DEVELOPMENT OF METHODOLOGY AND DATABASES FOR ESTIMATING LEAF MASSES IN CALIFORNIA AIRSHEDS

Contract No. 97-719

STATE OF CALIFORNIA AIR RESOURCES BOARD

FINAL REPORT

Principal Investigator

John F. Karlik

Collaborating Researcher

Alistair H. McKay

University of California Cooperative Extension
1031 S. Mt. Vernon Ave.
Bakersfield, CA 93307

July 15, 1999

ABSTRACT

To assemble reliable biogenic hydrocarbon (BHC) emissions inventories for California airsheds, spatially resolved, species-specific descriptions of leafmass distributions are required. Critical data deficiencies exist related to a quantitative description of leafmass in the SCOS97-NARSTO modeling domain. To address these deficiencies, and to assist in evaluating methodological approaches, literature pertaining to botany, ecology, and biogenic emissions estimations has been searched. This report reviews methods for obtaining quantitative descriptions of leafmass and compiles leafmass data obtained in previous studies which may be applicable to plant communities in the SCOS97 domain.

Methods for estimating leafmasses may be divided into three categories (Campbell and Norman 1989): (1) direct measurement methods, (2) allometric measurement methods, and (3) indirect measurement methods. Direct measurement methods include various forms of quadrat sampling, either in two or three dimensions, and also include whole-tree harvest and leaf removal (Winer et al. 1998). Direct measurement methods imply field sampling and weighing of leaves. These methods are time- and labor-intensive and therefore feasible for relatively small sample sizes, but can yield data of high precision and accuracy.

Allometric measurement methods, in general, refer to methods which define relationships between leafmass and more-easily measured biometric parameters, e.g. stem diameter. Field sampling is necessary to develop allometric equations and empirical coefficients, which are usually specific to individual plant species. After relationships of leafmass to other plant parameters have been established, allometric methods may be used to rapidly develop leafmass information at field sites.

Indirect measurement methods include measurement of light interception or spectral reflectance at various wavelengths. These methods have high potential for development of leafmass information over wide geographic areas because spectral data can be acquired through remote sensing technologies, including from instruments on satellite platforms. The computational linkage between spectral measurements and leafmass may be derived from analytical approaches or from empirical approaches. However, relationships between various kinds of spectral data or vegetation indices derived from spectral data, and leafmass are complex. Recent advances in algorithm development and remote sensing technologies suggest an increasing role for indirect leafmass estimation methods for developing BHC emissions inventories in California.

Quantitative values for leafmass and leafmass density (leafmass per unit ground area beneath plant canopies) have been compiled from studies conducted in California, from studies of Mediterranean plant communities in other regions of the world which may be similar to those found in the SCOS97 domain, and, for comparison, for other plant communities, especially those studied in conjunction with other BHC emission inventories. These values should be considered on a case-by-case basis for their applicability to plant communities in the SCOS97 domain or other plant communities in California.

ACKNOWLEDGMENTS

The contributions of several members of the California Air Resources Board staff, particularly Bruce Jackson, were greatly appreciated, and also the discussions with members of the Biogenic Hydrocarbon Working Group organized by Ash Lashgari. We especially appreciate comments and editing by Arthur Winer of the University of California, Los Angeles.

We gratefully acknowledge support for this research by the California Air Resources Board. This report was submitted in fulfillment of Contract No. 97-719.

DISCLAIMER

The statement and conclusions in this report are those of the contractors and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

Page

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

ARB	California Air Resources Board
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BHC	biogenic hydrocarbon
CASI	Compact Airborne Spectrographic Imager
DBH	diameter at breast height
EFID	Eastwide Forest Inventory Database
*f*PAR	fraction of PAR intercepted by a plant crown
GAP	Gap Analysis Project
GC	gas chromatography
LAI	leaf area index (m^2 m^{-2})
LMD	leafmass density (g m^{-2})
NDVI	normalized difference vegetation index
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary productivity
OTTER	Oregon Transect Ecosystem Research Project
PAR	photosynthetically active radiation
SCOS97-NARSTO	1997 Southern California Oxidant Study – North American Research Strategy for Tropospheric Ozone
SLA	specific leaf area (m^2 g^{-1})
SLW	specific leaf weight (g m^{-2})

SR	simple ratio
TMS	Thematic Mapper Simulator
USFS	United States Forest Service
VOC	volatile organic compound

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

Gridded biogenic hydrocarbon (BHC) emissions inventories require a spatially-allocated, species-specific description of leafmass distribution to accompany species-specific emission rates; algorithms to adjust emission rates to ambient conditions, and canopy models to account for the environment within plant canopies. Critical data deficiencies exist related to a quantitative description of leafmass in the SCOS97 domain. These data could possibly be developed from past studies of Mediterranean plant communities or other published work, and such data may allow translation of aereal coverage of plant species into quantitative descriptions of leafmass density (LMD) for respective plant communities.

Estimates of LMD, described in units of dry leafmass per unit area of land surface beneath the canopy (g m^{-2}), may be obtained through direct, indirect or allometric measurement methods (Campbell and Norman 1989). Indirect measurement methods or allometric methods may be coupled to data derived from remote sensing. The development of species-specific quantitative leaf-area-to-leafmass conversions may allow application of data not previously useful (Winer et al. 1998). Of particular interest is use of satellite derived vegetation indices which have shown high correlation to estimates of leaf area index (LAI). LAI is the ratio of one-sided leaf surface area to unit area of crown or canopy projection, usually expressed as m^2 m^{-2}. LAI describes the photosynthetic apparatus of a plant canopy or plant community and has been identified as one of the most useful descriptors of plant foliage for characterizing energy and mass exchange in global scale research (Spanner et al. 1990b). LAI has value when compiling a

BHC emissions inventory because it is proportional to total green leaf area (Landsberg and Gower 1997), and may be used to calculate LMD.

As an alternative approach, leafmass could be estimated through a volumetric method, in which leafmass for respective plant canopies is estimated by multiplying canopy volume by a leafmass constant to give a value for leafmass (Winer et al. 1983, Horie et al. 1991, Karlik and Winer 1998). Using this method, remote sensing derived estimates of aereal coverage of plant species could be converted into foliar volume by multiplying by canopy height, and then converted to leafmass through multiplying by the appropriate leafmass constant. This value may then be normalized per unit ground surface area of canopy projection.

The potential for using remote sensing to gauge plant biophysical properties in the SCOS97 NARSTO modeling domain has been addressed in previous reports (Winer et al. 1995). Estimates of leafmass or leaf area derived through remote sensing approaches are based principally on comparing measurements of red reflectance radiation (630-690 nm), which exhibits a nonlinear inverse relationship to green biomass, with measured near-infrared (760-900 nm) reflectance radiation, which exhibits a non-linear direct relationship as seen in Figure 3.1 (Tucker 1979). These relationships have lead to the development of a vegetation index (VI), such as the simple ratio (SR) and the normalized difference vegetation index (NDVI), that can be used to estimate the quantity of green biomass of vegetation from empirical relationships derived from field data.

1.2 PROJECT OBJECTIVES

Primary objectives of this report were to:

- To outline methods which may be used to estimate plant leafmass and leaf area.
- To obtain quantitative leafmass and leaf area data for Californian plant communities from the literature.

1.3 THE USE OF SATELLITE DERIVED VEGETATION INDICES FOR INDIRECT BIOMETRIC ESTIMATIONS

1.3.1 The Use of NDVI for Leafmass Estimation

Of the vegetation indices currently used in remote sensing, the normalized difference vegetation index (NDVI) may be most applicable to leafmass estimations in the SCOS97 modeling domain, although relatively few studies have compared NDVI to canopy structure and leafmass estimates in natural arid landscapes. Such landscapes contain vegetation of differing growth habits and phenologies and may also be exposed to seasonal or chronic stresses (Gamon et al. 1995). Until recently, the relationships between NDVI and canopy structure, leafmass, photosynthetic fluxes or net primary productivity (NPP) appeared to be most consistent in uniform vegetation; however, mounting evidence indicates that vegetation indices calculated from remote sensing data may be more useful than previously thought in communities where plants are separated and foliar characteristics are heterogeneous, such as in desert communities with low (< 1) overall LAI values (Gamon et al. 1995). For example, Gamon et al. (1995) showed the description of leafmass by NDVI to be most pronounced at low canopy densities, reaching an apparent maximum at LAI ≈ 2. This was supported in a recent study in which a simple radiative transfer model showed NDVI to be sensitive to changes in the fractional vegetation cover until canopy closure was reached, beyond which a further increase in LAI resulted in an additional small, asymptotic increase in NDVI (Ripley and Carlson 1997).

1.3.2 The Use of NDVI for Leaf Area Estimation

The NDVI is intrinsically suited to estimating the leaf area or LAI of plants because absorption of light in the photosynthetically active radiation (PAR) range is a primary determinant for changes in the ratio of IR/red reflectance. The NDVI is extremely sensitive to changes in canopy cover when the cover is low, but may not clearly distinguish between values relating to crown structure (such as leafmass or LAI) when the index ranges from 20 – 100 % of full scale. Analysis of the NDVI calculated from LANDSAT-TM data showed that the LAI of coniferous vegetation across a latitudinal gradient in central Oregon could be accurately estimated up to a maximum LAI of 7-8 (Peterson et al. 1987). Other estimates have placed the red radiance asymptote at a LAI of 4-5 in coniferous forests (Spanner et al. 1990a). These values are somewhat greater than the saturation values expressed in woodland trees (LAI 2-3), wheat (LAI 2-3) and other broadleaf type. This may be due to differences in the spectral reflectance properties of needle-type leaves compared to broad leaves. The size, shape and orientation of needle-leafed canopies may enhance diffusion of light within the canopy with attendant small-differences in the intensity of scattered radiation in the red (Peterson et al. 1987).

One criticism of the NDVI is that its sensitivity to changes in LAI decreases as LAI increases beyond a threshold value. These values approximately correspond to canopy closure thought to be ~2-3 for agricultural monocultures and ~ 7-8 for coniferous canopies (Peterson et al. 1987). The upper threshold is indicated by a flattening of the asymptotic shape characteristic of LAI vs. NDVI curves. Addition of more canopy layers makes little difference in the relative interception or reflectance of red and near-infrared radiation (Peterson et al. 1987). This feature of the NDVI may make it better suited to natural California biomes in which LAI values remain relatively low. To correct for saturation of the NDVI at relatively low LAI, it may be possible to scale the index to correspond to the values for bare soil (LAI = 0) and a surface with vegetative cover of 100 percent (Carlson and Ripley 1997). In addition, advances in remote sensing technologies are expected to improve pixel resolution, and thus reduce background effects which is especially important for modeling arid-region plant communities (Ustin et al. 1986). Also, recently developed radiative-transfer models and correction algorithms capture quite well the primary effects of differing illumination and viewing conditions on the reflectance of discontinuous vegetation covers may should improve canopy estimates in California plant communities (Wu and Strahler 1994). Other analytical models exist which may be used to derive LAI from a range of vegetation indices (Nikolov 1997a). Earlier work had indicated that application of NDVI was confounded in these environment types due to unpredictable soil reflectance properties (Asrar et al. 1992). However, a distinct paucity of data currently exists for relating the NDVI and other vegetation indices derived from remote sensing to canopy variables such as LAI and LMD in discontinuous arid landscapes like those of southern and central California. Quantitative data derived from ground-based surveys are needed to assess accuracy of LAI values derived from NDVI for California vegetation.

1.4 THE USE OF ALLOMETRIC EQUATIONS FOR BIOMETRIC ESTIMATIONS

Leafmass estimates of some BHC emissions inventories (Lamb et al. 1993, Geron et al. 1994, Lenz et al. 1997) have utilized allometric equations to estimate leafmass (as a dependent variable) based on stem diameter (as an independent variable) and these equations were used in the development of models for estimating biogenic isoprene emissions from forests in the eastern United States (Geron et al. 1994, Geron et al. 1997). Often, leafmass estimates from allometric equations are site and species-specific, largely influenced by an environmental component. Where site/species specific leaf area or leafmass data have not been obtained, it may be possible to estimate the leafmass of a site from allometric equations that exist for the same or a related species in a different environment. In some cases it may be possible to adjust allometric equations by an environmental component such as water balance, mean annual temperature, minimum winter temperature, etc. For example, Gholz (1982) studied a range of climatic predictors for correcting the equation $Y = a + b X$, where Y = LAI, Y = biomass or Y = NPP of trees in the Oregon transect. The best predictor over the range of environments tested was winter low temperature. Water balance, the difference of potential evaporation to rainfall (considered to be the most important variable of growth), was expected to provide an accurate correction factor for Y but did not work well over the range of environments. This was due mainly to an outlier entered by one environment, the sub-alpine region, an effect that distorted the fit. With this point removed, water balance provided the best correction factor for LAI ($r^2 = 0.99$), biomass ($r^2 = 0.95$) and NPP ($r^2 = 0.91$). At present, however, the environmental influence of many allometric relationships appears too complex to allow separation of individual environmental factors into significant components that may be used as adjustment algorithms for allometric equations.

Of the greater than 6000 plant species that grow in California, few have been described in terms of leafmass or LAI by allometric equations. The few species that have been described with allometric equations are promising candidates for field validation.

