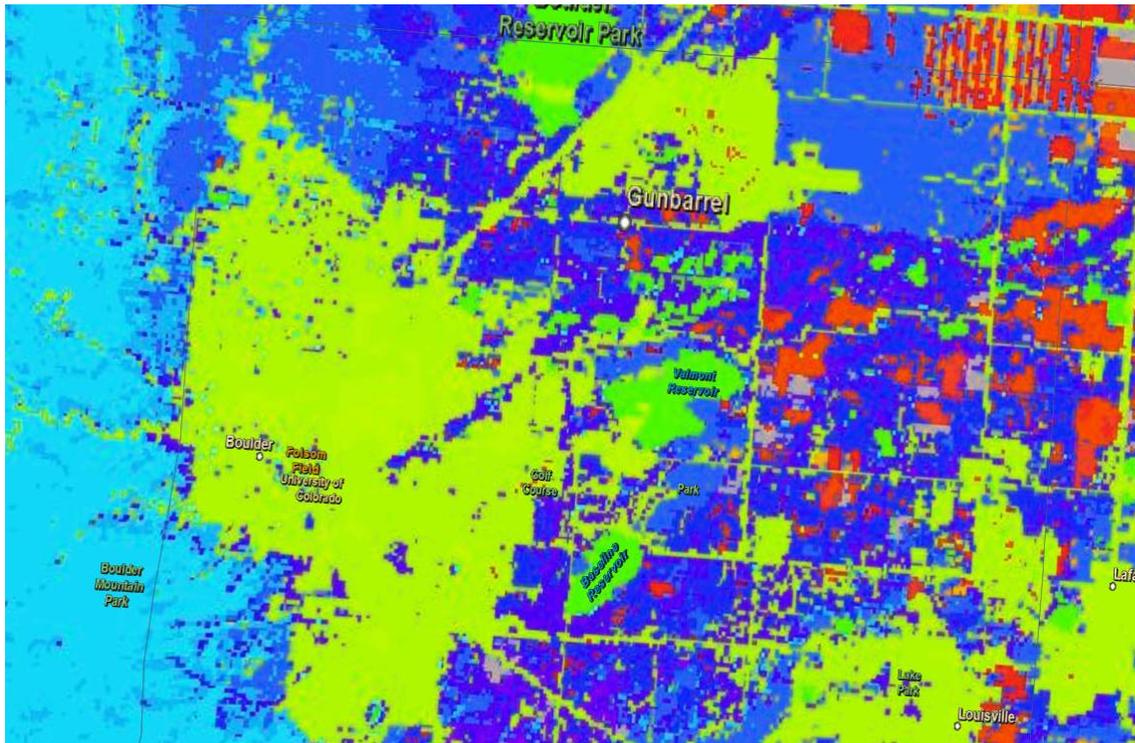
<b>Category</b>	<b>2008</b>	<b>2009</b>	<b>2010</b>
Corn	9983	11421	11447
Cotton	20809	25710	34830
Sorghum	1920	2364	1685
Sweet Corn	29	3	2
Barley	5759	11084	14307
Durum Wheat	20645	21775	9233
Spring Wheat	7538	578	12
Winter Wheat	1	1	594
Rye	0	0	83
Oats	1296	1803	1031
Millet	10	0	0
Alfalfa	128422	148208	132263
Other Hays	4157	4784	2842
Dry Beans	548	2	0
Potatoes	1228	1685	1792
Other Crops	990	234	1046
Misc. Veggies. & Fruits	911	0	0
Watermelon	2	102	38
Peas	0	0	1
Seed/Sod Grass	3197	1792	2012
Fallow/Idle Cropland	284622	233183	323918
Other Tree Nuts Fruits	175	0	0
Citrus	132	29	101
Other Tree Fruits	894	0	0
Pecans	0	740	951
Aquaculture	56	60	0
Open Water	13435	12352	13315
Developed/Open Space	122337	115537	132820
Developed/Low Intensity	215682	202034	190256
Developed/Medium Intensity	158816	165550	161291
Developed/High Intensity	21755	23486	28739
Barren	4425	4884	5396
Deciduous Forest	0	9	0
Evergreen Forest	29737	31797	32723
Shrubland	4667242	4704026	4626375
Grassland Herbaceous	117123	121767	119313
Pasture/Hay	1765	4847	4764
Woody Wetlands	39352	39483	40838
Herbaceous Wetlands	300	1032	145
Cantaloupe	8301	6512	4127
Olives	0	369	2128
Oranges	0	89	140
Honeydew Melon	0	2	0
Greens	0	5	0
Lettuce	115	1	505
Pumpkin	0	0	2
Dbl. Crop Lettuce/Durum Wht	1	0	0
Dbl. Crop Durum Wht/Sorghum	8947	1707	512
Dbl. Crop Barley/Sorghum	1069	2460	2145
Radish	0	215	0

**Table 5. Maricopa county AZ and Clark county NV landuse percentage for years 2008 to 2010 estimated from the CDL 56-m landcover product.**

<u>landuse</u>	<u>Maricopa county</u>			<u>Clark county</u>		
	<u>2008</u>	<u>2009</u>	<u>2010</u>	<u>2008</u>	<u>2009</u>	<u>2010</u>
Cropland	8.7%	8.2%	9.4%	0.1%	0.1%	0.1%
Urban	8.8%	8.6%	8.7%	4.1%	4.0%	4.1%
Wildland	82.2%	83.0%	81.6%	91.5%	91.5%	91.4%
barren	0.3%	0.3%	0.3%	4.4%	4.4%	4.4%

**2.2 VEGETATION SPECIES COMPOSITION DATA**

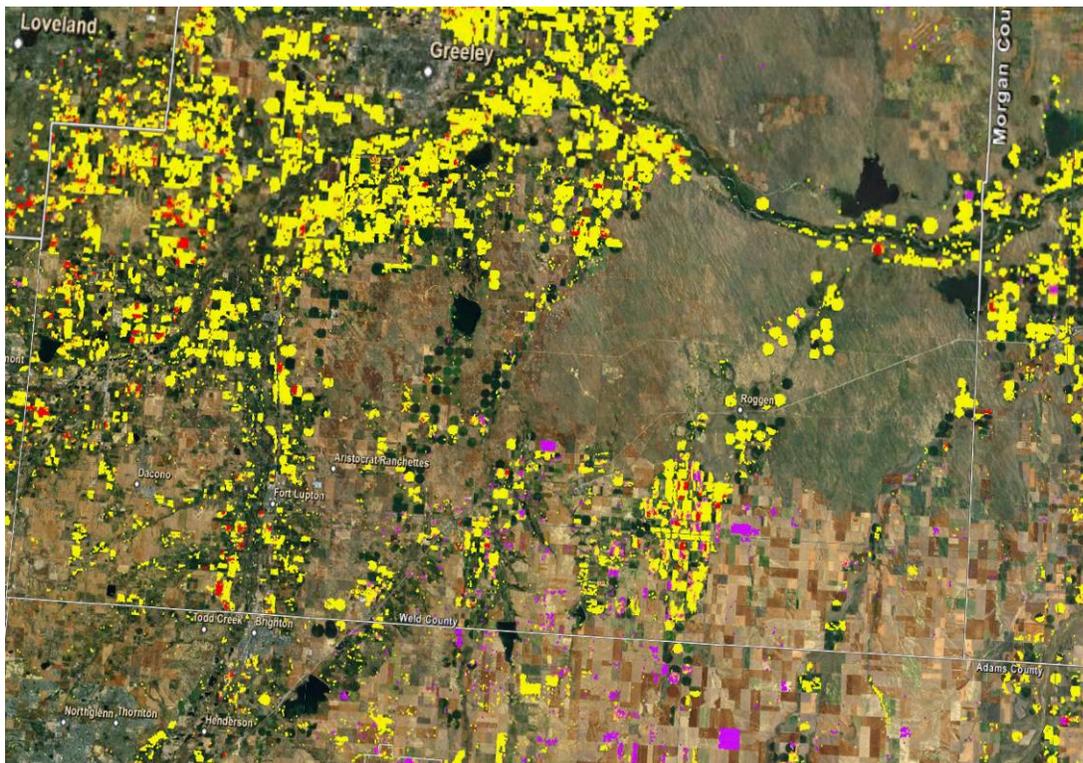
The CDL landcover data, described above, is used to classify landscapes as agricultural, wildland or urban and a different approach, using different databases, is used to characterize vegetation species composition in these three land use types. The approach used for each is described in this section.



**Figure 2.2a. CDL landcover distribution for Boulder CO for 2008 (yellow/green are urban types, red/orange are crop types, blues are wildland types).**

### 2.2.1 Agricultural landscapes

The USDA-NASS crop data statistics service compiles detailed annual information on U.S. cropland area and yield (see [www.nass.usda.gov](http://www.nass.usda.gov)) from annual surveys of about 70,500 farm operators. The NASS data has been used in the past for biogenic emission modeling including BEIS3.14 and MEGANv2.04 but it was county average statistics. The Cropland Data Layer (CDL, see <http://nassgeodata.gmu.edu/CropScape/>) provides geogridded information on crop distributions at a high (56-m) resolution (see Figure 2.2b). The plan for annual updates of the CDL provides a means for obtaining this information for specific years. This is important because interannual variations in cropland are expected to be greater than for urban and wildlands. For example, NASS reported a 25% increase in U.S. cotton between 2011 and 2010 (see [http://www.nass.usda.gov/Newsroom/2011/06\\_30\\_2011.asp](http://www.nass.usda.gov/Newsroom/2011/06_30_2011.asp)). Since cotton has a relatively high BVOC emission compared to other crops, this may represent a significant change in BVOC emissions in some regions.



**Figure 2.2b. Distribution of corn (yellow), sunflowers (purple) and sugar beets (red) in Weld County, CO.**

### 2.2.2 Wildland landscapes

The USDA-USFS Forest Inventory and Analysis (FIA, [www.fia.fs.fed.us](http://www.fia.fs.fed.us)) program is responsible for assessing U.S. forests through a census that previously was conducted periodically and now is conducted on an annual basis. The census consists of tree species and size measurements on more than 100,000 representative plots distributed across U.S. forests. The FIA program generally releases only regionally averaged statistics but plot level data was obtained for characterizing tree species distributions in BEIS. This plot level FIA database is used for

MEGANv2.04 and MEGANv2.1 and is supplemented for some regions (e.g., Texas) with poor coverage in the original database.

The USDA-NRCS provides an assessment of over 20,000 geo-located U.S. soil map units including potential tree, shrub, grass and forb species composition data for many of these units (see <http://sdmdataaccess.nrcs.usda.gov/>). While potential vegetation is not optimal, and coverage is not complete, there are no alternative comprehensive U.S. databases for characterizing shrub and grass species composition.

### 2.2.3 Urban landscapes

The USDA-USFS UFWU (urban forest work unit, see <http://www.nrs.fs.fed.us/units/urban/>) has compiled vegetation species composition data for selected U.S. urban areas. Additional information is available for other cities including the urban survey vegetation described by Duhl et al. (2011) and Baghi et al. (in preparation). The UFWU has divided the contiguous U.S. into 66 representative regions and provide landcover information which we have supplemented with additional information. It should be noted that urban vegetation does vary considerably among urban areas, even within these 66 regions, but this is currently the best available approach. BVOC emission modeling for a specific urban area will likely be substantially improved by obtaining vegetation species composition statistics for the city of interest.

Four studies have been conducted to improve biogenic VOC emissions from urban areas in Nevada, Arizona and Utah. All four studies included ground surveys of vegetation species composition and two of the studies also included measurements of species-specific emission factors. The studies generally show that urban vegetation cover is considerably higher than what was assumed from the generic urban landcover category used for BEIS/BELD. As a result, the studies generally resulted in an increase in emission estimates. Considerable increases in emissions, especially for isoprene, were also reported for some areas due to the improved species composition estimates. The two studies that included emission factor measurements found that these measurements resulted in even larger changes than were associated with improved vegetation species composition. The results of the four studies are summarized below.