1.5 DIRECT MEASUREMENT OF BIOMETRIC DATA

Leafmass is most accurately determined by harvesting all the leaves of a tree crown and measuring total dry weight. For example, in the recent ARB-funded study of Winer and co-workers (1998), 21 whole trees were harvested from urban landscapes for leafmass measurement. LMD for the trees from urban landscapes in Bakersfield, CA, ranged from 150 to 3200 with a mean of 940 g m^{-2}, higher than LMD values reported for forests and indicating the potential of urban trees to contain relatively more leafmass than trees in a continuous canopy environment

The harvest method is also the most basic procedure for measuring the crown leaf area of a tree or shrub. The leaves of an entire plant can be removed and passed through a leaf area meter, such as the LiCor LI3100 leaf area meter. Leaf areas that were calculated by using leafmass multiplied by SLW for two urban species (*Eucalyptus grandis* and *Rhus ovata*) were within 6 % of that measured with a LiCor leaf area meter (Winer et al. 1998).

Collecting and weighing the annual fall of leaves as litter may be used to estimate the productivity of a plant community. The technique assumes knowledge of the ratio of litter fall to total biomass production (Lieth and Whittaker 1975). Litter fall estimates were used by Geron et al. (1997) to validate indirect estimates of species composition and foliar mass in southeastern bottomland deciduous forests. Twenty-six 45 cm diameter litter traps were placed 7.5 m from each plot center normal to the transect azimuth. Leaf litter was collected every two weeks, dried, separated and weighed (Geron et al. 1997). Results from leaf litter analysis provide a precise determination of specific leaf area (m^2 g^{-1}) and by multiplying this by the specific leaf weight, LAI can be calculated. Using this method, Geron et al. (1997) estimated a total LAI for a Southeastern bottomland deciduous forest of 5.2 m^2 m^{-2}, which was in good agreement with LAI measurements of 4.4 - 5.9 made by measuring light interception with an LAI 2000 (LiCor, Inc.) canopy analyzer instrument.

A BHC emissions inventory of a test site at St. Quercio, Castelporziano, Italy was compiled by Lenz et al. (1997). Species-specific BHC emissions were measured and multiplied by leafmasses that had been calculated using a previously compiled database of biometric information. LAI (gathered indirectly with an LAI-2000 plant canopy analyzer), specific leaf weight and percent coverage were used to calculate leafmass and estimate BHC emissions of each species normalized to a standard set of conditions (30 °C, 1000 umol m^{-2} s^{-1} PAR). For the current report, LMD values were calculated for the site by multiplying LAI by specific leaf weight, and ranged from 200 g m^{-2} to 1100 g m^{-2}. For the two species in Table 4-2 (below) with complete data, *Quercus petraea* and *Q. pubescens,* LMD values were calculated as 160 and 92 g m^{-2}, respectively. The results of the Castelporziano site provide a valuable resource for future comparisons with California emissions inventories.

LMD data from multiple sources are summarized in this report. Ranges for LMD for specific plant communities and for specific species may vary by a factor of 2 or more, LMD data should be considered on a case-by-case basis.

2.0 INTRODUCTION AND PROJECT GOALS

2.1 INTRODUCTION AND BACKGROUND

Gridded biogenic hydrocarbon (BHC) emissions inventories require a spatially-allocated, species-specific description of leafmass distribution to accompany species-specific emission rates, algorithms to adjust emission rates to ambient conditions, and canopy models to account for the environment within plant canopies (Figures 2-1, 2-2). Critical data deficiencies exist related to a quantitative description of leafmass, particularly in the SCOS97 modeling domain. These data could possibly be developed from past studies of Mediterranean plant communities or other published work, and such data may allow translation of aereal coverage of plant species into quantitative descriptions of leafmass density for respective plant communities.

Estimates of leafmass density may be obtained through direct, indirect or allometric measurement methods (Campbell and Norman 1989). Indirect estimates of LMD or estimates obtained using allometric methods may be coupled to data derived from remote sensing which may then be scaled-up to represent the entire SCOS97 NARSTO domain. This process would be aided by the development of species-specific quantitative leaf-area-to-leafmass conversions (Winer et al. 1998) and may allow application of data not previously useful. Of particular interest is use of satellite derived vegetation indices which have shown high correlation to estimates of leaf area index. Or, as in past studies, aereal coverage of plant species could be converted into foliar volume by multiplying by canopy height, and then converted to leafmass through multiplying by the appropriate leafmass constant (Winer et al. 1983, Horie et al. 1991, Karlik and Winer 1998).

Although direct measurement of LMD through harvest techniques provides the most empirically accurate data, the methods are laborious and may not be feasible on a regional scale. The flow charts, of Geron et al. (1994) and Benjamin et al. (1998), reproduced as Figures 1 and 2, respectively, show examples of alternative approaches to leafmass estimation for development of BHC emissions inventories. Specifically, as seen in Figure 2, leafmass could be estimated through a volumetric approach, in which leafmass for respective plant canopies is estimated by multiplying canopy volume by a leafmass constant to give a value for leafmass (Winer et al. 1983, Horie et al. 1991, Karlik and Winer 1998). This value may then be normalized per unit ground surface area of canopy projection. Or, as seen in Figure 1, leafmass may be estimated by allometric equations using trunk diameter and crown width coupled to an appropriated database (Geron et al. 1994). In either case, leafmass for a particular plant species or plant community will be described in units of dry leafmass per unit area of land surface beneath the canopy (g m^{-2}).

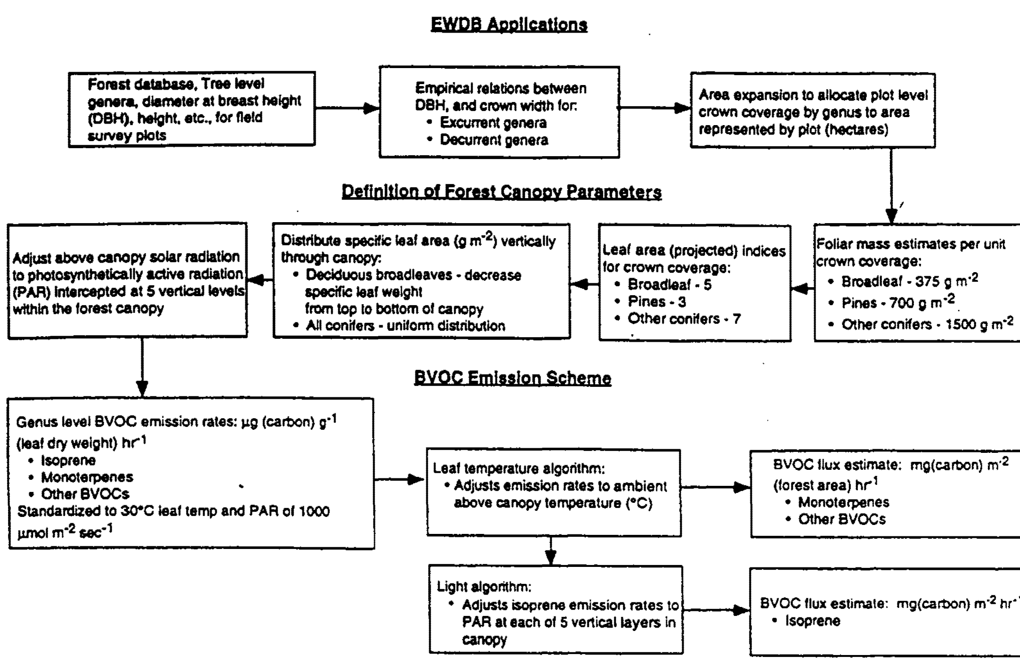


Figure 2-1. Flow diagram for proposed model of biogenic volatile organic compound emissions from forests. Reproduced from Geron et al. (1994).

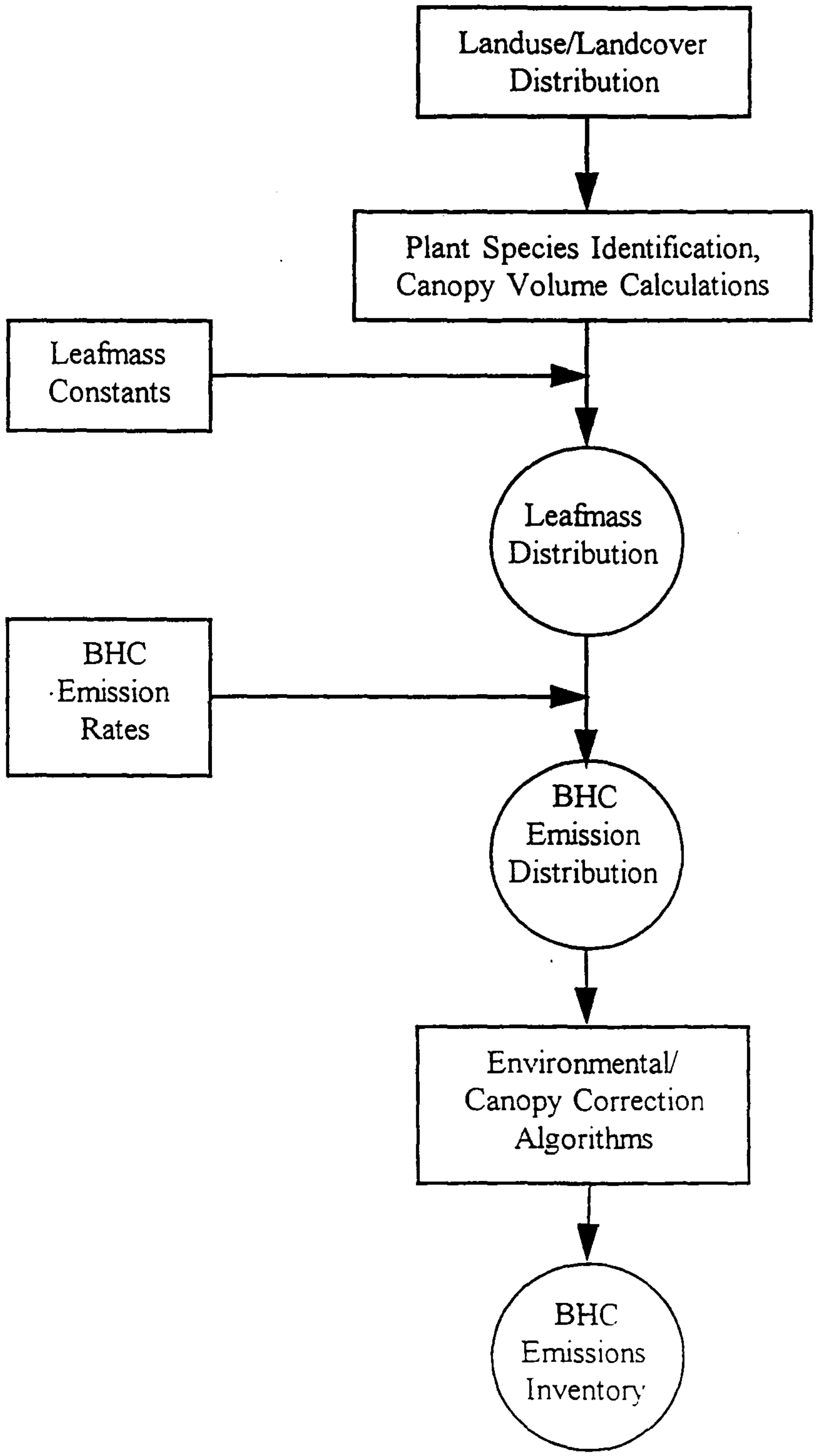


Figure 2-2. Generalized flowchart showing databases and steps involved in development of a BHC emissions inventory. Taken from Benjamin et al. (1998).

2.2 DEFINING TERMS FOR LEAFMASS AND LEAF AREA

2.2.1 Leafmass

Leafmass is usually expressed in units of grams dry leafmass. Leafmass is an important component of a BHC emissions inventory because BHC emissions in a given domain may be estimated by multiplying leafmass by an emission factor, expressed as micrograms of BHC per gram foliar dry mass per hour (ug g^{-1} h^{-1}) (Geron et al. 1994, Benjamin et al. 1997, Benjamin et al. 1998).

2.2.2 Leafmass Density and Leafmass Constant

For biogenic emissions inventories, leafmass is usually described as leafmass per unit area of land beneath foliar canopies (g m^{-2}). Leaf biomass density (denoted herein as LMD) is a term used in the literature (Lamb et al. 1987) which has units of (g m^{-2}) and refers to leafmass per unit planar area of canopy or crown projection. Leafmass constant (g m^{-3}) is a term that has been used in previous research (Winer et al. 1983, Miller and Winer 1984, Horie et al. 1991, Karlik and Winer 1998) to describe leafmass per unit volume within a crown of foliage. In this report, we use the term crown to refer to the above-ground foliage of discrete individual plants while canopy refers to the contiguous foliage of adjacent plants. Canopy closure refers to a temporal or physiological situation in which leaves and branches from adjacent individuals touch, and, as seen from above, foliage approximates a continuous plane.

2.2.3 Leaf Area Index

A convenient way to describe the leaf area of a plant crown is through the leaf area index (LAI). LAI is the dimensionless ratio of leaf surface area to unit area of crown or canopy projection, usually thought of as $m^2\ m^{-2}$. Leaf surface area may include one side or both sides of leaves. In this report LAI is based upon one-sided leaf surface area. LAI describes the photosynthetic apparatus of a plant canopy or plant community and has been identified as one of the most useful descriptors of plant foliage for characterizing energy and mass exchange in global scale research (Spanner et al. 1990b). Leaf area dominates the total aboveground surface area of trees at all canopy levels, but the biomass of stem tissues, which decreases steeply with height in the forest, far exceeds that of leaves (Parker 1995), a point clearly illustrated by Figure 2-3. LAI has value when compiling a BHC emissions inventory because it is proportional to total green leaf area (Landsberg and Gower 1997), and may be used to calculate LMD.

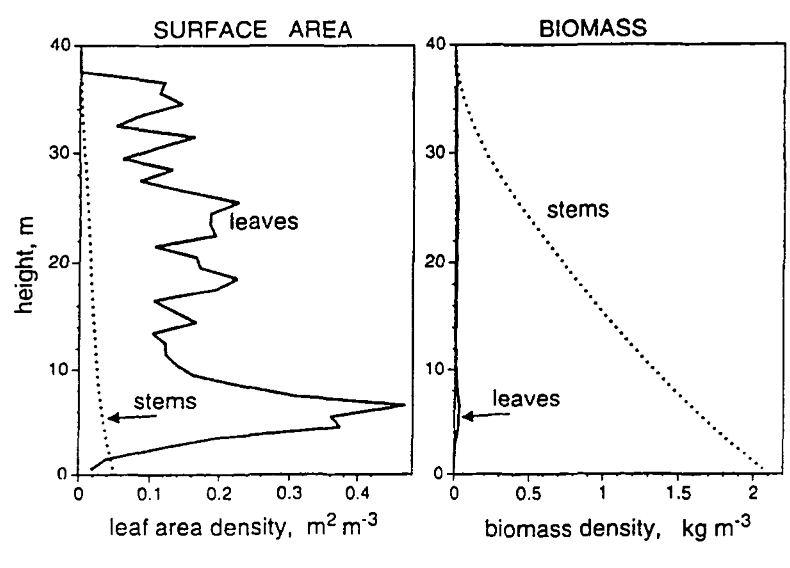


Figure 2-3. Mean vertical structure of canopy surfaces (left) and biomass (right) in a mixed species deciduous forest on the mid-Atlantic coastal plain. (Taken from Parker 1995).

2.2.4 Specific Leaf Weight

Specific leaf weight (SLW) is the ratio of mean mass of leaves of a plant species to one-sided leaf area. Leafmass may be calculated by multiplying specific leaf weight (SLW) by leaf area (LA) as seen in equation 1:

$$\text{SLW (g m}^{-2}\text{) x LA (m}^{2}\text{)} = \text{Leafmass (g)} \tag{1}$$

Multiplying LAI by SLW yields a value for LMD as seen in equation 2:

$$\text{SLW (g m}^{-2}\text{) x LAI (m}^{2}\text{ m}^{-2}\text{)} = \text{LMD (g m}^{-2}\text{)} \tag{2}$$

Specific leaf area (SLA) (m^2 g^{-1}) is the inverse of SLW. A compilation of specific leaf weight and specific leaf area data by [Nowak (1998)] is underway, which will make use of experimental results from several sources including those from a 1996-97 ARB-funded study of urban trees in the Bakersfield area in south central California (Winer et al. 1998).

2.3 STATEMENT OF THE PROBLEM

Leafmass density values for Mediterranean plant communities obtained directly from the field, from pre-existing literature sources, or derived from satellite based vegetation indices may be used to obtain the spatially-allocated, species-specific description of leafmass distribution needed to aid ARB staff in compiling a BHC emissions inventory for the SCOS97 domain. Often the method used to gather LMD values affects the precision accuracy of the estimate, which has a compounding effect on a scaled-up BHC emissions estimate. A small quantity of literature describes the leafmass for some of California's vegetation by using direct sampling methods, indirect estimation methods and allometric equations, but the available data are by no means complete. The data set may be expanded using LMD values from other Mediterranean-type biomes; however, this is unlikely to result in a full description of leafmass for all biomes in the SCOS97 domain. The most promising approach to regional estimates for leafmass is the use of satellite-derived descriptions of vegetation cover. Relatively few studies have quantified LMD using satellite-derived imagery, particularly in environments where vegetation is discrete and discontinuous such as south central California. Digital images obtained from aereal platforms have the potential for far greater coverage than surface based vegetation surveys and improving image processing technology and environmental correction algorithms attempt to make this methodology more reliable. Current capabilities in using satellite imagery, however, fall short of a quantified description of leafmass, particularly in discontinuous, arid landscapes, instead offering a clearer indication of species composition or photosynthetically active leaf area. Integrating these types of data with certain ground based biogenic parameters allows us to use image technology currently available to compile an estimate of regional LMD. Often an estimate of LMD is the first step in a full-scale regional BHC emissions inventory and thus it is important to understand the process involved in generating LMD estimates. The following sections thus seek to clarify the methods used to gather LMD values found in the literature and provide a compilation of those values with particular emphasis on California-like environments. A clear understanding of the methods used to arrive at a particular LMD value for a particular species in a particular environment can be used to assess the validity of using one leafmass value over another when modeling a given emissions scenario.

2.4 OBJECTIVES

The overall objective of the present project is to further the ARB modeling efforts by searching the scientific literature for applicable methodological information and, where available, quantitative leafmass data applicable to plant communities in California airsheds. The specific objectives are the following:

- Describe methods that have been used to make leafmass estimates, especially as pertaining to biogenic emission inventories.

- Evaluate the data needs of the respective leafmass estimation methods and provide qualitative and quantitative estimates of uncertainty, where possible.

- Provide methods to translate leafmass data between different quantitative expressions, such as LAI and LMD, thereby enabling ARB staff to use the quantitative expressions and unit systems of their choice.

- Compile leafmass density data, especially those data developed in California, data from similar plant communities outside of California, including data from plant communities in Mediterranean climate regions of the world.

- Provide ranges for leafmass densities for various plant communities from the literature.

3.0 LEAFMASS AND LEAF AREA ESTIMATION METHODS

Leafmass estimation methods may be placed into three categories: 1) indirect measurement methods, 2) allometric equations, and 3) direct measurement methods (Campbell and Norman 1989). Leaf area and LAI can also be estimated using indirect methods or measured directly and allometric equations have been used to describe the leaf area of urban trees (Nowak 1996).

3.1 INDIRECT LEAFMASS MEASUREMENT METHODS

These methods attempt to estimate leafmasses from a previously established relationship between a measurable variable and leafmass. Variables can include transmission or reflectance of specific wavelengths of light.

3.1.1 Leafmass Estimation from Spectral Data

Due to a strong absorption of certain wavelengths of light by the chlorophyll of green vegetation, LANDSAT data has been used to estimate the biomass of certain types of landcover based on measurements of reflective radiation (Tucker 1979). Red reflectance radiation (630-690 nm) exhibits a nonlinear inverse relationship to green biomass, whereas the near-infrared (760-900 nm) reflectance radiation component exhibits an non-linear direct relationship as seen in Figure 3.1 (Tucker 1979).

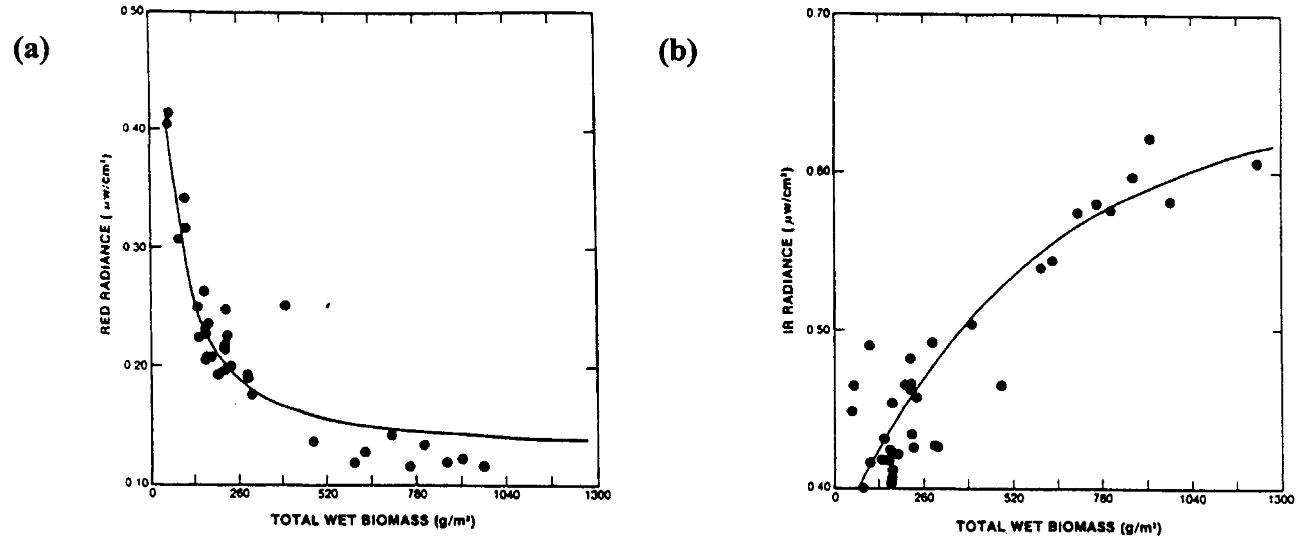


Figure 3-1. Radiance plotted against wet biomass of blue grama grass for a) 630-690 nm and b) 750-800 nm. (Tucker 1979).

These relationships have lead to the development of vegetation indices (VI) such as the simple ratio (SR) and the normalized difference vegetation index (NDVI) that can be used to estimate the quantity of green biomass of vegetation. A summary of vegetation indices and the equations used to derive them is shown in Table 3-1.

Table 3-1. Vegetation indices and the equations used to derive them. Reproduced from Fassnacht et al. (1997).

Index Name	*Acronym* [a]	*Equation*	*Reference*
Simple ratio	SR	nIR/R	
Normalized difference VI	NDVI	$(nIR-R)/(nIR+R)$	Rouse et al. (1973)
Transformed VI	TVI	SQRT (NDVI)	Deering et al. (1975)
Brightness VI	BVI	$0.3037 \cdot B+0.2793 \cdot C+0.4743 \cdot R +0.5585 \cdot nIR+0.5082 \cdot mIR1+0.1863 \cdot mIR2$	Crist and Cicone (1984)
Greenness VI	GVI	$-0.2848 \cdot B-0.2435 \cdot C-0.5436 \cdot R +0.7243 \cdot nIR+0.0840 \cdot mIR1-0.1800 \cdot mIR2$	Crist and Cicone (1984)
Wetness VI	WVI	$0.1509 \cdot B+0.1973 \cdot C+0.3279 \cdot R +0.3406 \cdot nIR-0.7112 \cdot mIR1-0.4572 \cdot mIR2$	Crist and Cicone (1984)
Fourth	TC4	$-0.8242 \cdot B+0.0849 \cdot C+0.4392 \cdot R -0.0580 \cdot nIR+0.2012 \cdot mIR1-0.2768 \cdot mIR2$	Crist and Cicone (1984)
Fifth	TC5	$-0.3280 \cdot B+0.0549 \cdot C+0.1075 \cdot R +0.1855 \cdot nIR-0.4357 \cdot mIR1+0.8085 \cdot mIR2$	Crist and Cicone (1984)
Sixth	TC6	$0.1084 \cdot B-0.9022 \cdot C+0.4120 \cdot R +0.0573 \cdot nIR-0.0251 \cdot mIR1+0.0238 \cdot mIR2$	Crist and Cicone (1984)
Mid-infrared VI 1	MVI1	$mIR1/mIR2$	
Mid-infrared VI 2	MVI2	$nIR/mIR2$	
Mid-infrared VI 3	MVI3	$nIR/(mIR1+mIR2)$	Thenkabail et al. (1994)
Corrected NDVI	$NDVI_c$	$NDVI \cdot [1-(mIR-mIR_{min})/(mIR_{max}-mIR_{min})]$	Nemani et al. (1993)

[a] Abbreviations for bands are as follows: B=blue (0.45–0.52 μm); C=green (0.52–0.60 μm); R=red (0.63–0.69 μm); nIR=near-infrared (0.76–0.90 μm); $mIR1$=first mid-infrared band (1.3–2.0 μm); $mIR2$=second mid-infrared band (2.0–3.0 μm).

3.1.2 Leafmass Estimation Using NDVI

Reflectance bands in the near-infrared (NIR) and red (RED) wavelengths are used to calculate the NDVI as follows (Peterson et al. 1987):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED}) / (\mathrm{NIR} + \mathrm{RED}) \tag{3}$$
$$\mathrm{NDVI} = ([760\text{-}900\ \mathrm{nm}] - [630\text{-}690\ \mathrm{nm}]) / ([760\text{-}900\ \mathrm{nm}] + [630\text{-}690\ \mathrm{nm}])$$

The NDVI can be used to estimate biomass by correlating index values to biomass values sampled from the field (Tucker 1979, Peterson et al. 1987, Law and Waring 1994a, Gamon et al. 1995). On a regional or global scale, the NDVI can be calculated using satellite data gathered with the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) or the Landsat-TM. Or, ground-based instruments may be used as in the study of Gamon et al. (1995), in which a portable spectroradiometer was mounted on an extendable boom and placed 1 – 4 m above the canopy to measure reflectance.

By using indices such as NDVI and SR as indicators of photosynthetically active radiation (PAR) absorption, potential photosynthetic activity can be estimated (Gamon et al. 1995, Asrar et al. 1984). Also, based on the work of Monteith (1977) (cited in Gamon et al. 1995) a radiation-use efficiency term can be used to relate PAR to biomass accumulation or net primary production (NPP). Other studies have attempted to relate vegetation indexes to crop biomass data obtained from the field. For example, one such correlation for blue grama grass is discussed in Section 4.2.