*Pima County (Tucson, AZ):* Diem and Comrie (2000) developed a high spatial resolution (30 m) landcover database for estimating BVOC emissions from Tucson AZ and combined this with ground surveys of vegetation species composition. The authors report that the heterogeneous landscapes of this region cannot be adequately described with 1 km resolution landcover. In comparison to BELD2, the 30-m landcover resulted in monoterpene emissions that were a factor of 2 higher and isoprene emissions that were a factor of 4 higher. Within the Tucson urban area, the revised isoprene emissions were a factor of 70 higher.

*Wasatch Front Range (Salt Lake City, Utah):* Oldham (2002) developed a high spatial resolution (30 m) landcover database and integrated these data with vegetation species composition surveys. The new landcover distribution resulted in emission estimates that were 65% higher for isoprene, 26% lower for monoterpenes and 28% lower for other VOC in comparison to BELD2 landcover. It should be noted that BELD2 assumed urban landscapes to be 11% forested, 18% grass, 71% barren and had constant emissions throughout a county. BELD3 estimates

emissions with a spatial resolution of 1 km<sup>2</sup> and so would better represent heterogeneity within the county.

*Clark County (Las Vegas, Nevada):* Papiez et al. (2009) combined a high resolution vegetation survey with field measurements of biogenic VOC emission rate factors. In comparison to BELD/BEIS, the new vegetation survey increased emissions while the new emission factors decreased emissions. The changes in emission factors generally had a greater impact than the changes in foliar density and species composition.

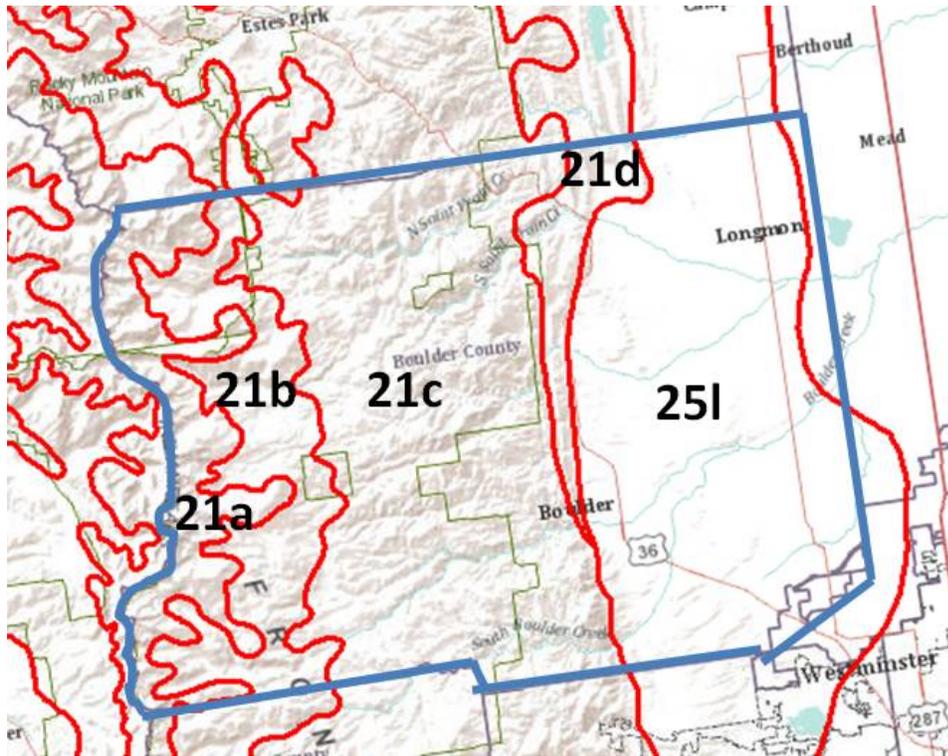
*Maricopa County (Phoenix, AZ):* Mansell et al. (2006) conducted surveys of vegetation species composition and species-specific emission factors in Maricopa County. The resulting emissions were compared to MAGBEIS2 which was based on a previous landcover study that provided species composition data. The revised emissions were about a factor of two higher outside of the urban area and a factor for two lower within the urban area. In addition, Duhl et al. (2011) conducted a high resolution (1-m) study of vegetation cover in the Phoenix urban area which showed that 30-m resolution is not sufficient in urban areas and that calibration with 1-m imagery is needed to provide reasonable tree cover estimates.

#### **2.2.4 Landscape averaging**

The species composition data are typically obtained as statistics for representative locations and then must be averaged over some region. BEIS, for example, has used U.S. counties for this purpose. While this is convenient for data, such as crop areas, that were reported on a county basis, counties are a political unit and often do not represent a uniform vegetation type. The BEIS approach is reasonable for many eastern U.S. counties, which are often small and relatively homogeneous, but not for western U.S. counties which are often much larger and cover heterogeneous landscapes that may span several major biomes. For example, Figure 2.2c demonstrates that landcover in Boulder County Colorado ranges from grassland to shrubland to several types of forest. The tree species composition of the ecoregions in Boulder county range from cottonwood dominated in the eastern grassland (25l), to 30% Ponderosa pine, 21% Douglas fir, 15% aspen etc. in mid-elevation forest (21c); and 70% Engelmann spruce in the alpine zone. Clearly, a single tree species composition for Boulder county would not accurately represent these individual ecoregions.

The MEGANv2.04 used the USGS GAP landcover distributions (see <http://gapanalysis.usgs.gov>) for zones to average species composition data. The GAP data is based on 1-km resolution MODIS satellite data and ground observations and divides U.S. landscapes into 590 types. This is a considerable improvement over a county based approach and in some regions can adequately describe species composition variations. However, the GAP has only one category for cultivated crops and can be difficult to link to species distribution data since the units are based on 1-km landcover distributions. MEGANv2.1 uses the U.S. ecoregion scheme (see <http://www.epa.gov/wed/pages/ecoregions.htm>) which divides the U.S. into about 1000 level 4 ecoregions. The distributions around Las Vegas NV and Salt Lake City UT are shown in Figure 2.2d. Heterogeneity within an ecosystem is accounted for by combining the ecoregion distribution with high resolution satellite based landcover (see LANDSAT-TM/NLCD and CDL/AWiFS descriptions in section 2.1). This approach uses 6 growth forms (shrub, grass,

broadleaf deciduous tree, broadleaf evergreen tree, needleleaf evergreen tree, needleleaf deciduous tree) to generate ~6000 vegetation types within the ~1000 ecoregions. The highly specific Level 4 ecoregions (e.g., Laramie Basin, san Luis shrublands and hills, Yellowstone Plateau) can be successively collapsed into higher levels up to level 1 which are very broad categories (e.g., Northwestern Forested Mountains, North American Deserts) which is useful for assessing the ecosystem average data.



**Figure 2.2c. Distribution of level 4 ecoregions in Boulder County, CO. 25I= Front range fan grassland, 21d =Foothill shrublands, 21c =Crystalline mid elevation forests, 21b =Crystalline subalpine forests, 21a =alpine zone**

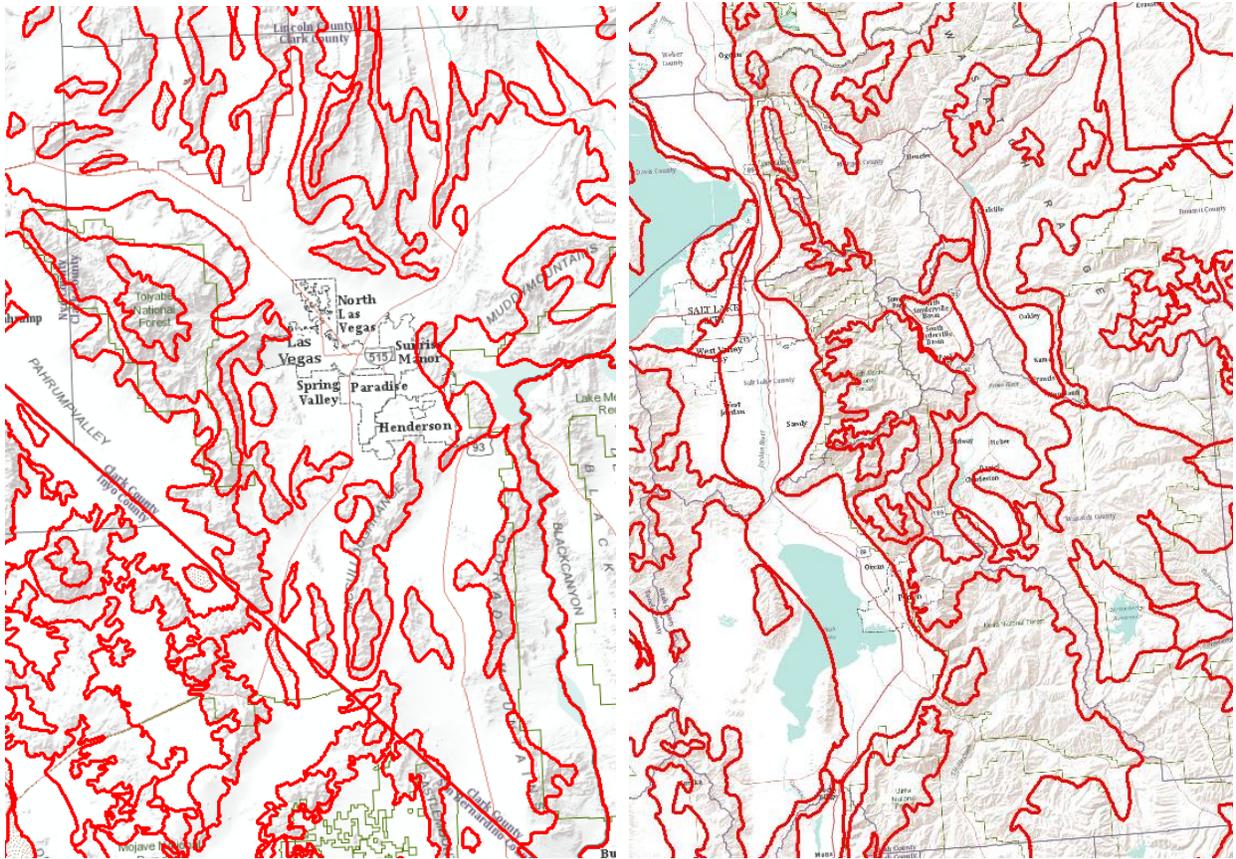


Figure 2.2d. Ecoregion distributions around Las Vegas, NV (left) and Salt Lake City, UT (right).

## 2.3 BIOGENIC EMISSION MEASUREMENTS

### 2.3.1 Measurement techniques

BVOC emission models are dependent on accurate and representative measurements that can provide a quantitative understanding of the processes controlling the magnitude and variations in biogenic emissions. The processes controlling emissions over a range of scales and so multi-scale measurements are needed to develop and evaluate these models. The five key scales and associated observational techniques are summarized in Figure 2.3a and briefly described in this section.

Biochemical measurements provide a basic understanding of the cellular processes that control biogenic emissions. Most of the main biochemical pathways responsible for the production of biogenic VOC have been investigated and are reasonable well known (Kant et al. 2009). Cellular level investigations are beginning to provide an understanding of genetic (e.g., Karl et al. 2010) and enzymatic (e.g., Schnitzler et al., 2010) controls over BVOC exchange that can be used as the basis of quantitative algorithms.

Most of the measurements used to develop BVOC emission measurements have been based on leaf or branch enclosure techniques. This approach involves enclosing part of a plant in an inert enclosure and estimating the emission from the difference in the inlet and outlet concentrations (see Figure 2.3c left panel). This has the advantage of enabling investigators to associate emissions with specific environmental conditions (e.g., temperature and light) and

many systems even provide the means to control light and temperature enabling studies where one parameter is varied while others remain constant. The disadvantages are that only a small part of an ecosystem can be enclosed (i.e. each measurement represents only a few of the millions of leaves occurring in a 1 km<sup>2</sup> landscape) and that the enclosure perturbs the environment surrounding the leaf and often results in considerable stress. In addition, enclosing some western U.S. desert species can be especially challenging (Figure 2.3c right panel). Enclosure measurements reported in the peer-reviewed literature include results from six Western U.S. states including Arizona (Geron et al. 2006, Jardine et al. 2010), California (Winer 1989, Arey et al. 1995, Geron et al. 2001, Bouvier-Brown et al. 2009, Ormeño et al. 2010, Fares et al. in press), Colorado (Guenther et al. 1996, Kim et al. 2010), Nevada (Geron et al. 2006, Papiez et al. 2009), New Mexico (Martin et al. 1999) and Oregon (Geron et al. 2001).