The relationships of NDVI with canopy structure, photosynthetic fluxes or NPP appear to be most consistent in uniform vegetation. Relatively few studies have compared NDVI to canopy structure and PAR absorption in natural landscapes with vegetation of differing growth habits and phenologies that may be exposed to seasonal or chronic stresses (Gamon et al. 1995). However, mounting evidence indicates that the NDVI may be useful in cases where plants are separated and foliar characteristics are unpredictable, such as in desert communities with low (< 1) overall LAI values (Gamon et al. 1995). Earlier work indicated that application of NDVI was confounded in these environment types due to unpredictable soil reflectance properties (Asrar et al. 1992). However, recently developed radiative-transfer models and correction algorithms capture quite well the primary effects of differing illumination and viewing conditions on the reflectance of discontinuous vegetation covers and should improve canopy estimates in California's communities (Wu and Strahler 1994). Also, advancing remote sensing technologies are expected to improve pixel resolution, and thus reduce background effects which are especially important in arid region plant communities (Ustin et al. 1986).

3.1.3 Leafmass Estimation Using SR

Like the NDVI, the SR vegetation index is derived from canopy reflectance in the red and near-infrared wave bands (equation 4).

$$SR = R_{NIR\ (760\text{-}900\ nm)} / R_{RED\ (630\text{-}690\ nm)} \qquad (4)$$

The two indices are mathematically interchangeable (equation 5). NDVI and the natural log of SR showed very similar correlation values as indicators of green biomass and canopy structure (Gamon et al. 1995).

$$SR = (1 + NDVI) / (1 - NDVI) \qquad (5)$$

3.1.4 Vegetation Indices and Field Data Acquisition.

It is important to note that extensive ground surveys and collection of empirical field data have been included in past studies where a spectrally-derived vegetation index has been used to estimate biometric descriptors such as crown area, leafmass, leaf area index, and leafmass density. At least limited measurements of plant parts are necessary to tether index values derived from spectral reflectances to quantifiable biometric parameters. For example, in the analysis of IR/NIR bandwidth ratios and combinations by Tucker (1979), six grass canopy variables including wet and dry weights were measured in the field and plotted against the various spectral indices (Section 4.2).

Peterson et al. (1987) conducted extensive field sampling in 18 of the component biomes found along a transect of western Oregon as part of an investigation of the use of spectral reflectance indices to quantify vegetation growth. All trees within a sample plot of 0.1 ha that had a bole diameter of greater than 5 cm were measured for various crown parameters including LAI. Sapwood and stemwood diameters were also measured so that foliage mass could be calculated using established allometric equations. In cases where vegetation indices successfully describe leafmass, the quantity of field data available for validation is extensive. For this reason field measurements are possibly more critical to the evaluation of vegetation indices for use in biomass modeling in California due to a paucity of useful biometric data for indigenous plant communities. A distinct scarcity of data still remains correlating NDVI values to LMD distribution in regions dominated with Mediterranean-type or desert vegetation. Before LMD estimates derived from the NDVI are integrated into a BHC emissions inventory for the SCOS97 domain, additional field validation of remotely derived estimates with field-based leafmass values should be a priority for BHC emissions research.

3.2 INDIRECT LEAF AREA MEASUREMENT METHODS

As with indirect leafmass estimation, leaf area may also be estimated using a previously established relationship between a measurable variable, such as below-canopy light interception or spectral reflectance and leaf area. Data may be acquired through remote sensing methods including digital photography or infrared or color photography.

3.2.1 Methods for Estimating Leaf Area Index with Spectral Analysis

The spectral reflectance of solar radiation by plant canopy components can be used to estimate leaf area index of plant canopies (Spanner et al. 1990a). VI values change according to the amount of light absorbed (and thus reflected) by the vegetation. A vegetation canopy can at most absorb 90 – 94 % of incident PAR (Myneni et al. 1992). The fraction of PAR intercepted by a plant crown (*f*PAR) is calculated as the difference between incoming light in PAR wavelengths (~400–700 nm) minus reflectance radiation at PAR wavelengths. Thus, VI's are descriptive of how much radiation a plant crown intercepts, which is more closely related to leaf area rather than leafmass.

On a regional basis, the interception of PAR will depend primarily on leaf area but also on the dominant plant species, growth habit, foliage clumping, leaf angle distribution, soil reflectance, and, to some extent, atmospheric conditions and azimuth angle. For these reasons VI values calculated for a particular biome have inherent site/species specificity. Attempts to reduce the variability in spectral reflectance indices between different locations have concentrated on the use of improved environmental correction algorithms that can account for much of the variation attributable to atmosphere or azimuth (Loveland et al. 1991). Also, by integrating a component of plant community composition and landcover such as the GAP database suggested for the SCOS97-NARSTO modeling domain (Benjamin et al. 1998) or by using endmember spectral mixture models (Roberts et al. 1996) community/site-specific reflectance components can be better corrected. For a discussion of NDVI scaling see Section 3.2.3.

In partially closed canopies the accuracy and precision of estimating LAI from reflected radiation depends on the contrast of the reflectances from the soil background and the green vegetation. (Asrar et al. 1984) Leaf pigments absorb most of the visible radiation (400 to 700 nm) but the reflectance of vegetation in the near infrared (700 - 900 nm) waveband contrasts sharply with the reflectance of soil. A combination of the visible and near-infrared reflectance that best estimates the fraction of incident radiation absorbed by the plant canopy has been used to generate vegetation indices (such as the NDVI and SR) which may then be used to estimate LAI.

NDVI, SR, or another VI derived from spectral reflectance data may be used to arrive at an estimate of LAI. To couple the VI to LAI, either an empirical approach or an analytical approach may be used (Nikolov 1997a). In an empirical approach, field measurements of LAI are correlated with the VI. In an analytical approach, a canopy radiative transfer model is used to relate the dependent variable, LAI, to VI. An additional LAI retrieval algorithm has been developed, which is based upon an inversion of a canopy radiative transfer model (Nikolov 1997a,b). Use of this algorithm may give more accurate values for LAI than those from earlier algorithms, especially at higher values of LAI, and may not require development of empirical VI-LAI relationships for all plant communities.

3.2.2 NDVI and Estimation of LAI

Section 3.1.2 discussed the use of the NDVI to directly estimate leafmass density of vegetation cover. The potential application for this data would be enormous but integration of this method into an emissions inventory should not be attempted until a great deal of field validation has been completed. Alternatively leaf area index estimates derived from the NDVI may be used, when integrated with equation 2, to derive LMD with a somewhat more practical requirement for field validation. The NDVI is intrinsically related to the leaf area index of a plant crown because absorption of light in the PAR range is a primary determinant for changes in the ratio of IR/red reflectance. Examples of this relationship were the close linear correlation between LAI estimates of coniferous forest ecosystems and IR/red reflectance combinations shown by Running et al. (1989) and Spanner et al. (1994). For further discussion of this relationship, see Sections 4.3 and 4.4.

Spectral data have been acquired with infrared imaging spectrometers mounted on various types of platforms, thus-far without a clearly defined optimum method. Nemani and Running (1989) compared data of two satellite-mounted instruments used to gather the spectral imagery used to calculate the NDVI for correlation with the field LAI of coniferous forests in Oregon and Montana. Spectral images for the Oregon forests were gathered from a LANDSAT Thematic Mapper (LANDSAT-TM) overpass on July 18, 1984 ($r^2_{(NDVI)}$ =0.58) and images of the Montana ecosystem were gathered by a NOAA-9/AVHRR overpass on September 25, 1985 ($r^2_{(NDVI)}$ =0.88). The NDVI calculated from either method could predict LAI to a maximum of about 4-5 m^2 m^{-2} (Spanner et al. 1994).

Gamon et al. (1995) calculated the NDVI in a study of a 20 hectare area of Stanford University's Jasper Ridge Biological Preserve in San Mateo County, California using a portable spectroradiometer (model SE590 with detector model CE390WB-R, Spectron Engineering, Incorporated, Denver, Colorado) on a boom placed 1 - 4 meters above the canopy. The instrument detected radiance in 252 bands with a mean bandwidth of approximately 3 nm, uniformly distributed between 368.4 and 1113.7 nm. Very good correlations were observed for the logarithmic relationships between NDVI and canopy greenness factors, i.e. green leaf biomass and green LAI (Table 3-2). Plotting the log of green leaf biomass (g m^{-2}) or green LAI of the cover in five environment types against NDVI produced a straight line (Gamon et al. 1995). A similar portable spectroradiometer was used by Law and Waring (1994b) for LAI estimation of understory vegetation of open ponderosa pine (*Pinus ponderosa*) stands.

Table 3-2. Pearson correlation matrix (*r* values) comparing the vegetation indices NDVI, SR and ln(SR) to various indicators of the canopy structure in Californian chaparral woodland. Reproduced from Gamon et al. (1995).

Variable	NDVI	SR	ln(SR)
		r value	
ln(total LAI)	0.912**	0.861**	0.908**
ln(green LAI)†	0.949**	0.899**	0.947**
ln(N)	0.901**	0.865**	0.901**
ln(chl)	0.944**	0.898**	0.942**
ln(total biomass)	0.844**	0.721	0.814**
ln(green biomass)†	0.937**	0.835**	0.914**
F_{IPAR}	0.794**	0.626	0.746*
F_{IPAR} × % greenness	0.925**	0.902**	0.935**

* $P \leq 0.01$; ** $P \leq 0.001$ (Bonferroni-adjusted probability that $r \neq 0$).

Gamon et al. (1995) posit that NDVI may be well suited to leaf area estimations in environments where canopy coverage of ground surface is less than 100 % and such environments may include natural communities within the semi-arid regions of California. This position was supported in a recent study in which a simple radiative transfer model that showed NDVI to be sensitive to changes in the fractional cover until canopy closure was reached, beyond which a further increase in LAI resulted in an additional small, asymptotic increase in NDVI (Ripley and Carlson 1997).

3.2.3 Scaling the NDVI to LAI

One criticism of the NDVI is that its sensitivity to changes in LAI decreases as LAI increases beyond a threshold value, which is thought to be LAI ~ 2-3 for agricultural monocultures and LAI ~ 7-8 for coniferous canopies (Peterson et al. 1987). These values approximately correspond to canopy closure. The upper threshold is indicated by a flattening of the asymptotic shape that is characteristic of LAI vs. NDVI curves (see Figure 4-6). To correct for saturation of the NDVI at relatively low LAI, the index can be scaled to correspond to the values for bare soil (LAI = 0) and a surface with vegetative cover of 100 percent (Carlson and Ripley 1997).

Scaled NDVI (N^o) is defined (Carlson and Ripley 1997) as:

$$N^o = (NDVI - NDVI_o) / (NDVI_s - NDVI_o) \quad (6)$$

$NDVI_o$ = NDVI value for bare soil.
$NDVI_s$ = NDVI value for a surface with 100% vegetation cover.

3.2.4 Estimating LAI Using the SR

The simple ratio can be measured using a variety of different instruments on a variety of different platforms. Spanner et al. (1994) compared four methods for calculating SR: 1) the Thematic Mapper Simulator (TMS), 2) the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), 3) the Compact Airborne Spectrographic Imager (CASI), or the 4) Spectron SE590 spectroradiometer. TMS and AVIRIS data imagery was gathered using a National Aeronautics and Space Administration (NASA) ER-2 aircraft flown at an altitude of 20 km. CASI data were acquired using a single-seat aircraft at an altitude 1.4 -1.8 km, and SE590 data were acquired from a micro-lite aircraft overpass approximately 100 m above ground level. The VI's calculated using these techniques were compared with empirical data gathered from below-canopy measurements made using a ceptometer. For LAI estimation, the SR appears to be better suited than NDVI to coniferous forests when approaching 100% canopy coverage. The form of the relationship between the SR and LAI is dominated by chlorophyll absorption in the red, as the denominator of the equation, combined with a flat response in the NIR due to near asymptotic reflectances from multiple scattering caused by conifer needles, the term in the numerator.

At < 90 % coverage, understory vegetation and background reflectance reduce the strength of the relationship between LAI and SR (Spanner et al. 1994). The correlation between LAI and NDVI derived from data supplied by these instruments for coniferous forests are further discussed in section 4.4.

An example of applying the analytical method for deriving LAI from a calculated VI is discussed by (Nikolov 1997a). The approach employed a modified canopy radiative transfer model (Camillo 1987) to simulate variation of SR as a function of changes in LAI for a 5.64 x 4.65 km cotton site a 1.50 x 1.23 km grape site and a 4.80 x 3.45 km grassland site in the San Joaquin Valley, California. LAI predictions using the model appeared to agree well with measured LAI values that had been reported earlier. For a fuller description of the analytical method for canopy LAI prediction see Nikolov (1997a).

3.2.5 Estimating LAI Using Digital Photography

Digital photography utilizes an image captured on a digital camera. The image integrates broad blue, green and red bands that can be processed to estimate vegetation descriptors such as LAI and light interception (*f*PAR) by shrubs in chaparral and by open canopy forests (Law 1995). In the methods of Law (1995), each pixel of the digital image was assigned into one of the following four categories: 1) illuminated leaves 2) shaded leaves 3) illuminated background, or 4) shaded background. The percentage of the image occupied by each category was calculated and the variables were then combined to produce equations depicting leaf area or *f*PAR as shown in Table 3-3.

Table 3-3. Regression equations for combinations of percentage of scene occupied by illuminated leaves (I), shaded leaves (S), and shaded background (B) in digital video images as the independent variable. Reproduced from Law (1995).

	LAI			f_{IPAR}		
	Model	*MSE*	R^2	*Model*	*MSE*	R^2
Dependent variable (y):						
manzanita						
$\Sigma(I+S)$:	$y = 30.062 + 58.102\log(x)$	0.011	0.83	$y = -5.174 + 89.679x$	0.007	0.63
$\Sigma(I+S+B)$:	$y = 38.305 + 57.057\log(x)$	0.008	0.88	$y = 4.374 + 87.226x$	0.007	0.66
bitterbrush						
$\Sigma(I+S)$:	$y = 44.913 + 30.187\log(x)$	0.054	0.49	$y = 21.582 + 53.838x$	0.017	0.42
$\Sigma(I+S+B)$:	$y = 58.885 + 29.382\log(x)$	0.037	0.65	$y = 34.026 + 55.280x$	0.011	0.61

Leaf area index (LAI) and the fraction of incident photosynthetically active radiation intercepted by vegetation (f_{IPAR}) are independent variables in separate relationships ($n = 23$ bitterbrush plots, $n = 27$ manzanita plots).