Above canopy flux measurements integrate over the entire landscape without disturbing the ecosystem. These systems directly quantify emissions using eddy flux techniques such as relaxed eddy accumulation (e.g., Guenther et al., 1996) and eddy covariance (Guenther and Hills, 1998; Karl et al. 2001). Capabilities for quantifying biogenic VOC fluxes have been steadily improving over the past decade including recent analytical advances such as Time-of-Flight Proton Transfer Reaction Mass Spectrometer (TOF-PTRMS) that enable accurate and reliable measurement of nearly all of the most important BVOC fluxes. Tower-based flux systems (see examples in Figure 2.3d) typically have a footprint of hundreds of meters and are well suited for quantifying temporal variations (i.e. diurnal, seasonal, and inter-annual variations). The existence of a global network of more than 500 flux towers (see [www.fluxnet.ornl.gov](http://www.fluxnet.ornl.gov)) constructed for water, carbon and energy flux studies provides an opportunity to add biogenic VOC measurements without the cost of basic site development. Measurements at a large number of sites can be accomplished with low-cost and low-power measurements systems (e.g., relaxed eddy accumulation) while eddy covariance techniques are suitable for long-term, continuous whole canopy measurements of seasonal and inter-annual variations (e.g., Pressley et al. 2004, Schade et al. 2001).

Biogenic VOC fluxes can be measured on the regional scales relevant for regional models using an airborne Proton Transfer Reaction Mass Spectrometer - Eddy Covariance (PTRMS-EC) flux system. Karl et al. (2009) have recently demonstrated that the technique is suitable for quantifying VOC fluxes and the system was deployed in the western U.S. in June 2011 (see figure 2.3e). Area-average BVOC emissions were characterized over hundreds of km of oak woodlands, conifer forests, grasslands, shrublands and croplands with a spatial resolution of ~ 1 km<sup>2</sup>. These observations are suitable for constraining and evaluating biogenic VOC emission models and will greatly enhance our ability to identify and correct deficiencies in biogenic VOC emission models.

The development of satellite chemical sensors has enabled continuous global observations of two important biogenic VOC: isoprene and methanol. These data represent concentrations that can be related to emissions through inverse modeling with a chemistry and transport model. Given our limited knowledge of chemistry and transport, these data are most useful for evaluating emissions by identifying regions of disagreement with emission models. Satellite based estimates of isoprene generally indicate that Western U.S. landscapes are generally low (figure 2.3f) which is in agreement with the MEGAN and BEIS emission models. An initial satellite-based assessment of methanol distributions indicates that the MEGAN model is

generally in good agreement except for semi-arid regions such as central Asia and the Western U.S. (figure 2.3g).

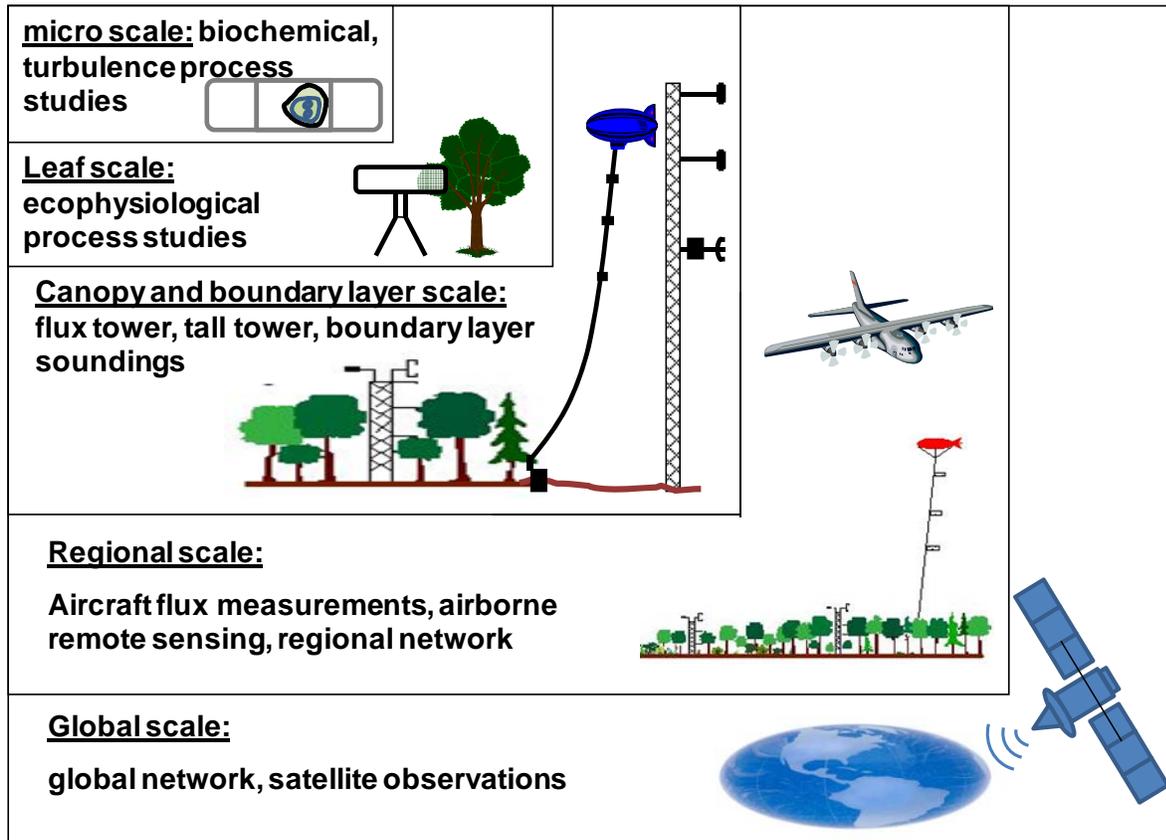


Figure 2.3a. Multi-scale observations of biogenic emissions (from Guenther et al. 2011).

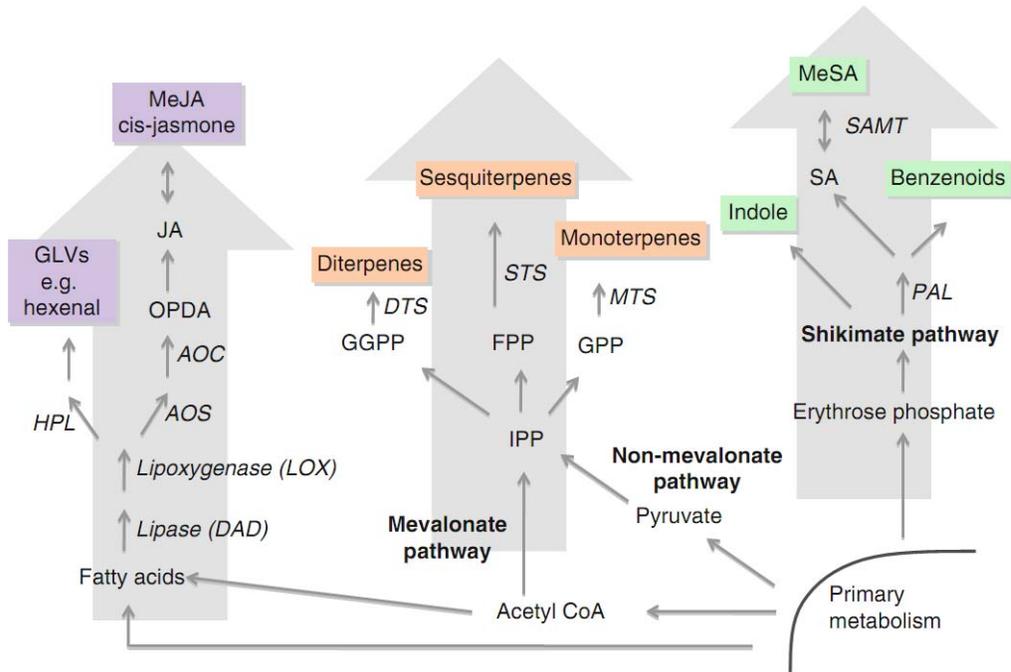


Figure 2.3b Biochemical pathways for producing biogenic VOC (from Kant et al. 2009)



Figure 2.3c. Enclosure BVOC measurement systems deployed in Maricopa County, Arizona for measuring desert trees and shrubs (left) and Saguaro cactus (right).



**Figure 2.3d. NCAR relaxed eddy accumulation system measuring BVOC emissions above an Oregon poplar plantation (left). NCAR tower and movable lift platforms for BVOC emission measurement systems within and above a Ponderosa pine woodland in Colorado (right).**



**Figure 2.3e. NCAR airborne eddy covariance measurement system deployed on CIRPAS twin otter for measuring regional scale BVOC emissions above a California forest (left) and shrubland (right).**

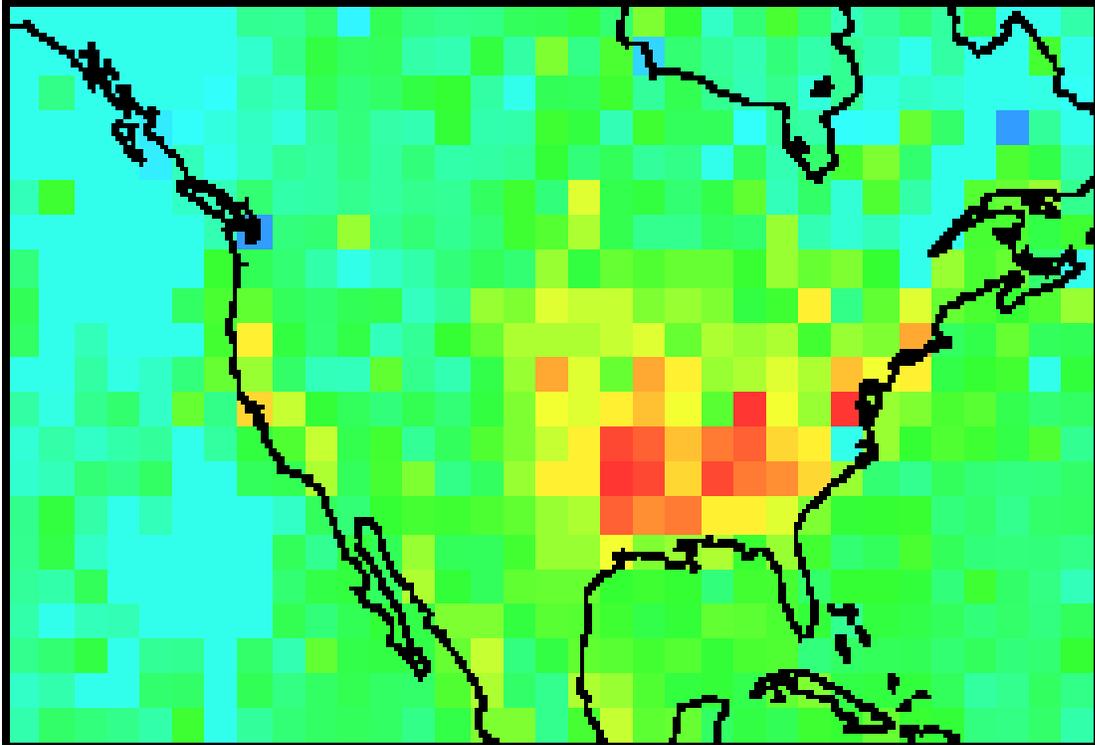


Figure 2.3f July 2001 relative isoprene emission estimated from GOME satellite observations. Red is high, yellow is moderate, green is low, blue is negligible (from Guenther et al. 2006).