3.3 ALLOMETRIC EQUATIONS FOR ESTIMATING LEAFMASSES

Many of the allometric techniques for estimating leafmasses of tree canopies have been derived from forest mensuration methodology. Allometric equations often include exponential or logarithmic relationships because leafmass is sustained by vascular tissues, which increase in cross-sectional area as the square of stem diameter increases (Kittredge 1944). In practice, a set of sample trees is cut down and subjected to intensive measurement, so that biomass, wood production and other dimensions can be related (as dependent variables) to stem diameter (or other independent variables) in logarithmic regressions (Lieth and Whittaker 1975). One of the easiest measurements to take is stem diameter or diameter at breast height (DBH), the stem or trunk diameter of a tree at 4½ feet or 1.37 m. Allometric equations may be the most useful for coupling site-specific and species specific data useful for field validation of LAI or leafmass estimates derived through remote sensing methods.

3.3.1 Relationship Between DBH and Leafmass

Because DBH is easy to measure it is often used as a variable in allometric equations that predict the height, crown area, leaf area or leaf biomass of forest stands or individual urban trees (Hall et al. 1989, Nowak 1996). For leafmass analysis of shrubs, stem diameter at 10 cm is commonly used (Nicholson 1975).

Most allometric equations for leafmass are in the form of simple linear relationships

$$Y = a + b X \tag{7}$$

where Y is leafmass (kg), X is DBH and a and b are regression coefficients Gholz (1982). The values of a and b are often species and site-specific, describing the growth of a particular species in a particular environment. Depending on the complexity of the relationship between the predicted component (Y) and the determinant variable (X) a logarithmic or exponential adjustment may be used to improve the regression fit.

In some cases it may be possible to adjust allometric equations developed for plants from another location to an environmental component such as water balance, mean annual temperature or minimum winter temperature, so that they could be used for plants of the same species or genus that grow in the SCOS97-NARSTO domain. For example, Gholz (1982) studied a range of climatic predictors for correcting the equation $Y = a + b X$, where Y = LAI, Y = biomass or Y = NPP of trees in the Oregon transect. The best predictor over the range of environments tested was winter low temperature. Water balance, the difference of potential evaporation to rainfall (considered to be the most important variable of growth), was expected to provide an accurate correction factor for Y but did not work well over the range of environments. This was due mainly to an outlier entered by one environment, the sub-alpine region, an effect that distorted the fit. With this point removed, water balance provided the best correction factor for LAI (r^2= 0.99), biomass (r^2= 0.95), and NPP (r^2= 0.91).

3.3.2 Relationship of DBH to Crown Variables and Leafmass

In the study of BVOC emissions from forests in the eastern United States conducted by Geron et al. (1994), leafmass of a stand was estimated based on the relationship between crown diameter and the DBH of individual trees. The relationship of leafmass to DBH was demonstrated in Scots pine as long ago as 1928 by Zieger and has since been shown in many other conifers and hardwoods from the Northern Hemisphere (Howard 1991). Geron et al. (1994) and Guenther et al. (1994) used allometric equations derived from empirical data found in the literature to calculate crown diameter based on ground measurements of DBH available from the Eastwide Forest Inventory Database (EFID). The relationships were used in biomass estimations for BHC emissions modeling.

Howard (1991) discussed the use of aereal photography to estimate crown diameter of *Eucalyptus obliqua* in southeastern Australia. Crown diameter measuring scales developed by the U.S. Forest Service were used on stereoscopic pairs of aereal photographs to estimate photo crown diameter. Estimated crown diameter from photographic data was correlated linearly with area of crown projection estimated in the field (r^2 = 0.87) as shown in Figure 3-2a. Crown diameter is also known to be correlated with DBH (Fig 3-2b).

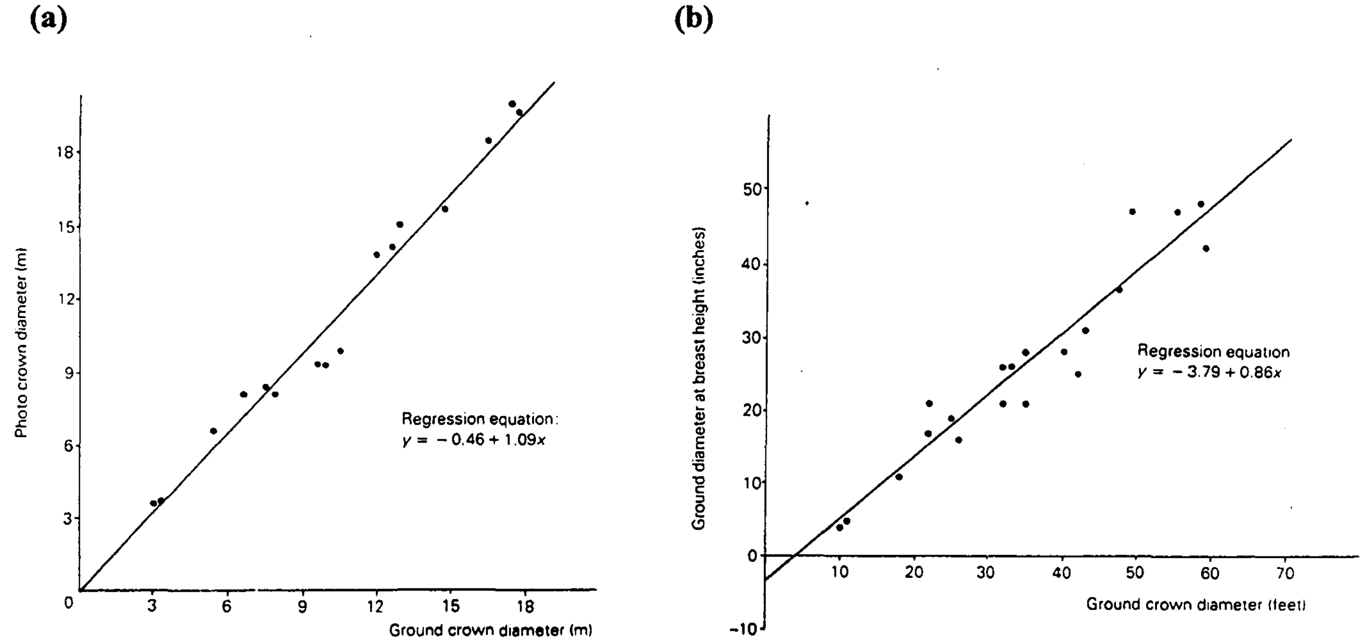


Figure 3-2. a) Regression relationship for *Eucalyptus obliqua* between crown diameter measured from aereal photograph and crown diameter measured on the ground. b) correlation of crown diameter and DBH in *Eucalyptus obliqua*. Reproduced from Howard (1991).

3.3.3 Dimension Analysis

Dimension analysis is jargon which refers to a more complex form of allometric derivation combining direct sampling techniques with the use of allometric equations to estimate leafmass of an entire environment based on allometric relationships of a sub-sample. In a study of coastal sage scrubland in the Santa Monica Mountains (Los Angeles County), purple sage (*Salvia leucophylla*) and California sagebrush (*Artemisia californica*) leafmasses were determined by dimension analysis (Gray and Schlesinger 1981). Using this technique, random selections of the shrubs were harvested, the stem diameter at 10 cm above ground was measured, and biomass components were separated into twigs, branches and leaves. After drying, linear regressions were calculated relating dry weights of the component parts to stem diameter. On a community level, the diameters of individual stems were measured in 1 x 1 m quadrats, entered into regression equations, and the biomass of the plant component parts was estimated. Results from this study are presented in Table 4.6.

3.4 ALLOMETRIC METHODS FOR ESTIMATING LEAF AREA

Leaf area may be calculated using allometric equations, or by using leafmass to leaf area conversions (Nowak 1996). Two equations were developed from data of eastern U.S. urban trees. Equation 8 is based upon crown dimensions and is of the form:

$$\ln Y = -4.3309 + 0.2942H + 0.7312D + 5.7217S - 0.0148C + \text{error} \qquad (8)$$

and equation 9 is based upon trunk diameter and is of the form:

$$\ln Y = 0.2102 + 0.0586X + 4.0202S + \text{error} \qquad (9)$$

where Y is leaf area (m^2). In these allometric equations, H is crown height (m), D is average crown diameter (m), S is a shading factor (fraction light intensity intercepted by foliated tree crowns), C is ($\pi D(H + D)/2$) based on the outer surface area of the tree crown (Gacka-Grzesikiewicz 1980), and X is DBH (cm). Nowak (1996) states these equations (8 and 9) are applicable only to trees with crown height to crown width ratios between 0.5 - 2.0 and with DBH between 11 and 53 cm. The error terms, which were of the form exp(MSE/2), can be added to these equations to correct for logarithmic bias. The coefficients, shading factors and the error terms were taken from tabulated values (Nowak 1996).

Leaf areas and LAI of trees harvested in a 1996 - 1997 study funded by ARB (Winer et al. 1998) were calculated using these equations. Most of the trees had a calculated LAI of 2.8 - 4.6, which was similar to the range of 4.4 – 5.8 for southeastern forests as estimated by Geron et al. (1997). The LAI for four trees with columnar growth habit, calculated using equation 8 (above) ranged from 8.6 - 38 which was two to six times higher than the estimates for southeastern forests. Columnar habit may allow higher LAI because layers of leaves are arranged over a relatively small area.

In the study of Winer et al. (1998), leaf areas of two plants calculated using SLW data with Eqn.1 were compared to leaf areas measured with the leaf area meter. All the leaves of one tree, a *Eucalyptus grandis*, were passed through the leaf area meter and the total measured leaf area was 47 m^2. The value for total leaf area for this tree calculated from Eqn. 1 was 44 m^2, 94 % of the measured leaf area of 47 m^2.

All leaves of a *Rhus ovata* (sugar bush) shrub, a plant with a form approximated by a rectangular prism, were removed, measured for leaf area, dried and weighed. The plant measured 2.4 x 2.4 x 1.8 m in length, width, and height, respectively, with a calculated volume of 11 m^3. The measured leafmass of 14,400 g was multiplied by the experimentally determined SLA factor of 0.00312 m^2 g^{-1} for this species to give a calculated leaf area of 45 m^2, which was 96 % of the measured leaf area of 47 m^2. Thus, in this very limited comparison using only two plants, leaf areas calculated with mass-to-volume conversions were within 6 % of the measured leaf areas. For a summary of leafmass and leaf area data obtained by Winer and co-workers (1998) see Table 4-14.

3.5 DIRECT LEAFMASS MEASUREMENT METHODS

3.5.1 Whole Tree Harvest

Leafmass is most accurately determined by harvesting all the leaves of a tree crown and measuring their total dry weight. For example, in the recent ARB-funded study of Winer and co-workers (1998) harvests were made in 1996 and 1997 of trees in the Bakersfield area selected to represent a variety of species and growth forms. Sample trees were subject to the limitations of accessibility and permission to harvest. For all trees or shrubs, crown height was measured and crown radius was approximated by the average dripline measured in four directions. Quadrat samples were made from within the canopy of each tree so that sub-sample estimation techniques could be later tested with the harvest data. For each sample tree all leaves were removed and leafmass was measured. This technique provided quantitative data for some urban tree species in the SCOS97-NARSTO domain but was extremely time-consuming and labor-intensive.

3.5.2 Selective Sampling and Random Quadrat Analysis

A quadrat is a frame of any shape that can be placed over vegetation so that cover can be estimated, species listed or plants counted or harvested (Barbour 1980). Quadrats can be located randomly by constructing two imaginary axes along the edges of an area to be sampled, dividing the axes into units and picking pairs of units from a random numbers table. For biomass analysis of vegetation growing in arid landscapes relatively large circular quadrats give the most precise estimates (Barbour 1980). For analysis of small herbaceous cover, all aboveground plant matter can be clipped and weighed. For larger plants, clearing large plots is not practical; instead, relatively few individuals of different age and size classes can be harvested and allometric equations are developed relating size and biomass. Campbell and Norman (1989) described the use of a stratified-clip method for assessing structural characteristics of tree canopies as a direct method. A three dimensional quadrat is then used to sample the canopy at different strata. Leaves from within the quadrat are then clipped and analyzed for leaf area and biomass characteristics.

Three-dimensional quadrats were used by Winer et al. (1998) in a slightly modified version of the stratified-clip to quantify the leafmass of urban trees. Samples were clipped from the contents of an open cube with a volume of 1 ft^3. Ten sampling locations within the crown were chosen based on a three digit random sampling system (Winer et al. 1998). This system did not give leafmass constants that were as representative of tree crowns as the 1 m^3 frames used in earlier studies of Winer and co-workers (Winer et al. 1983, Miller and Winer 1984).

3.5.3 Litter Fall

Collecting and weighing the annual fall of leaves as litter may be used to estimate the productivity of a plant community. The technique assumes knowledge of the ratio of litter fall to total biomass production (Lieth and Whittaker 1975). Litter fall estimates were used by Geron et al. (1997) to validate indirect estimates of species composition and foliar mass in southeastern bottomland deciduous forests. Twenty-six 45 cm diameter litter traps were placed 7.5 m from each plot center normal to the transect azimuth. Leaf litter was collected every two weeks, dried, separated and weighed (Geron et al. 1997). Results from leaf litter analysis provide an accurate determination of specific leaf area (cm^2 g^{-1}) and by multiplying this by the specific leaf weight, total LAI can be extrapolated. Using this method Geron et al. (1997) estimated a total LAI for a Southeastern bottomland deciduous forest of 5.2 m^2 m^{-2}, which was in good agreement with LAI measurements of 4.4 - 5.9 made by measuring light interception with an LAI 2000 (LiCor, Inc.) canopy analyzer instrument. LAI values were again used (Equation 2) to calculate leafmass.

3.5.4 The Volumetric Method

The volumetric method described by (Winer et al. 1983, Miller and Winer 1994, Winer et al. 1998, Karlik and Winer 1998) is considered to be a direct method of leafmass estimation. The method is possibly most applicable to heterogeneous and discontinuous land cover types such as urban landscapes. Using this method, the volume of a plant crown is estimated based on the shape of a simple geometric solid which has been assigned to that tree based on a) a visual assessment, e.g. the preferred solid method (Winer et al. 1998, Karlik and Winer 1998) b) species, or c) growth habit and environment. Leafmass is calculated by multiplying the calculated crown volume by the appropriate mass-to-volume ratio (leafmass constant). For application of the volumetric method in BHC emissions inventories, many more species-specific leafmass constants need to be experimentally determined through sampling within plant crowns, particularly for plants in natural landscapes.

The Geometric-Optical Canopy Reflectance Model that was developed by Li and Strahler (1985) makes estimations, primarily of conifer tree crown volumes, based on the geometric-optical relationships of the shadows that are cast by the crowns. The model treats conifer tree crowns as cones, and vegetation parameters (plant size and density) can be estimated using remotely sensed images of the forest stand. The model is driven by interpixel variance generated from three sources: 1) the number of crowns in the pixel, 2) the size of individual crowns, and 3) overlapping of crowns and shadows. The model uses parallel-ray geometry to describe the illumination of a three-dimensional cone and the shadow it casts. The model can also be inverted to provide estimates of the size, shape, and spacing of the conifers as cones using remote imagery and a minimum of ground measurements (Li and Strahler 1985).

3.6 DIRECT LEAF AREA MEASUREMENT METHODS

3.6.1 Leaf Area Meters

The harvest method is the most basic procedure for measuring the leaf area of a tree or shrub crown. The leaves of an entire plant can be removed and passed through a leaf area meter, such as the LiCor LI3100.

4.0 LEAFMASS AND LEAF AREA ESTIMATES FOR PLANT COMMUNITIES

A primary objective of this report was to obtain as much quantitative leafmass and leaf area data as possible for Californian plant communities. This was in part a response to analysis by Winer et al. (1995) who stated that models commonly used to calculate BHC emissions in the United States (BEIS, BEIS-2, GEMAP, VEGIES) showed limitations when applied to California. Many of the models were designed for environments with close to 100 % vegetation coverage such as temperate forests of the eastern United States. The arid Mediterranean-type climate of the SCOS97-NARSTO modeling domain, encompassing a large proportion of Southern California, differs from the temperate forests of the eastern United States in that the composition of vegetation is often heterogeneous and ground cover is less than 100%. Another reason for focusing on collecting leafmass density values for California species is the apparent scarcity of quantitative information for many California species and biomes. Most studies using satellite data to characterize vegetation in California have been performed in U.S. National Forests where the main emphasis has been the assessment of timber resources (Basham May et al. 1997).

4.1 LEAFMASS DATA FOR CALIFORNIAN PLANT COMMUNITIES GATHERED THROGH INDIRECT MEASUREMENT METHODS

The potential for using remote sensing to gauge plant biophysical properties in the SCOS97 NARSTO modeling domain has been addressed in previous reports (Winer et al. 1995). Specifically addressed here is the use of spectrally derived vegetation indices, including the NDVI and SR, to estimate the biomass of certain cover types including grasslands, crops, woodlands and semiarid rangelands.

4.1.1 Leafmass Estimated Using NDVI

The NDVI was used in an assessment of canopy structure in a large number of species from three Californian vegetation types (grassland, chaparral, and oak woodland); located at the Jasper Ridge Biological Preserve near the Stanford University campus, Palo Alto, California (Gamon et al. 1995). The NDVI showed a logarithmic increase when applied to field sampled oven-dried LMD up to a threshold foliage density of approximately 1500 g m^{-2} (Fig 4-1a). A logarithmic transformation of the same data set resulted in a linear correlation with NDVI (r^2 = 0.937) as shown in Figure 4-1b.

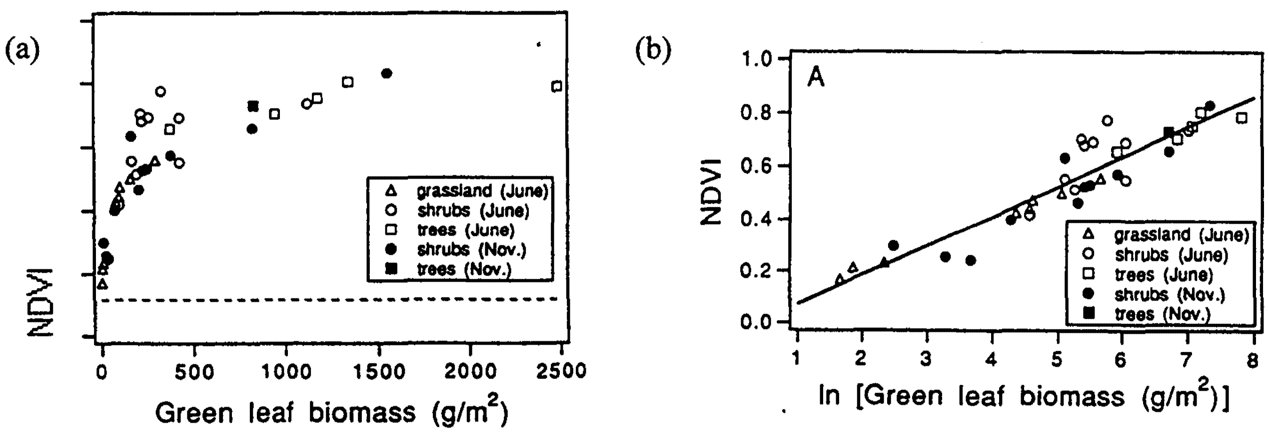


Figure 4-1. **(a)** Relationship of NDVI to green leaf biomass (g m^{-2}), for three types of California vegetation in two different seasons. **(b)** Relationship between NDVI and green leaf biomass (expressed on a natural log scale) of three California vegetation types in two seasons. Reproduced from Gamon et al. (1995).

The description of leafmass by NDVI is most pronounced at low canopy densities reaching an apparent maximum which corresponded to canopy coverage of LAI ~ 2. The NDVI is extremely sensitive to changes in canopy cover when the cover is low, but may not clearly distinguish between values relating to crown structure (such as leafmass) when the index ranges from 20 – 100 % of full scale (Gamon et al. 1995). Addition of more canopy layers makes little difference in the relative interception or reflectance of red and near-infrared radiation, and thus causes an asymptotic relationship between NDVI and LAI at low levels of LAI (Peterson et al. 1987). As mentioned in Section 3.2.2 this feature of the NDVI may make it better suited to natural California biomes in which LAI values remain relatively low. (For a range of LAI values for Californian communities see Table 4-5 and 4-15.)

4.1.2 Leafmass Estimates from Below-Canopy Light Interception

The relationship between leafmass and light interception by the canopy of a plant is also apparent from below canopy light measurement. Using below-canopy light interception measurements made with a quantum photometer (Lambda Instruments Corporation, Model LI-185), Schlesinger and Gill (1980) observed a linear relationship of PAR light interception and LMD (g m^{-2}) in 12 stands of *Ceanothus megacarpus* in the Santa Ynez Mountains, California (Figure 4-5). The LMD's calculated through below-canopy light interception were verified with leafmass estimates made with random quadrat analysis and allometric equations as described in Section 4.2.1.

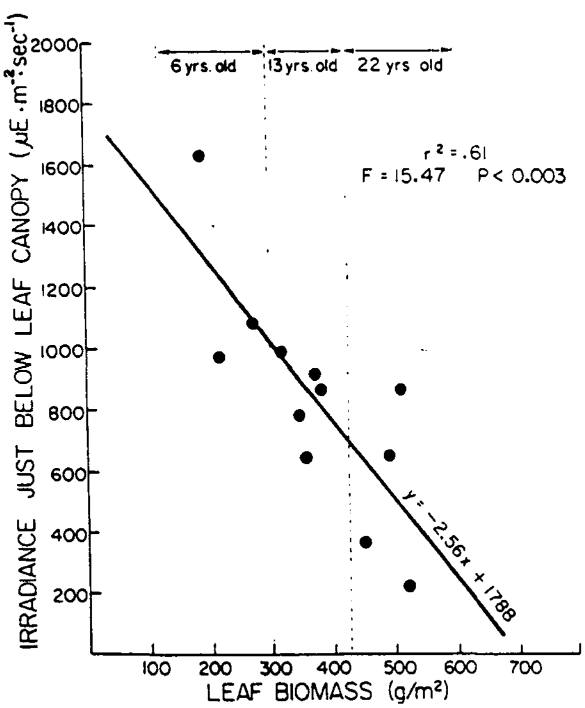
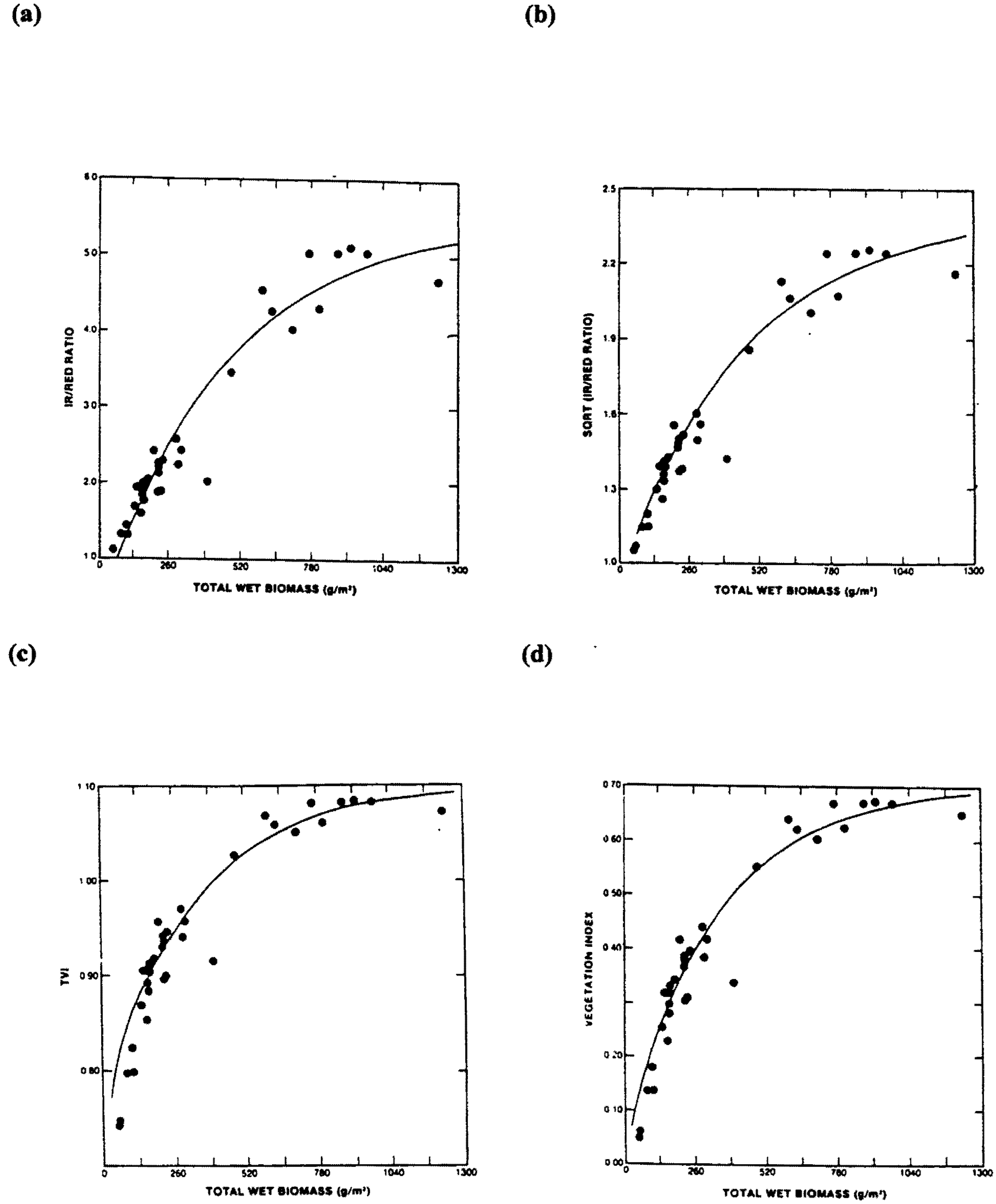


Figure 4-2. Mean light intensity measured just beneath the canopy in pure stands of *Ceanothus megacarpus* of varying age and thus varying amounts of leafmass (Schlesinger and Gill 1980).