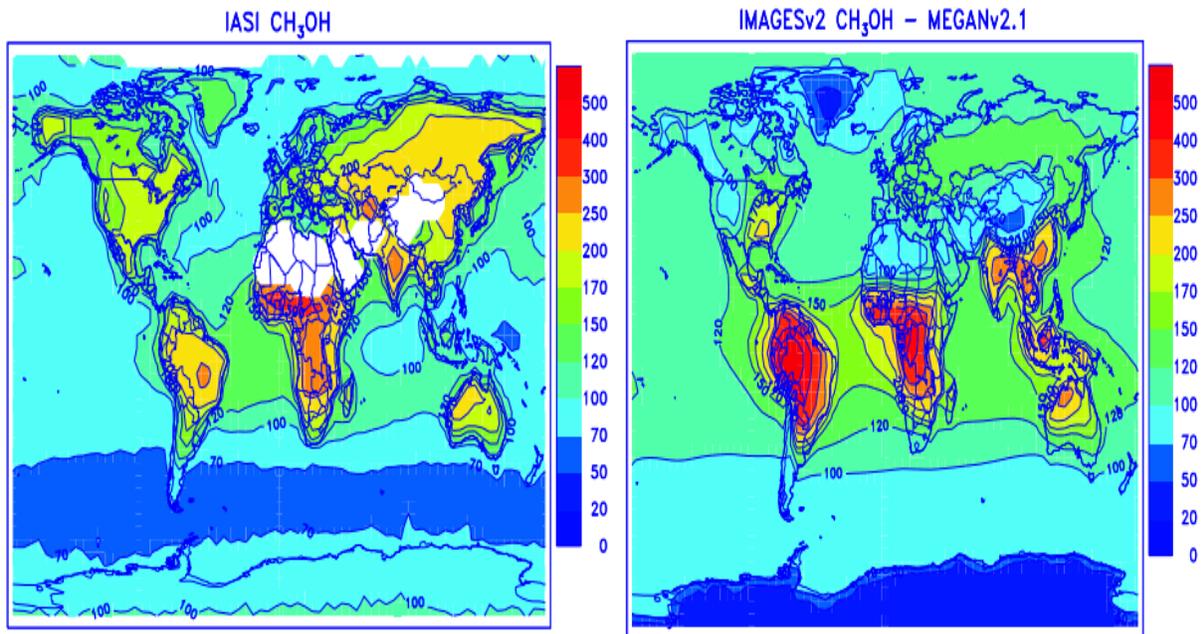


Figure 2.3g. Global methanol distributions for 2009 from the IASI satellite (left panel) and from MEGANv2.1 (right panel). Units are  $10^{14}$  molec.  $\text{cm}^{-2}$  (from Stavrou et al. 2011).

### 2.3.2 Isoprene and monoterpene measurements

Isoprene (C<sub>5</sub>H<sub>8</sub>) is the dominant BVOC emission into the atmosphere (Guenther et al., 1995) and so has been the focus of many BVOC emission studies. Isoprene is emitted in substantial amounts by less than half of all plant species but most of those that do emit isoprene can have very high emissions so that a relatively small fraction of the plant species in some landscapes are responsible for the bulk of the emissions. Isoprene is emitted by soil bacteria, algae, animals (including humans) and plants (Wagner et al. 1999). However, only vegetation emissions have been shown to occur at levels that can influence atmospheric composition. The isoprene emission rates of different plant species range from < 0.1 to > 100 µg g<sup>-1</sup> h<sup>-1</sup>. Very low and very high emitters often occur within individual plant families and even within some globally important plant genera including *Quercus* (oaks), *Picea* (spruce), *Abies* (firs) and *Acacia*. The large taxonomic variability makes the characterization of isoprene emission factor distributions a challenging task. Isoprene emission is rarely observed from plants that are entirely “non-woody”. However, there are a number of isoprene-emitting plants that are not trees or shrubs. Some of the important isoprene emitting genera in this category include *Phragmites* (a reed), *Carex* (a sedge), *Stipa* (a grass) and *Sphagnum* (a moss). Reported isoprene emission factors for herbaceous landscapes range from about 0.003 mg m<sup>-2</sup> h<sup>-1</sup> for grasslands in Australia (Kirstine et al., 1998) and central U.S. (Fukui and Doskey, 1998) to about 0.4 for a grassland in China (Bai et al., 2006) and about 1.2 mg m<sup>-2</sup> h<sup>-1</sup> for forests and wetlands in southern U.S. (Zimmerman, 1979), northern U.S. (Isebrands et al., 1999), Canada (Klinger et al., 1994) and Scandinavia (Janson et al., 1999). At least one enclosure measurement has characterized each of the 25 globally dominant crop genera and none have been found to emit isoprene. However, agricultural landscapes are isoprene sources in at least some regions. Plantations of isoprene emitting trees (e.g., poplar, eucalyptus, oil palms) could be classified as crops. In addition, isoprene emitting plants are introduced into croplands to increase nitrogen availability and to provide windbreaks. Nitrogen-fixing plants that are grown in croplands to provide “green manure” include Velvet beans (*Mucuna pruriens*, a legume) in cornfields and *Azolla*, an aquatic fern, in rice paddies. Both of these plants produce substantial amounts of isoprene (Silver and Fall, 1995). While the use of Velvet bean is relatively limited, *Azolla* is widely used in the major rice producing regions (Clark, 1980). Tropical kudzu (*Pueraria phaseoloides*) is the most widely used “green manure” plant in tropical agricultural lands. Although there are no reported isoprene emission measurements for tropical kudzu, all other examined *Pueraria* species have been identified as isoprene emitters (e.g., Guenther et al., 1996).

Emission enclosure studies have shown that much of the previously observed isoprene variability among plant species with significant emission rates (e.g., *Quercus*, *Liquidambar*, *Nyssa*, *Populus*, *Salix*, and *Robinia* species) can be attributed to weather, plant physiology and the location of a leaf within the canopy rather than genetics (Geron et al., 2000). Other studies have characterized how emissions respond to various factors including leaf age (Petron et al., 2001), nutrient availability (Litvak et al., 1996), weather of the past 1 to 10 days (Sharkey et al., 1999; Geron et al., 2000a; Hanson and Sharkey, 2001) and the chemical composition of the atmosphere (Loreto et al., 2004; Rosenstiel et al., 2003). One implication of this is that the observations reported from many earlier studies, where these factors were not considered, are useful only to qualitatively categorize vegetation into emitting and non-emitting categories.

The landcover data described in section 2.2 were used to assess the adequacy of existing emission measurements for characterizing isoprene emission factors. There are 74 tree genera

found in the western U.S., but the most common 32 genera comprise 99% of the total tree cover so it is unlikely that the remaining genera are important contributors to western U.S. BVOC although they could be dominant in limited areas. At least a few emission measurements have been made on the dominant 32 genera and these observations indicate that only 19% (6 of 32 genera) emit isoprene: oaks (*Quercus*), aspen/poplars (*Populus*), spruce (*Picea*), willows (*Salix*), Gum (*Nyssa*) and sweetgum (*Liquidambar*). Another 16 genera together contribute only about 1% of the total western U.S. tree cover and include 25% (4 of 16) isoprene emitters: locust (*Robinia*), sycamore (*Platanus*), ironwood (*Olneya*) and eucalyptus. The 74 tree genera include 245 tree species. The emissions of some of these species have not been measured and it is possible that some of these genera include both emitters and non-emitters.

An assessment of current emission factors and tree distribution data indicates that oaks are responsible for about 62% of total isoprene emission potential in the western U.S. with aspen/poplars (27%), spruce (6%), and willows (2%). Above canopy flux studies in the western U.S. have targeted an oak forest (Lamb et al., 1986) and a poplar plantation (Guenther et al., unpublished data) and enclosure studies have characterized spruce and willows which suggests that efforts have been directed appropriately. However, each of these studies obtained a very small number of measurements. A somewhat larger database of leaf level isoprene measurements for the western U.S. has been reported by Geron et al. (2001) and Papiez et al. (2009).

Western U.S. shrubs, grasses and forbs include over 500 genera and thousands of species. There have been fewer BVOC emission measurements on these species so our ability to quantify their emissions is much less. Some Western U.S. sedges (e.g., *Carex*), rushes (e.g., *Juncus*), ferns (e.g., *Polystichum*) and shrubs (e.g., *Ephedra*, *Larrea*, *Psoralea*, *Simmondsia*, *Condalia* and *Berberis*) have been identified as isoprene emitters and are currently assumed to be the dominant source of isoprene emission from ground cover. The limited number of measurements on western U.S. grass and shrub species leads to large uncertainties in these estimates.

### 2.3.3 MBO (methyl butenol)

MBO is an "isoprene alcohol" that is emitted at high rates ( $>20 \mu\text{g C g}^{-1} \text{ h}^{-1}$ ) from needles of some, but not all, pine species (Harley et al., 1998). Since this includes two widespread western North American tree species, lodgepole (*Pinus contorta*) and Ponderosa (*P. ponderosa*), MBO is the dominant emission from some western U.S. landscapes. MBO emission factors vary with light and temperature in a manner similar to isoprene (Harley et al., 1998; Schade et al., 2000).

An assessment of western U.S. MBO emission factors and tree species distributions indicates that ponderosa pine dominates MBO emissions with most of the remainder from lodgepole pine. Jeffrey pine (4%) and Gray pine (1%) make small contributions and all other trees comprise less than 2% of the total. MBO emissions have not been observed from crop, grass/forb or shrubs. Whole canopy (including enclosure and above canopy fluxes) MBO studies have focused on lodgepole pine (e.g., Baker et al., 2001; Karl et al., 2002) and Ponderosa pine (e.g., Schade et al., 2000; Kim et al. 2010) indicating that efforts to characterize western U.S. MBO emissions have been targeted appropriately.

### 2.3.4 Monoterpenes

Geron et al. (2000) summarized monoterpene ( $C_{10}H_{16}$ ) emission enclosure data for the dominant U.S. tree species including those in the Western U.S. As is discussed above for isoprene emission factors, monoterpene emission factors may be biased under some physiological conditions, and that tree and needle age, needle wetness, relative humidity, phenological state (e.g., bud-break, senescence), and stomatal control must be considered in attempts to realistically model monoterpene emissions and establish emission factors (Kim, 2001; Schade et al., 1999). Characterizing monoterpene emissions using enclosure measurements is considerably more difficult than for isoprene or MBO due to the presence of storage structures which can be disturbed and emit at rates an order of magnitude or more higher than for undisturbed conditions. It was previously thought that all or most monoterpene emanated from these storage pools but recent studies have shown that a large fraction of the emission from both broadleaf and conifer trees are from recently synthesized carbon which is emitted in a manner similar to isoprene.

Most western U.S. tree species have substantial monoterpene emission rates so that the contribution to total western U.S. monoterpene emissions is similar to the contributions to total tree cover. Some species with relatively low emission factors, such as junipers, comprise 9% of tree cover and only 4% of emission potential whereas pines are responsible for 23% of tree cover and 36% of monoterpene emission potential. Above canopy flux measurements in western U.S. landscapes have characterized monoterpene emissions from several of the dominant tree species associations (Ponderosa pine, Lodgepole pine with subalpine fir and Engelmann spruce, pinyon/juniper woodland).

The foliage of many southwestern shrubs contain aromatic compounds, including monoterpenes, that can be emitted to the atmosphere. Some enclosure measurements indicate high emission rates although some recent measurements indicate much lower rates which agrees with some ambient concentration observations. Above canopy flux studies are needed in shrublands to confirm these findings.

### 2.3.5 Sesquiterpenes

Sesquiterpenes (SQT) are terpenoid hydrocarbons with the molecular formula  $C_{15}H_{24}$ . These compounds have high yields of atmospheric secondary organic aerosol. Although this makes these compounds extremely important for regional air quality modeling, there are relatively few studies that have characterized the emissions of these compounds. This is partly due to the very challenging analytical methods required to quantify emissions of these compounds. SQT emissions have been detected from numerous plant species, including conifer and broadleaf trees, shrubs and agricultural crops. Duhl et al. (2008) have reviewed SQT measurements including several studies in the Western U.S. Emission factors for major PFT types were recommended although a large variability within each type was also noted. Laboratory studies have examined the leaf age, light and temperature controls over SQT emissions (Duhl et al. 2008).