4.2 LEAFMASS DATA FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA GATHERED THROUGH INDIRECT MEASUREMENT METHODS

LANDSAT analyses of the IR/red ratio, the square root of the IR/red ratio, the VI and TVI (TVI = SQRT (VI+.5)) were shown to be sensitive to the photosynthetically active biomass of a blue grama grass canopy (Tucker 1979). The various indices were descriptive of wet biomass (g f. wt. m^{-2}) to within 94 % of the fresh weight estimated from random quadrat analysis (Figs 4-3a-d). The indices were descriptive of dry green leafmass (g m^{-2}) to within 52 % of sampled dry weight. (Figs 4-4a,b).



Figures 4-3a-d. Radiance variables plotted against the total wet biomass (g f. wt. m^{-2}) for the 35 blue grama grass plots sampled by quadrat analysis in June 1972 (Tucker 1979).

(a) (b)

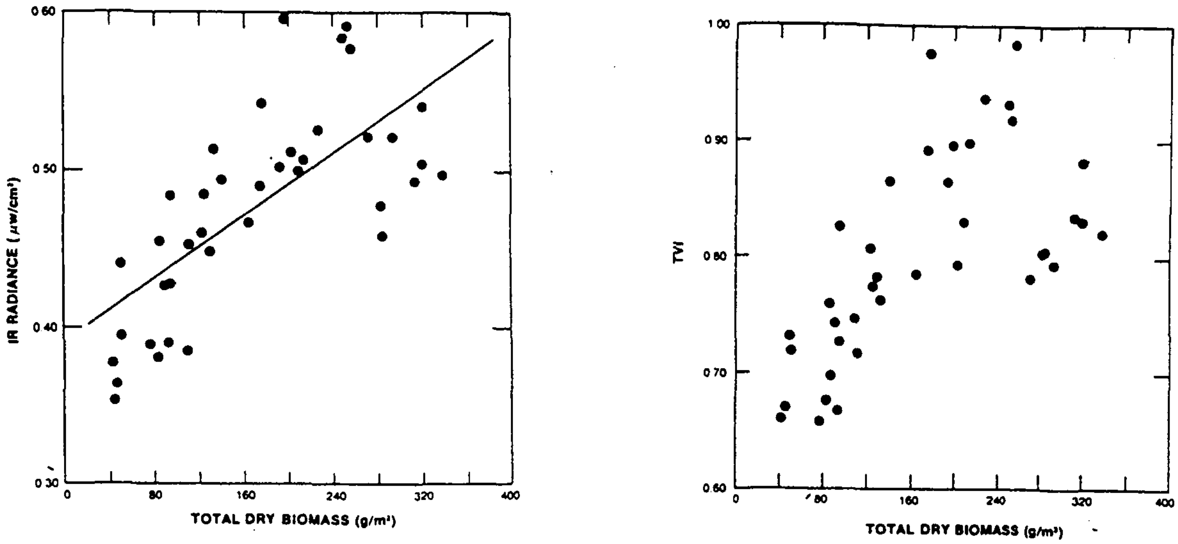


Figure 4-4a and b. Radiance variables plotted against dry biomass (g m^2) for the 35 blue grama grass plots sampled by quadrant analysis in September 1971 (Tucker 1979).

The BHC emissions inventory of a test site at St. Quercio, Castelporziano, Italy was assembled by Lenz et al. (1997). Species-specific BHC emissions were measured and multiplied by leafmasses that had been calculated using a previously assembled database of biometric information. LAI (gathered indirectly with an LAI-2000 plant canopy analyzer), specific leaf weight and percent coverage were used to calculate leafmass and estimate BHC emissions of each species normalized to a standard set of conditions (30 °C, 1000 umol m^{-2} s^{-1} PAR). For this report, LMD values were calculated for the site by multiplying LAI by specific leaf weight according to equation 2. The LMD values ranged from 200 g m^{-2} to 1100 g m^{-2} as seen in Table 4-3. For the two species in Table 4-2 (below) with complete data, *Quercus petraea* and *Q. pubescens,* LMD values were calculated as 160 and 92 g m^{-2}, respectively. The results of the Castelporziano site provide a valuable resource for future comparisons with California emissions inventories. The climate at Castelporziano is Mediterranean with pronounced summer aridity and is comparable to areas in Southern California. Also, application of the methodology used to calculate LMD values for the Castelporziano inventory appears to be promising given the development of remote sensing methods for estimating LAI.

Table 4-1. SLW, LAI and coverage of 11 plant species at St. Quercio, Italy (sampled in May 1994). The three categories of biometric data were used to calculate total emission fluxes per unit area. Table reproduced from Lenz et al. (1997).

Species	Normalized emission rates ($\mu g\ g^{-1} h^{-1}$) Isoprenes (May 94)	Monoterpenes (May 94)	SLW spec. weight per unit area ($g\ m^{-2}$)	LAI projected	Cov% St. Quercio	Emission fluxes ($ng\ m^{-2} s^{-1}$) Isoprenes	Monoterpenes
Arbutus unedo		0.12	75	5	0.5		< 1
Cistus salvifolius		0.34	75	3	3		< 1
Erica arborea	7.3	< 0.01	96.1	6.4	1	12	< 1
Myrtus communis	19.8	< 0.01	47.3	2.4	1	6	< 1
Pinus pinea	< 0.01	3	309.3	3.8	51	< 1	500
Phillyrea angustifolia		0.39	100	5	1		< 1
Quercus cerris	< 0.2	3.10	37	4.8	1	< 1	1.5
Quercus frainetto	134		56	4	0.5	42	
Quercus ilex	< 0.01	16	128	6.75	13	< 1	500
Quercus petraea	45		43	4	0.5	11	
Quercus suber	< 0.2		87	5	0.5	< 1	
Soil							30
Sum						73	1032

Table 4-2. SLW, LAI and coverage estimates used to calculate VOC emission fluxes per unit area of the vegetation type pseudosteppe, a semi-desert community with different grasses and herbs, Castelporziano, Italy. Sampled in May 1994. Lenz et al. (1997).

Species	Emission rates isoprenes ($\mu g\ g^{-1} h^{-1}$)	SLW spec. weight per unit area ($g\ m^{-2}$)	LAI projected	Cov% Pseud	Cov% Pseud/trees	Emission fluxes isoprene ($ng\ m^{-2} s^{-1}$)
Asphodelus type	0.38	894	?	80		94
Cistus type	0.44	1290	?	20		158
Pteridium aquilinum	0.8	?	3.5	1	90	200
Quercus petraea	45	43	3.7		5	358
Quercus pubescens	90.70	33	2.8		5	419

Table 4-3. SLW, LAI and coverage for 11 species of the vegetation types dunes and dunes/suppressed macchia, a gradient environment from seashore to inland beach communities, Castelporziano, Italy (sampled in May, 1994). The three categories of biometric data were used to calculate total VOC emission fluxes per unit area. Table reproduced from Lenz et al. (1997). We calculated LMD for this report.

	Emission rates ($\mu g\ g^{-1}\ h^{-1}$)		Spec. weight per unit area ($g\ m^{-2}$)	LAI projected	Cov%		Emission fluxes ($ng\ m^{-2}\ s^{-1}$)				LMD ($g\ m^{-2}$)
Species	Isoprene (May 94)	Monoterpene (May 94)			Dunes	Dunes macchia	Isoprene dunes	Isoprene dunes macchia	Monoterpene dunes	Monoterpene dunes macchia	
Arbutus unedo		0.12	153	7.2	3.5	7.5			1.3	2.8	1101
Chrysanthemum praecox		0.51	100	2	0.5				< 1		200
Cistus incanus		0.30	173	4	7	55			4	32	692
Erica multiflora	2.00	0.03	150	6.2	8	1.5	41	< 8	< 1	< 1	930
Helichrysum stoechas		4.8	100	2	0.5	2			1.3	5.3	200
Juniperus oxycedrus	0.08	0.96	150	6.2	13	0.5	2.7	< 1	32	1.3	692
Juniperus phoenica		0.77	150	6	1	0.5			1.9	< 1	900
Phillyrea angustifolia		0.47	137	6.3	25	7			28	8	863
Pistacia lentiscus	< 0.01	0.40	169.9	6	13	3.5	< 1	< 1	15	4	.019
Quercus ilex	< 0.01	14.7	133	5	7	15	< 1	< 1	190	407	665
Rosmarinus officinalis	< 0.01	2.10	115.7	7.2	1	3.5	< 1	< 1	5	17	833
Sum							44	10	279	480	

4.3 <u>LEAF AREA DATA FOR CALIFORNIAN PLANT COMMUNITIES GATHERED THROUGH INDIRECT MEASUREMENT METHODS</u>

4.3.1 <u>LAI Estimated Using NDVI</u>

Gamon et al. (1995) argue that the NDVI is ideally suited for detecting subtle differences in cover of sparse canopies, LAI between 0 and 2, making it a sensitive index of growth in young crops, grasslands or semi-arid regions. The index is becoming potentially more useful due to more advanced equipment providing improved pixel resolution and the development of improved correction algorithms.

Using the NDVI, Gamon et al. (1995) estimated the green leaf area of three California vegetation types grassland, chaparral and oak woodland, located at the Jasper Ridge Biological Preserve near Stanford, California (Fig. 4.5a-c). In canopies with LAI between 0 and 2, NDVI was a sensitive indicator of canopy closure. For cover with an LAI greater than 2, typical of dense shrubs and trees, NDVI was relatively insensitive to changes in canopy structure.

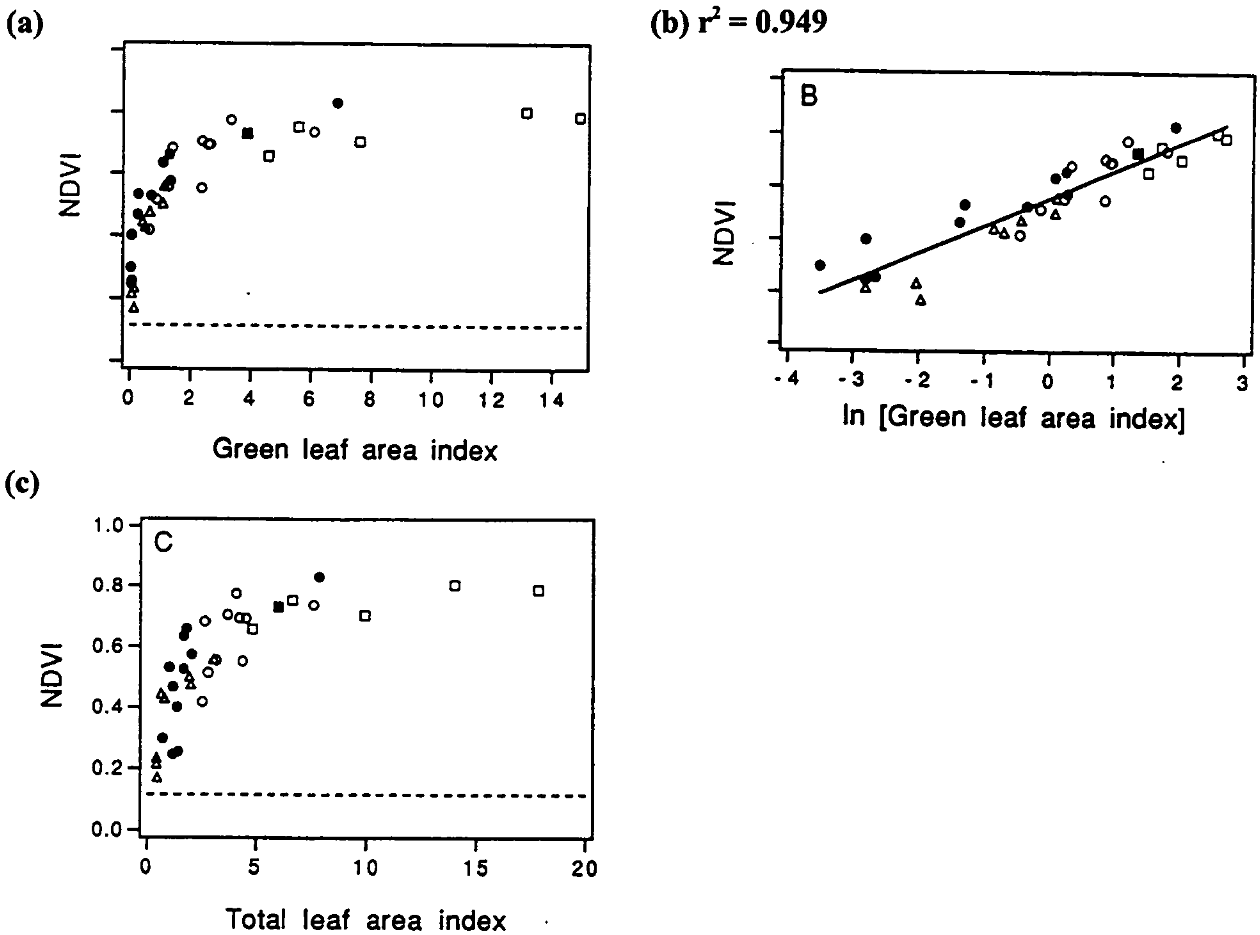


Figure 4-5. Relationship of NDVI to **(a)** green leaf area index and **(b)** ln green leaf area index, for three California vegetation types in two seasons. Green leaf area index was derived by multiplying the total LAI by the percentage of leaf area that was green as opposed to twigs, stems and dead material. **(c)** Relationship of NDVI to total LAI of three California vegetation types in two seasons. Reproduced from Gamon et al. (1995).