### 2.3.6 NO (Nitric oxide)

The primary means for developing NO emission factors from soils has been through measurements with static or dynamic chambers. Thousands of measurements have been made in the southeastern U.S. by Thornton et al. (1997) and in many other parts of the world (Davidson and Kinglerlee, 1997). These studies have shown that there is very large small scale heterogeneity in soil NO emissions. Above canopy flux studies have the advantage of averaging over a larger footprint and accounting for canopy losses. However, there have been relatively few of this type of measurement. Yienger and Levy (1995) summarize the factors controlling NO emissions and developed algorithms for describing the response of soil NO emissions to temperature, soil moisture and fertilization applications. The Yienger and Levy model that is used for the BEIS3 soil NO emission rates is the best available approach. More mechanistic soil NO emission models have been developed but they are heavily parameterized and so cannot be applied in the Western U.S. without considerable effort to measure the appropriate parameters.

The overall uncertainties in biogenic VOC and NO emissions are of a similar magnitude. Global annual emission estimates for both range over about a factor of 3 with estimates of about 6 to 18 Tg of NO and 500 to 1500 of VOC. The uncertainties for specific locations and time periods are considerably greater and difficult to quantify due to limited observations. Airborne regional flux measurements provide an effective approach for quantifying these fluxes.

### 2.3.7 Other biogenic compounds

Ethene production is widespread in plants and is likely to be a significant emission from most landscapes (Goldstein et al., 1996). Propene and butene are emitted at lower rates but are still significant (Goldstein et al., 1996). Other hydrocarbons (e.g., ethane, toluene) have been reported as emissions, but are relatively insignificant (Guenther et al., 2000).

Warneke et al. (2002) measured large above-canopy fluxes of methanol from an undisturbed alfalfa field in Colorado and a much smaller flux of hexenal. Emissions of the two compounds were greatly increased during harvesting and continued to emit at high rates as the alfalfa was drying. In addition, fluxes of hexenylacetate, hexenol, hexanal, butanone were observed during harvesting. Similar results have been observed for hay harvesting and lawn mowing (Karl et al. 2001). These emissions could dominate total fluxes from some regions during periods of harvesting (Karl et al. 2001)

Substantial acetaldehyde and formaldehyde emissions have been observed from European conifer and broadleaf trees (Kesselmeier et al., 1997; Kreuzwieser et al., 1999) and are particularly high during flooding (Kreuzwieser et al., 2000). Other stress factors such as hypoxia, drought, chilling, and wounding cause an increased production of formaldehyde in plants (see Kreuzwieser et al., 2001). Formic and acetic acid were emitted at somewhat lower rates. Emissions of all of these compounds have a atmospheric compensation point below which plants emit the compounds and above which the plants take up the compounds (Kesselmeier, 2001). Martin et al. (1999) and Knowlton et al. (1999) report similar results for trees found in montane forests in New Mexico.

Acetone emissions have been observed from conifer and broadleaf trees and the emissions have a compensation-point (Janson et al., 1999; Janson and de Serves, 2001). Methanol,

acetaldehyde and acetone are the major non-terpenoid BVOC emissions observed above most plant canopies (Karl et al. 2001, 2002, 2004; Baker et al. 1999; Schade et al. 2001).

The formation and emission of CO on or in live plant foliage is the result of direct photochemical transformation and occurs inside the leaf (Tarr et al., 1995). The factors controlling these emissions are not well known and biogenic CO emission estimates are very uncertain. Guenther et al. (2000) recommended an emission factor of 0.3 carbon  $\mu\text{g g}^{-1} \text{h}^{-1}$  which results in a small but significant contribution to total U.S. CO emissions.

## 3.0 Emission model algorithms and input files

### 3.1 MEGAN, BEIS, AND GLOBEIS MODEL DESCRIPTIONS

#### 3.1.1 MEGAN model description

The Model of Emission of Gases and Aerosol from Nature (MEGAN) is being developed as a community effort led by the National Center for Atmospheric Research (NCAR) and including the USEPA, NOAA, U. Colorado, Colorado State U., MIT, California Inst. Tech., U. Minnesota, Harvard U., Washington State U., U. Texas, Lancaster U., U. Edinburgh, Sun-Yat Sen University, ENVIRON and other institutions. MEGAN is a modeling system for estimating the net emission of gases and aerosols from terrestrial ecosystems into the atmosphere (Sakulyanontvittaya, 2008; Guenther et al., 2006). It is driven by land cover, weather, and atmospheric chemical composition. MEGAN is a global model with a base resolution of  $\sim 1$  sq km that can either run as a stand-alone model for generating emission inventories or can be incorporated as an on-line component of chemistry/transport and earth system models.

The MEGAN model components and their linkages are shown in Figure 3.1a. Model inputs include geogridded data files that contain a value for each location in a model grid. These include weather data (e.g., hourly temperature, solar radiation and soil moisture output from WRF or another meteorological model), LAI data (e.g., 8-day averages from MODIS satellite), PFT data (e.g., annual values from CDL and NLCD), and emission factors maps based on vegetation species composition and emission factors. Additional inputs include tables with CO<sub>2</sub> concentrations, PFT average emission factors, and parameters for various model components. The main modules are leaf age, soil moisture and CO<sub>2</sub> models (accounting for emission response to leaf age, soil moisture and CO<sub>2</sub>, respectively) and a canopy environment model that calculated leaf temperature and leaf light levels on sun and shade leaves at 5 canopy depths and accounts for emission response to these variables. Each model component is described in detail by Guenther et al. (2006), Sakulyanontvittaya (2008), Heald et al. (2009), Millet et al. 2010 and Stavrakou et al. (2011), Additional details and the model code are available at <http://bai.acd.ucar.edu/Megan/>.

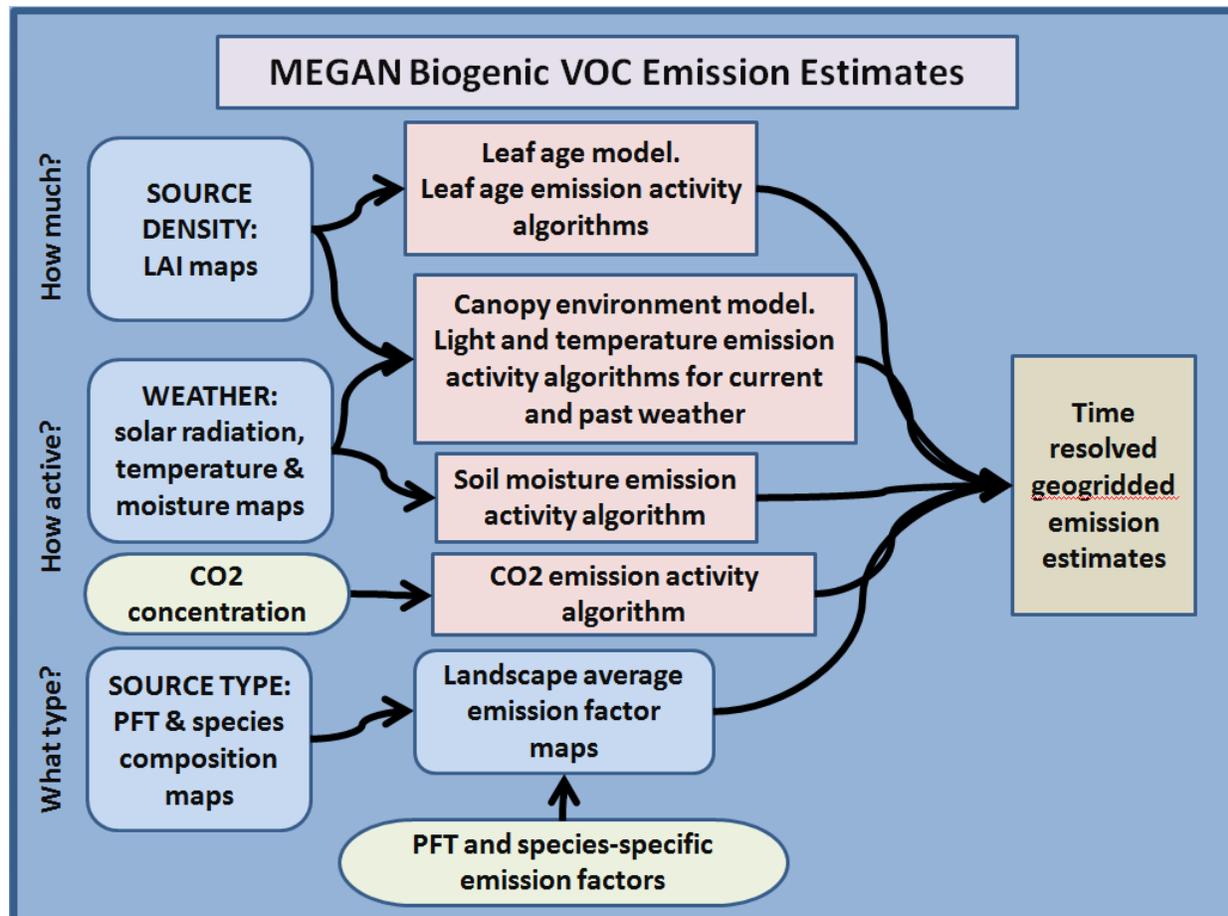


Figure 3.1a. MEGAN schematic diagram.

### 3.1.2 BEIS model description

The Biogenic Emission Inventory System (BEIS; Pierce and Waldruff, 1991) was first used to generate biogenic VOC inputs for regional air quality modeling in 1988. This first version was based primarily on the emission factors and algorithms described by Lamb et al. (1987). The Lamb et al. procedures were based on field measurement studies conducted in the late 1970s and early 1980s. This first generation model placed all biogenic VOC into four categories: isoprene,  $\alpha$ -pinene, other monoterpenes, and "unidentified". The model had 17 vegetation categories with emission factors specified for each of these categories. The BEIS vegetation categories included three forest types (oak, other deciduous, and coniferous), three grass/shrub categories (hay/scrub, range, and grass/pasture), ten crop categories and one urban vegetation category.

The second version of the Biogenic Emission Inventory System (BEIS2) was developed in 1994 and included a new land use inventory, updated emission factors and revised environmental correction factors. In addition, BEIS2 introduced soil NO emission estimates. BEIS2 isoprene emissions tended to be about 5 times higher than BEIS isoprene emission estimates for forested areas which generated considerable concern regarding the accuracy of BEIS or BEIS2 emission estimates. The updated emission factors, based on Guenther et al. (1994), were the primary reason for the difference between BEIS and BEIS2 estimates. BEIS2 generates hourly emissions on the county level. BEISv2.3, released in 1998, is the latest PC version of BEIS.

BEISv3 was developed in 2001 and is the latest generation in the BEIS family. All BEIS3 versions are designed for use with the Sparse Matrix Operational Kernel Emissions (SMOKE) system. BEISv3.09 is currently the default version in SMOKE. BEIS3.10 was developed for the 2002 release of the Community Multiscale Air Quality (CMAQ) modeling system. It includes a 1-km vegetation database that resolves forest canopy coverage by tree species; emission factors for 34 chemicals including 14 monoterpenes and methanol; a soil NO algorithm dependent on soil moisture, crop canopy coverage, and fertilizer application; and speciation for the CB4, RADM2, and SAPRC99 mechanisms. BEISv3.11 revises the soil NO algorithm in BEIS3.10 to better distinguish between agricultural and nonagricultural land, and to limit adjustments from temperature, precipitation, fertilizer application, and crop canopy to the growing season and to areas of agriculture. A leaf shading algorithm is added for estimating methanol emissions from non-forested areas. BEISv3.12 was released in November 2003 as a stand-alone module to the SMOKE system for generating gridded, hourly emissions in a format consistent for air quality modeling. BEISv3.14 includes sesquiterpenes emissions but is otherwise the same as BEISv3.12. Additional details and the model code are available at <http://www.epa.gov/asmdnerl/biogen.html>.

### 3.1.3 GloBEIS description

GloBEIS is a biogenic emissions modeling system developed by NCAR and Environ International Corporation, based on the BEIS emission factors and algorithms but with an easier-to-use interface and compatibility with a wider range of input data sources and enhanced algorithms including canopy environment, leaf age, variable LAI, and the influence of antecedent temperature conditions (Yarwood et al., 2010). GLOBEIS was developed to allow users to estimate biogenic emissions of volatile organic compounds, carbon monoxide and soil NO<sub>x</sub> emissions for any time scale and domain. It is used for biogenic emission modeling in southcentral U.S. by TCEQ and has been continually improved over the past decade. Additional details and the model code are available at [www.globeis.com](http://www.globeis.com).

## 3.2 MEGAN, BEIS, AND GLOBEIS COMPARISON

GloBEIS, BEIS, MEGAN and most other biogenic VOC emission models estimate emissions as a function of emission factors, foliage distributions, and emission activity factors that include solar radiation, temperature and other factors. Almost all of these components can be easily compared and are transferable among these models. The one exception is the procedures used to develop vegetation type distributions which are specific to each model. Table 6 summarizes differences in the emission factor, foliage distributions, and emission activity algorithms used in MEGAN2.04, MEGAN2.1, BEIS3.14 and GloBEIS3.5. A detailed description of the differences in model approaches for each of these categories is given in this section and the contribution to overall differences is discussed.

### 3.2.1 Emission Factors

GloBEIS3.5 and BEIS3.14 emission factors are within a few percent for isoprene and the BEIS3.14 monoterpene emission factors are about 10% lower than GloBEIS3.5. The BEIS3.14 OVOC emission factors are an order of magnitude higher than the GloBEIS3.5 values for crops and grass, a factor of ~3 higher for broadleaf trees and ~50% higher for conifers. The BEIS3.14 sesquiterpene emission factors are more than a factor of 2 lower than the GloBEIS3.5 values for woody plants and are about the same for crops and grass. The MEGAN2.1 isoprene emission factors are ~ 37% higher than GloBEIS3.5 for most isoprene-emitting species including *Quercus* (Oaks), *Populus* (Poplars) Liquidambar (sweetgum) and Eucalyptus. Exceptions include a factor of ~5 higher emission rates for *Nyssa* (Tupelo Gum) and *Robinia* (Locust) species, a factor of ~2 higher for *Salix* (Willow) and *Platanus* (Sycamore) and a factor of ~2 lower for *Picea* (spruce). The MEGAN2.1 monoterpene emission factors tend to be ~40% lower than the GloBEIS3.5 emission factors for conifers and range from ~40% lower to more than a factor of 2 higher for broadleaf trees. MEGAN2.1 considers much of the broadleaf tree emission to be light-dependent which results in much lower emissions at nighttime. The GloBEIS3.5 and MEGAN2.1 sesquiterpene emission factors are about the same. The BEIS3.14 and MEGAN2.1 NO emission factors are the same.

Table 6. Comparison of GloBEIS3.5 with MEGAN2.04, MEGAN 2.1, and BEIS 3.14.

Category	MEGAN2.04	MEGAN2.1	BEIS3.14	GloBEIS3.5	GloBEIS vs BEIS	GloBEIS vs MEGAN2.1
<b>Emission Factors</b>						
Isoprene EF (mg/m <sup>2</sup> /h)	oaks=24	oaks=24	oaks=17.5	oaks=17.5	↓↓↓	=
Monoterpene EF (mg/m <sup>2</sup> /h)	pine=1.45	pine=1.45	pine=2.1	pine=2.38	↑↑	↑↑↑
Sesquiterpene EF (mg/m <sup>2</sup> /h)	pine=0.2	pine=0.2	pine=0.08	pine=0.2	↑↑↑	=
OVOC EF (mg/m <sup>2</sup> /h)	oak=2	oak=2	oak=2.4	oak=0.55	↓↓↓	↓↓↓
<b>Foliage distributions</b>						
Peak LAI	satellite data	satellite data	constant	both options	↓	≈
LAI variations	satellite data	satellite data	constant	both options	↓	≈
<b>Solar radiation</b>						
Solar constant (W/m <sup>2</sup> )	1367	1367	1320/1300	1367	↑	≈
Visible fraction	f(diffuse frac)	f(transmission)	f(diffuse frac)	46% of total solar	↑	≈
Diffuse fraction	f(transmission)	different for PPFD	f(P, zenith angle, Q)	f(transmission)	↓	↓↓↓
μmol photons per Joule	4.55	diffuse=4.3, direct=4.6	4.6	4.55	≈	↑
Sun vs shade leaves	40% sun	xx% sun	37% sun	40% sun	↑	≈
Canopy PPFD	5 levels; xx% transmitted	5 levels; xx% transmitted	1 level; 1xx% transmitted	5 levels; xx% transmitted	↓	≈
Isoprene response to light	$\alpha, C_L = f(\text{past light})$	$\alpha, C_L = f(\text{past light})$	$\alpha = 0.00185, C_L = 1.42$	$\alpha, C_L = f(\text{LAI depth})$	↑↑	↓
MT/SQT response to light	5 to 80% light dependent	parameters vary	none	none	=	↑
OVOC response to light	5 to 80% light dependent	parameters vary	none	100% light dependent	↓	↓
<b>Temperature</b>						
Canopy leaf temperature	energy balance	energy balance	equal to air temperature	energy balance option	↑	=
Isoprene response to T	$E_{opt}, T_{opt} = f(\text{past T})$	$E_{opt}, T_{opt} = f(\text{past T})$	$E_{opt}=1.9, T_{opt}= 312.5$	$E_{opt}, T_{opt} = f(\text{past T})$	↑↑↑	↑↑
MT response to T	$\beta = 0.09$ or $0.12$	$\beta = 0.1$	$\beta = 0.09$	$\beta = 0.09$	=	↓
SQT response to T	$\beta = 0.12$ or $0.17$	$\beta = 0.17$	$\beta = 0.17$	$\beta = 0.17$	=	↓
OVOC response to T	$\beta = 0.08$ to $0.13$	$\beta = 0.08$ to $0.13$	$\beta = 0.09$	$\beta \approx 0.12$	↑	≈
<b>Other activity factors</b>						
Leaf age	Guenther et al. 2006	Guenther et al. 2006	none	Guenther et al. 1999	↓	≈
Drought	=f(soil moisture)	=f(soil moisture)	none	=f(drought index)	↓	≈
CO <sub>2</sub>	none	=f(ambient CO <sub>2</sub> )	none	none	≈	≈

Comparisons are for late summer, midday conditions in Western U.S.; = indicates there is no difference; ≈ indicates GloBEIS is within 3%; ↑ (↓) GloBEIS is 3 to 7% higher (lower); ↑↑ (↓↓) GloBEIS is 8 to 15% higher (lower); ↑↑↑ (↓↓↓) GloBEIS is > 15 % higher (lower); XX represents varying amount which is depended on internal calculations.

### 3.2.2 Foliage Distributions

BEIS assumes a constant LAI for areas covered by vegetation while MEGAN uses satellite observations to assign the peak LAI and weekly to interannual variations. GloBEIS provides options for using either the BEIS or MEGAN approaches. The use of satellite derived foliage distributions will generally result in somewhat (~10%) lower emissions since it allows vegetation covered surfaces to have less than peak foliage. However, it is possible to have substantially (>30%) lower or higher emissions when using the satellite derived LAI in comparison to the constant peak LAI approach. The higher emissions result when the assumed peak LAI is lower than the value derived from satellite observations. Figure 3.2a illustrates that a 10% change in LAI at high LAI results in a small (~3% change in isoprene emissions while a 10% change in LAI at low LAI results in ~10% change in emissions. This figure also shows that GloBEIS3.5 and MEGAN2.04 have a similar response to changes in LAI.

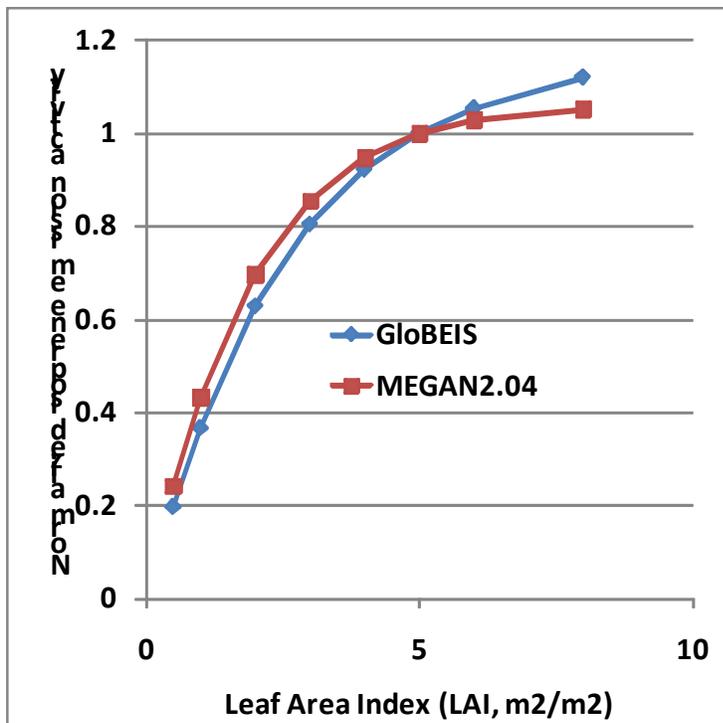
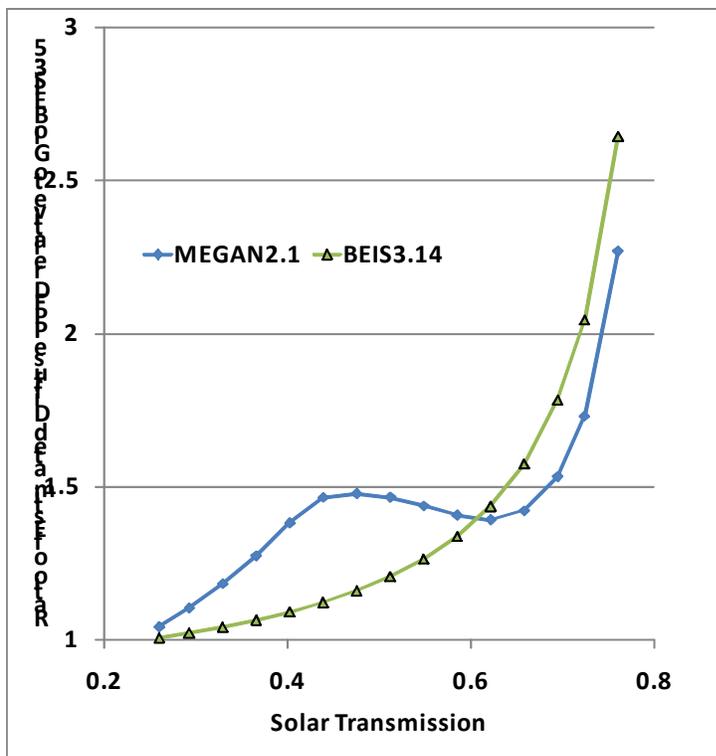


Figure 3.2a. GloBEIS3.5 and MEGAN2.04 response of normalized (to LAI=5) isoprene emission response to LAI.

### 3.2.2 Solar Radiation

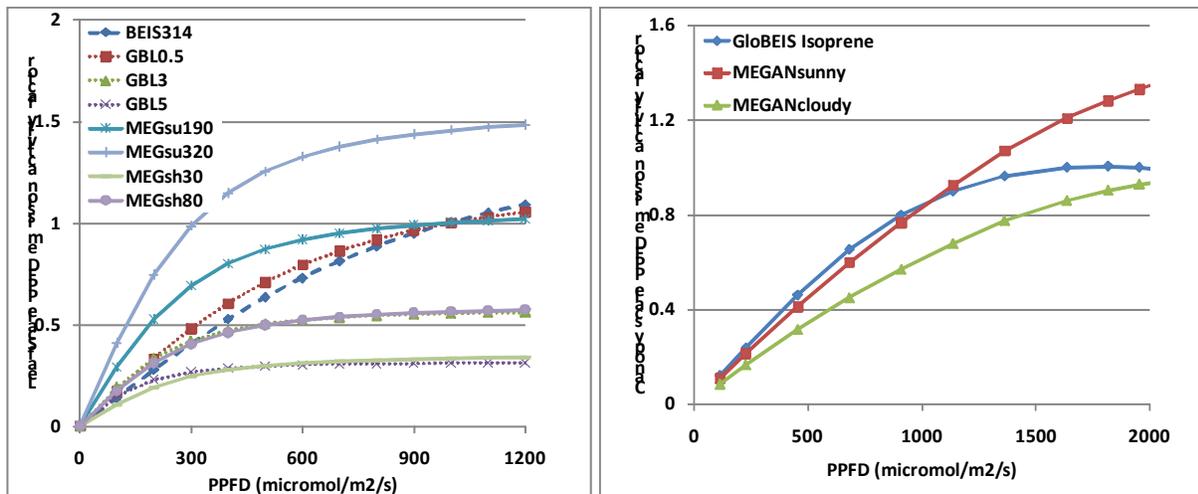
The emission of isoprene and many other BVOC are very sensitive to photosynthetic photon flux density (PPFD) levels. In addition, solar radiation can also influence leaf temperature which is an important driver of all BVOC emissions and is discussed below. The procedures used in GloBEIS3.5 and MEGAN2.04 are very similar and are based on the approach described in Guenther et al. 1999. MEGAN and GloBEIS use the above canopy solar radiation calculated by WRF, which accounts for altitude, clouds, aerosols and other factors while BEIS estimates above canopy solar radiation is using a simple equation that includes altitude and cloud cover fraction. A number of updates to the solar decomposition and canopy environment algorithms are being

incorporated into MEGAN2.1 that are based on a recent review of the literature. These studies show that there is a substantial range in the reported values of these variables. For example, isoprene emission algorithms require solar radiation inputs in units of  $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$ . Since atmospheric values are in units of  $\text{W m}^{-2}$ , models must apply a conversion factor. A value of  $4.6 \mu\text{mol photons per Joule}$  is used in BEIS and  $4.55$  is used for GloBEIS3.5 and MEGAN2.04. Reported values for different sites and conditions range from less than 4 to greater than  $5 \mu\text{mol photons per Joule}$  which could lead to differences in isoprene emissions of  $\pm 25\%$ . None of these models account for the observations that show that the value for diffuse PPFD is considerably less than what is observed for direct PPFD. MEGAN2.1 accounts for this by using different values,  $4.6 \mu\text{mol photons per Joule}$  for direct PPFD and  $4.3 \mu\text{mol photons per Joule}$  for diffuse PPFD. Of the nine solar radiation model components listed in Table 3.2a, the two that result in the largest differences between GloBEIS and the other models are 1) the decomposition of solar radiation into direct and diffuse components and 2) the algorithm that describes the response of isoprene to variations in PPFD. As shown in Figure 3.2b, the diffuse PPFD estimated by MEGAN2.1 and BEIS3.14 are 10 to 50% higher than GloBEIS3.5 estimates under cloudy skies and a factor of 2 or more higher under clear sky conditions. A higher fraction of diffuse light can increase isoprene emissions by increasing light on shade leaves. However, GloBEIS shade leaves are not very responsive to increases in light and so a 25 to 50% increase in diffuse light results in only a 5 to 10% increase in isoprene emissions under cloudy skies and a factor of 2 increase in diffuse light under clear skies results in  $\sim 5\%$  increase in emissions.



**Figure 3.2b. Ratio of diffuse PPFD estimated by BEIS3.14 and MEGAN2.1 relative to diffuse PPFD values estimated for GloBEIS3.5 (which is the same as MEGAN2.04) for a range of solar transmission conditions.**

BEIS, MEGAN and GloBEIS all use the same general equation to simulate leaf level response of isoprene emission to PPFD. The only difference is in the coefficients which are kept constant in BEIS and are varied with LAI depth for GloBEIS and with past light levels for MEGAN. The BEIS values were intended to represent the response of leaves at the top of the canopy but the resulting equation is a linear increase to PPFD > 1000 which is not typically observed. Figure 3.2c shows that the GloBEIS curves for LAI = 3 and 5 are similar to the MEGAN curves for shade leaves with past daily average PPFD of 80 and 30  $\mu\text{mol}/\text{m}^2/\text{s}$ . The GloBEIS curve for LAI = 1 is similar to the MEGAN curve for sun leaves with past daily average PPFD of 190 except that the MEGAN values are higher at low light. Since the MEGAN response changes with environmental conditions, MEGAN has higher emissions if the past days have been sunny and lower emissions if the past days have been cloudy. The BEIS light response curve generally results in lower emissions than GloBEIS and MEGAN because most leaves are at PPFD levels of 500  $\mu\text{mol}/\text{m}^2/\text{s}$  or lower.



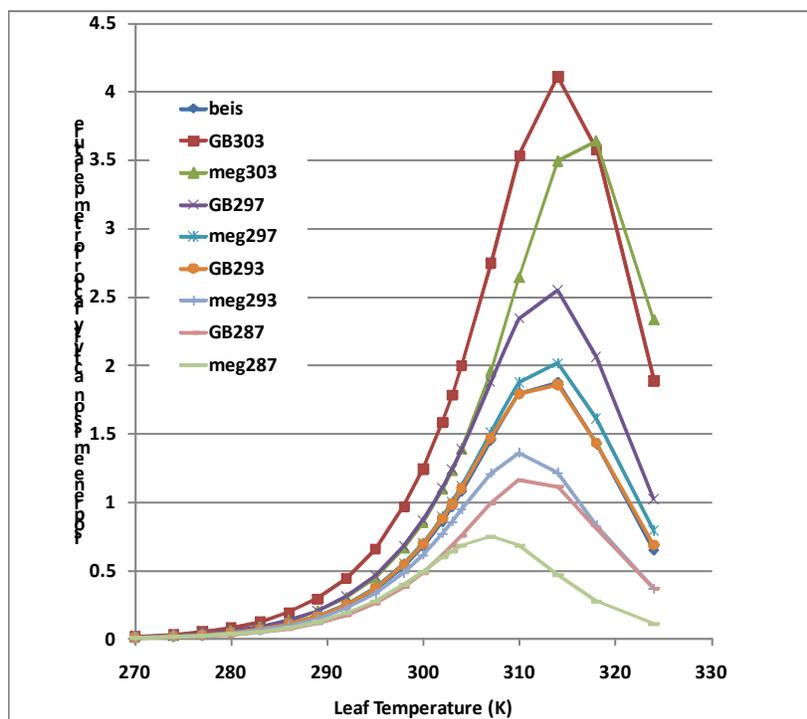
**Figure 3.2c Leaf (left panel) and canopy (right panel) scale isoprene emission response to PPFD. GloBEIS light response curves are shown for canopy LAI depths of 0.5 (GBL0.5), 3 (GBL3) and 5 (GB5). MEGAN responses are shown for sun leaves with past daily average PPFD of 190 (MEGsu190) and 320 (MEGsu320)  $\mu\text{mol}/\text{m}^2/\text{s}$  and shade leaves with past daily average PPFD of 80 (MEGsh80) and 30 (MEGsh30)  $\mu\text{mol}/\text{m}^2/\text{s}$ . MEGANsunny refers to a past daily average PPFD of 240  $\mu\text{mol}/\text{m}^2/\text{s}$  while MEGANcloudy refers to a past daily average PPFD of 120  $\mu\text{mol}/\text{m}^2/\text{s}$ .**

### 3.2.3 Temperature

All BVOC emissions are very sensitive to variations in leaf temperature. MEGAN calculates leaf temperature but BEIS assumes leaf temperature is equal to ambient temperature which typically results in small underestimates in emissions. GloBEIS gives users the option to do either approach. The same general equation is used to describe BVOC emission response to leaf temperature in all of these models but different coefficients are used which can result in large differences in emissions. Isoprene emission is driven by the current temperature in BEIS and the current, past 24 hour average and past 240 hour average temperature in MEGAN. This results in large (>30%) underestimates in BEIS after periods of hot days and large overestimates

after periods of cool days. GloBEIS users have the option of using just the current temperature or using the current, past 24, past 48 and past 360 hour average temperatures. Because of different assumptions used for developing these normalized algorithms, using the past temperature option in GloBEIS results in an isoprene emission temperature activity factor that can be >20% higher than the MEGAN value for the same conditions (figure 3.2d). This is because GloBEIS assumes that emission factors were measured on plants that have a past daily average temperature of 293K while MEGAN assumes that emission factors were typically measured on plants with a past daily average temperature of 297K. Biological activity will cease at very high leaf temperatures although it should be noted that plants can often maintain leaf temperatures that are lower than ambient temperatures through the cooling effects of transpiration. MEGAN use soil moisture to indicate the presence of drought conditions which can turn off isoprene emissions.

All three models use the same temperature dependence for sesquiterpene emissions while the monoterpene dependence is slightly higher in MEGAN2.1. The BEIS3.14 OVOC temperature dependence is considerably higher than the value used in GloBEIS3.5. MEGAN uses different values for various OVOC which range from lower than the GloBEIS value to higher than the BEIS value. The use of a higher temperature dependence will result in higher emissions at temperatures above the standard condition (e.g., 303K) and lower emissions at lower temperatures.



**Figure 3.2d Isoprene emission activity factors response to leaf temperature. Values shown include BEIS, GloBEIS with past temperatures of 303K (GB303) 297K (GB297), 293K (GB293) and 287 (GB287) and MEGAN with past temperatures of 303K (meg 303) 297K (meg 297), 293K (meg 293) and 287 (meg287).**

### **3.2.4 Stress and Other Activity Factors**

GloEBIS3.5, MEGAN2.04, and MEGAN2.1 all include algorithms to account for seasonal variations in emissions due to changes in leaf age. BEIS3.14 does not account for emission changes associated with leaf age which generally causes BEIS to overestimate isoprene emission in the early and late growing season. The leaf age algorithm used in GloBEIS3.15 was updated for MEGAN and extended from one compound (isoprene) to include other compounds such as monoterpenes, sesquiterpenes and methanol.

Both GloBEIS and MEGAN include algorithms that decrease isoprene emissions during drought conditions. BEIS does not consider this and so will greatly overestimate isoprene emissions during severe drought. GloBEIS uses drought index to drive emissions while MEGAN uses soil moisture. Two advantages of using soil moisture are 1) it can be observed in field and laboratory studies and so is used to develop quantitative relationships, 2) it is an output of some regional and global weather models and so may be more readily available.

Some plants produce and store terpenoid compounds within specialized tissues that act as a physical barrier to insects and pathogens and as a feeding deterrent if consumed (Tholl 2006). The biochemistry of these compounds, and the genetic and ecological controls, have been investigated due to the importance of this plant defense mechanism for economically significant plants such as pine trees. Some biogenic VOC (e.g, ethane, hexenal, methyl salicylate) are produced in unspecialized plant tissues and also play a role in defending plants against disease and herbivory. These compounds can act by repelling pests or attracting predators. Plants can repel pests with VOC either by acting as an antibiotic or by making the plant less appetizing. In other cases the VOC acts as a signal that can induce neighboring plants to increase their defenses (Karl et al. 2008). While we have a general understanding of how at least some biogenic VOC respond to stress, including abiotic (e.g., drought) and biotic (e.g. pine beetle) stresses, this process have not yet been incorporated into a biogenic VOC emission model (Niinemets 2010). The relationship between VOC emissions and stress is an active research area with genetic, physiological and field studies underway which could result in predictive algorithms for future models.

## **3.3 MEGANV2.1 CODE UPDATES FROM V2.04**

### **3.3.1 Previously implemented changes**

MEGANv2.1 advances over version 2.04 include the following:

- Implementation of an explicit canopy environment and leaf energy balance models that calculate solar radiation and leaf temperature of sun and shade leaf components for 5 canopy depths
- Modification of the 20 emission categories to emphasize and add some categories (e.g., compounds with bi-directional exchange, compounds that are sensitive to stress levels) and de-emphasize others (e.g., methane no longer has its own category but is included in the other category)
- Revised parameterization for the temperature dependence of light-dependent emissions

- Revised emission factors and emission algorithm coefficients
- Introduction of a deposition term to account for bi-directional exchange
- The code was made more modular, to simplify future changes, and more parameters were included as input files to facilitate future changes.

### **3.3.2 Additional changes implemented for this project: File I/O and Soil NO**

The improved landcover data developed for this project (8-day LAI data and a larger number of PFT categories) required some modifications to the code. These changes are relatively straightforward and will be thoroughly tested.

MEGANv2.04 uses the soil NO<sub>x</sub> emission scheme developed by Williams et al. (1992). This will be replaced in MEGANv2.1 with the soil NO<sub>x</sub> model of Yienger and Levy (1995) as implemented in SMOKE BEIS v3.14. This is expected to result in improved soil NO<sub>x</sub> emissions due to the ability to account for fertilizer application rates and soil-moisture variations. MEGAN will use the BEIS approach for NO<sub>x</sub> emission factors but will relate them to the landcover developed for this project and so we expect some differences between MEGAN and BEIS.

## **3.4 MEGAN LANDCOVER AND EMISSION FACTOR FILES FOR WESTERN U.S.**

### **3.4.1 Leaf Area Index (LAI)**

A set of 46 eight-day 1-km spatial resolution LAI<sub>v</sub> files for North America were generated to cover the entire year for 2008. Each file has been viewed in ARCGIS and ecoregion average and minimum and maximum values have been examined for quality assurance. The spatial and temporal variations generally follow the expected patterns as shown in section 2.1. For example, landscapes dominated by deciduous species are low in winter and have a peak foliar density in summer time. In addition, higher LAI is observed in regions dominated by forests. These files will be used to calculate LAI<sub>v</sub> for each location in the WRAP model domains to provide model-ready MEGAN LAI input files for year 2008.

An evaluation of the 8-day LAI, in comparison to monthly LAI, indicates that there may be relatively few cases where the 8-day LAI provides a substantially better representation of the LAI seasonal behavior. Given the possibility that the 8-day product is likely to be more “noisy” than the monthly average, there is the potential that the 8-day product could even degrade the accuracy of emission estimates. An accurate assessment requires comparisons to ground observations which is beyond the scope of this project but should be considered for future studies.

### **3.4.1 Plant Functional Type (PFT)**

A set of 9 PFT files, each at both 56-m and 1-km spatial resolution, for the contiguous U.S. were generated for 2008. MEGAN includes a total of 17 PFTs but other types (e.g., tropical and boreal PFTs) did not occur within the domain. Each file has been viewed in ARCGIS and ecoregion average and minimum and maximum values have been examined for quality assurance. The spatial and temporal variations generally follow the expected patterns. For example, Western American deserts are dominated by grass and shrub while Northwestern Forest mountains are dominated by needleleaf trees. These files will be used to calculate PFTs

for each location in the WRAP model domains to provide model-ready MEGAN PFT input files for year 2008.

The landcover databases described in section 2.1 and 2.2 provide tree cover fraction and an impervious fraction. The remainder is assumed to be comprised of shrub, grass/forb, crop and barren fractions. A scheme was developed to divide each landcover type (e.g., shrubland, grassland, deciduous forest, mixed forest, various croplands, etc.) into these 4 fractions. This assignment was made as follows:

Cropland: 90% crop, 0% grass/forb, 0% shrub, 10% barren

Grassland: 0% crop, 70% grass/forb, 10% shrub, 20% barren

Shrubland: 0% crop, 20% grass/forb, 40% shrub, 40% barren

Forests and woodlands: 0% crop, 40% grass/forb, 40% shrub, 20% barren

The total tree cover was divided into four PFTs: needleleaf evergreen trees, needleleaf deciduous trees, broadleaf evergreen trees, broadleaf deciduous trees. An example of the results are shown in Figure 3.4a. This assignment was made using ecoregion average statistics based on the USFS FIA tree species composition data described in section 2.2. Initially the assignments were made as follows:

**Deciduous forest:** The ecoregion average ratio of broadleaf deciduous to needleleaf deciduous trees in the USFS FIA database is used to divide the tree cover into broadleaf and needleleaf components.

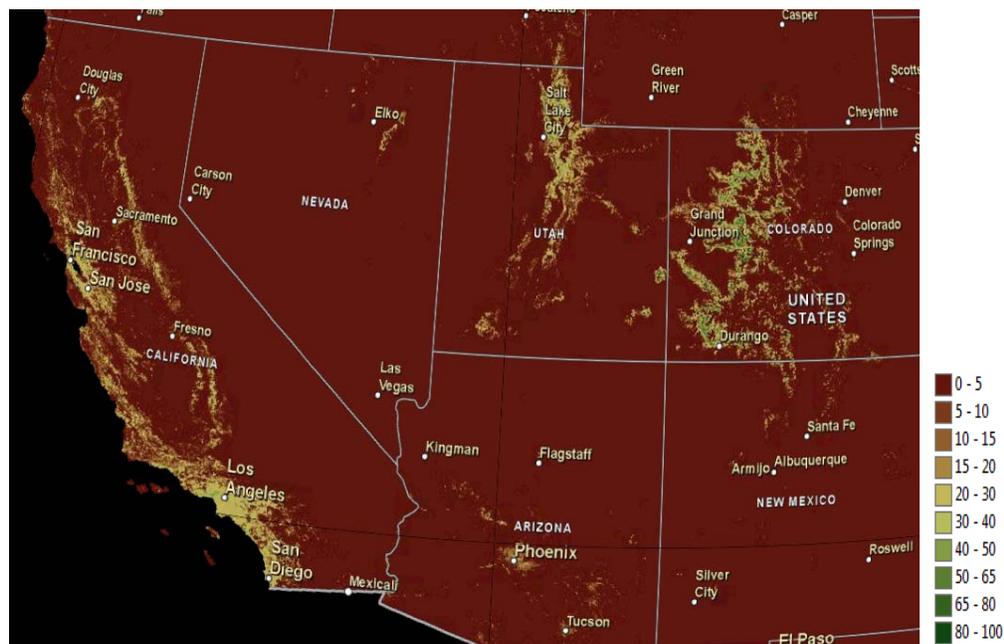
**Evergreen forest:** The ecoregion average ratio of broadleaf evergreen to needleleaf evergreen trees in the USFS FIA database is used to divide the tree cover into broadleaf and needleleaf components.

**Other landcover:** The ecoregion average ratio of broadleaf to needleleaf trees in the USFS FIA database is used to divide the tree cover into broadleaf deciduous and needleleaf evergreen components.

An assessment of this approach indicated that this tended to result in a substantial underestimate of needleleaf deciduous trees and a substantial overestimate of broadleaf evergreen trees. In addition, there was an underestimate of needleleaf trees in some ecoregions. As a result, the approach was modified so that the ecoregion average fractions of broadleaf evergreen, needleleaf evergreen, broadleaf deciduous, and needleleaf deciduous trees in the USFS FIA database was used to divide the tree cover into all landcover. This diminishes the ability to correctly distribute tree PFTs within an ecoregion but ensures that the ecoregion total is correct. Future studies should be focused on improving tree species distributions within an ecosystem if it is determined that this has a significant impact on air quality model results.

While the NLCD 30-m tree cover data is a substantial improvement over the MODIS based 1-km tree cover data used for BEISv3.14 and MEGANv2.04, Figure 3.4a shows that even the NLCD has

difficulty providing tree cover in heterogeneous regions such as urban areas where NLCD underestimates tree cover. The UFWU data described in section 2.2 was used to adjust the NLCD tree cover. The UFWU divided the contiguous U.S. into 66 regions and assessed urban tree cover in each region and provided an adjustment factor for each region. The UFWU data was used to create a geogridded database of adjustment factors that were used to correct the NLCD tree cover in all urban areas in the contiguous U.S.



**Figure 3.4a Broadleaf deciduous tree distribution calculated for the western U.S.**

### 3.4.1 Emission Factors (EF)

A set of 10 EF files, each at both 56-m and 1-km spatial resolution, for the contiguous U.S. were generated for 2008. This includes files for NO and 9 VOC (isoprene, methyl butenol, alpha-pinene and 6 other monoterpenes). Each file was viewed in ARCGIS and ecoregion average and minimum and maximum values were examined for quality assurance. The spatial and temporal variations generally follow the expected patterns. For example, isoprene was highest in ecoregions dominated by oaks and aspen, poplar trees and low in grassland and cropland dominated regions. These files will be used to calculate EFs for each location in the WRAP model domains to provide model-ready MEGAN EF input files for year 2008.

The species composition data described in section 2.2 and emission factor data described in section 2.3 were integrated to calculate landscape weighted average emission factors. MEGAN calculates emissions for 20 categories of biogenic compounds. Some represent individual compounds while others are groups of compounds with a speciation provided and a scheme to convert each compound into common atmospheric chemistry reaction schemes. Geogridded EF maps were calculated based on species composition and species specific emission factors for 8 biogenic compounds. PFT-average emission factors are combined with the geogridded PFTs for an additional 12 categories. The geogridded EF maps are based on the species composition

distributions derived for the ~6000 vegetation types (VT) and species (or genus) specific emission factors described in section 2.2. A weighted average is estimated for each location based on the VT fraction distribution for a specific year (e.g., year 2008) and the VT emission factors. As a result, the geogridded emission factor maps vary on an annual basis.

## 4.0 References

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## 5.0 Glossary

AWiFS- Advanced Wide Field Sensor  
BESS- Biogenic Emissions Software System  
BEIS – Biogenic Emission Inventory System  
BVOC- Biogenic Volatile Organic Compounds  
CAMx – Comprehensive Air Quality Model with Extensions  
CB05 – 2005 version of the Carbon Bond chemical mechanism  
CDL- Cropland Data Layer  
CMAQ – Community Multi-scale Air Quality model  
CO- carbon monoxide  
EC- Eddy Covariance  
EF- Emission Factor  
EPA – U.S. Environmental Protection Agency  
FIA- Forest Inventory Analysis  
GAP- Gap Analysis Program  
GLOBEIS- GLObal Biogenic Emissions inventory System  
LAI- Leaf Area Index  
LAIv- Leaf Area Index of vegetation covered surface  
LANDSAT-TM- land satellite Thematic Mapper  
MBO – methyl butenol  
MEGAN- Model of Emissions of Gases and Aerosol from Nature  
MRLC - Multi-Resolution Land Characteristics  
MODIS- MODerate Resolution Imaging Spectrometer  
NASA- National Aeronautics and Space Administration  
NASS- National Agricultural Statistics Service  
NCAR - National Center for Atmospheric Research  
NLCD- National Land Cover Dataset  
NO – nitrogen oxide  
NO<sub>2</sub> – nitrogen dioxide  
NO<sub>x</sub> – nitrogen oxides (NO + NO<sub>2</sub>)  
NRCS- Natural Resources Conservation Service  
OH – hydroxyl radical  
PFT- Plant Functional type  
PFTf- Plant Functional type fraction  
ppb – parts per billion  
PPFD- Photosynthetic Photon Flux Density  
ppm – parts per million  
ppt – parts per trillion  
SAPRC99 – 1999 version of the Statewide Air Pollution Research Center chemical mechanism  
SAPRC07 – 2007 version of the Statewide Air Pollution Research Center chemical mechanism  
SMOKE – Sparse Matrix Operational Kernel Emissions  
SQT - Sesquiterpenes

TOF-PTRMS – Time of Flight Proton Transfer Reaction Mass Spectrometer

UFWU – urban forest work unit

USEPA- United States Environmental Protection Agency

USDA- United States Department of Agriculture

USFS- United States Forest Service

VOC – volatile organic compounds

VT – vegetation type

WRAP- Western Regional Air Partnership

WRF- Weather Research and Forecasting