4.4 LEAF AREA DATA FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA GATHERED THROUGH INDIRECT MEASUREMENT METHODS

4.4.1 LAI Estimated Using NDVI

Wheat (*Triticum aestivum*) is among the crop species in which spectral analysis has been used to estimate leaf area index. Asrar et al. (1984) measured reflectance from the vegetation of wheat fields using a hand-held radiometer (Exotech Model 100A) at an altitude of 1.5 m above the ground surface. The normalized difference was calculated from the ratio of reflectance radiation from the canopy to reflectance radiation from a white barium sulfate panel that was measured concurrently as a reference. As shown in Figure 4-6, NDVI increased logarithmically from LAI values between 0 and 3 before reaching a plateau when LAI was between 3 and 7 (Fig. 4-6).

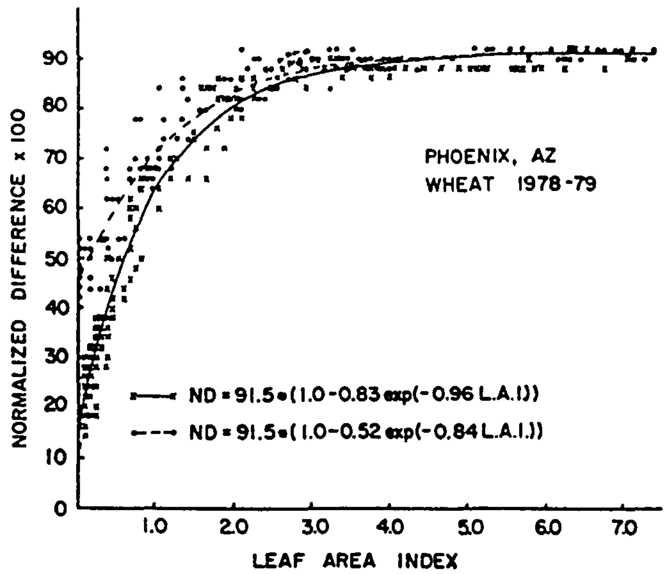


Figure 4-6. Relationship between NDVI and green leaf area for wheat. (Asrar et al. 1984).

To date, substantial information has been gathered showing the relationship between spectral reflectance and the LAI of temperate coniferous forests. Analysis of the NDVI calculated from LANDSAT-TM data showed that the LAI of coniferous vegetation across a latitudinal gradient in central Oregon could be accurately estimated up to a maximum LAI of 7-8 (Peterson et al. 1987) which is greater than the maximum described previously for woodland trees (LAI 2-3) and wheat (LAI 2-3). Other estimates have placed the red radiance asymptote at an LAI of 4-5 in coniferous forests (Spanner et al. 1990a) which is still somewhat greater than the saturation values expressed in broadleaf type vegetation. This may be due to differences in the spectral reflectance properties of needle-type leaves when compared to broader leaves. The size, shape and orientation of needle-leafed canopies may enhance diffusion of light within the canopy with attendant small differences in the intensity of scattered radiation in the red (Peterson et al. 1987). Broadleaf trees have different reflective properties than needle-leaf conifers to the extent that relationships developed between spectral indices and LAI for coniferous forests are not applicable to broadleaf forests (Spanner et al. 1994). Coniferous forest trees have received considerable attention when investigating the relationship between LAI and NDVI whereas trees in natural landscapes have not been thoroughly studied. In order to quantify leafmass in the SCOS97 modeling domain, greater attention should be placed on NDVI based estimates of LAI for natural Californian plant communities.

The fraction of photosynthetically active radiation absorbed by a plant crown or canopy (*f*PAR) is an indicator of how much significant radiation is intercepted by the leaf area of a plant crown, and is easy to interpret from remote sensing data. For example, Asrar et al. (1992) observed a linear relationship between the NDVI and *f*PAR for desert scrub vegetation in West Texas (Fig. 4-7). Application of this type of relationship may prove valuable for leafmass quantification in the SCOS97 domain perhaps by establishing correlations of *f*PAR to leafmass directly or through the asymptotic relationship with LAI that has been described in previous studies on vegetation (Law and Waring 1994a).

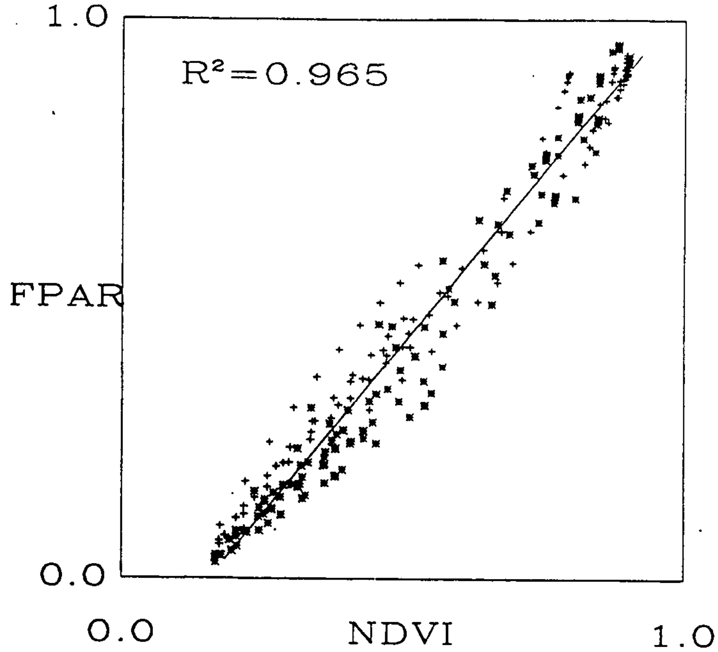


Figure 4-7. Fraction of absorbed PAR (*f*PAR) versus the normalized difference vegetation index (NDVI) (Asrar et al. 1994).

4.4.2 <u>LAI Estimated from the SR</u>

LAI was also estimated for coniferous forests in Oregon using the SR calculated from remotely sensed data that had been acquired using four remote-sensing instruments on three different aircraft platforms. Vegetation indices derived from either the Thematic Mapper Simulator (TMS), the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the Compact Airborne Spectrographic Imager (CASI) or the Spectron SE590 spectro-radiometer were compared with empirical LAI's that were calculated with data gathered from below-canopy measurements made using a ceptometer. The SR calculated from TMS (r^2 = 0.97) and AVIRIS (r^2 = 0.82) reached an asymptote at an LAI greater than 7. The SR calculated from CASI (r^2 = 0.92) and SE590 (r^2 = 0.95) continued to increase to a maximum LAI of 10.6, a result which is primarily illustrative of the finer spatial resolution of the CASI and SE590, but also indicates that the SR may have value as a predictor of LAI in dense canopies (Spanner et al. 1994).

Description of LAI in broadleaf canopies using the SR is limited in the literature; however, remote sensing was used to quantify the LAI of the understory shrubs bitterbrush (*Purshia tridentata*) and greenleaf manzanita (*Arctostapylos patula*) from within open ponderosa pine (*Pinus ponderosa*) plantations in Oregon (Law and Waring 1994a). The SR increased linearly as the LAI increased to approximately 8 in manzanita (r^2 = 0.86) and to approximately 9 in bitterbrush (r^2 = 0.74). Logarithmic transformation of the SR provided a similar estimation of LAI in California woodland trees to that provided by the NDVI (Gamon et al. 1995).

4.5 ALLOMETRIC ESTIMATES OF LEAFMASSES FOR CALIFORNIAN PLANT COMMUNITIES

Many of the literature leafmass and LMD values presented for Californian communities have been based on allometric relationships calculated from random sub-samples of the community being described, including some species from some environments in California as seen in Tables 4-4, 4-5 and 4-6. This information, although scarce, has value for field validation of leafmass estimates.

Because many California plant communities are shrubland, biomass or crown-area values are related to the stem diameter at 10 cm rather than DBH. Schlesinger and Gill (1978) calculated the linear allometric equation, seen in Table 4-4, for leafmass estimation of *Ceanothus megacarpus* in the Santa Ynez Mountains.

Table 4-4. Allometric relationship for leafmass of *Ceanothus megacarpus* from stem diameter (Schlesinger and Gill 1978). Diameter (X) measured at 10 cm, Y is grams dry leafmass.

Species, leafmass ln (Y) =	a	b	r^2
Ceanothus meagacarpus	1.04	2.17	0.72

Using the above equation, Schlesinger and Gill (1980) undertook a productivity study of 15 *Ceanothus* stands in the Santa Ynez Mountains after a fire. LMD values were calculated to be 228, 335 and 465 g m^{-2} at 5, 12 and 21 years after the fire, respectively.

A productivity study of a chaparral landscape in Echo Valley, San Diego County, California was done using allometric relationships compiled from mean values for a sub-sample of five mature specimens from each of eleven species (Table 4-5). Specimens were randomly selected from within the community.

Table 4-5. Field biomass data for a range of drought deciduous and evergreen trees and shrubs collected from Echo Valley, San Diego County, California (Mooney 1977). Values are based on mean values for five mature specimens per species. LMD was calculated for this report according to equation 2 (Section 3.1.4).

Species.	Height (m)	Diameter (m)	LAI (m^2 m^{-2})	Total leafmass (g)	LMD (g m^{-2})
Evergreen community					
Rhus ovata	1.48	1.81	1.95	1,187	460
Ceanothus leucodermis	1.75	1.11	2.11	282	290
Heteromeles arbutifolia	1.68	1.56	2.81	1,220	640
Arctostaphylos glauca	1.76	1.36	3.58	1,346	930
Adenostoma fasciculatum	1.16	0.98	3.09	221	290
Quercus agrifolia	2.08	1.49	3.61	805	460
Quercus dumosa	1.52	1.37	2.46	514	350
Ceanothus greggii	1.96	1.24	1.61	720	590
Drought-deciduous					
Encelia californica	0.90	0.79	0.73	22	50
Salvia mellifera	1.35	1.30	2.43	306	230
Artemisia californica	1.10	1.24	0.78	77	60

In another study, Gray and Schlesinger (1981) used dimension analysis (as described in section 3.2.5.3) to estimate productivity of a coastal sage scrub in the coastal mountains of Southern California. The stand was co-dominated by the drought deciduous shrubs *Salvia mellifera* and *Artemisia californica.* Two forms of an allometric equation based on equation 6 were developed for the co-dominants; a logarithmic form which best described the growth of *Salvia mellifera* and a cubic form to describe *Artemisia californica.* Included in the analysis was an estimate of leafmass density for the stand, as seen in Table 4-6.

Table 4-6. Mean biomass density and LMD values for a coastal sage stand in the Santa Monica Mountains, Los Angeles County based on random harvests of either entire plants or quadrats (Gray and Schlesinger 1981). LMD was calculated for this report.

Species	Total plant biomass ($g\ m^{-2}$)	LMD ($g\ m^{-2}$)
Salvia leucophylla	619.8	64
Artemisia californica	530.2	51
Eriogonum parvifolium	130.1	19
Yucca whipplei	116.3	33
Eriophyllum confertiflorum	10.3	2.4

4.6 ALLOMETRIC ESTIMATES OF LEAFMASSES FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA

In cases where site/species specific leaf area or leafmass data has not been documented it may be possible to estimate the leafmass of a site from allometric equations that exist for the same or related species in a different environment.

An assessment of leaf dry mass was made for a pine-oak plantation at St. Quercio, Castelporziano, Spain, using an integrated approach based on allometric relationships of stem diameter (X = DBH) to needle biomass (Y) as seen in equation 10:

$$Y = 2.31X + 1.03497 \tag{10}$$

The estimated needle biomass of *Pinus pinea* was 56 kg per tree. The leafmass of *Quercus ilex* was estimated to be 12.95 kg per tree based on equation 11:

$$Y = -0.003332 + 0.03797X + 0.004952X^2 \tag{11}$$

Using the variables D = diameter at approximately 1.0 cm from ground level, and H = height of the woody shrub, Elliot and Clinton (1993) derived allometric equations for estimating foliage biomass of successional species approximately 1 year after a clear-cut and burn in a forest in western North Carolina. Many of the relationships listed below were developed for young plants or foliage regrowth after fire and thus may have value for predicting leafmass in California shrublands after fire or disturbance.

Table 4-7. Equations for predicting foliage biomass for woody vegetation on southern Appalachian clear-cut and burned sites. Adapted from (Elliot and Clinton 1993).

Species	Equation	r^2
Acer rubrum	Foliage = 1.420 + 0.184 D^2H	0.943
Betula lenta	Foliage = 0.136 + 0.228 D^2H	0.755
Carya glabra	ln(Foliage) = 3.053 + 2.375 lnD	0.821
Castanea pumila	Foliage = 2.337 + 0.289 D^2H	0.966
Ilex ambigua	Foliage = 1.238 + 0.189 D^2H	0.622
Kalmia latifolia	Foliage = 4.267 + 0.006 D^2H	0.985
Liriodendron tulipifera	Foliage = 0.335 + 0.198 D^2H	0.998
Nyssa sylvatica	Foliage = 2.073 + 0.181 D^2H	0.913
Oxydendrum arboreum	Foliage = 3.981 + 0.102 D^2H	0.904
Quercus alba	Foliage = 1.510 + 0.421 D^2H	0.920
Quercus coccinea	Foliage = 6.025 + 0.195 D^2H	0.682
Quercus prinus	ln(Foliage) = 3.238 + 2.680 lnD	0.924
Quercus velutina	ln(Foliage) = 3.164 + 2.271 lnD	0.840
Rhus glabra	Foliage = 1.238 + 0.444 D^2H	0.974
Robinia pseudoacacia	ln(Foliage) = 2.748 + 2.667 lnD	0.965
Rubus argutus	Foliage = 0.297 + 0.469 D^2H	0.854
Sassafras albidium	Foliage = 2.152 + 0.408 D^2H	0.831
Vaccinium vacillans	Foliage = 0.787 + 0.025 D^2H	0.674

Considerable biogenic data has been compiled for the Oregon Transect Ecosystem Research (OTTER) project, which has integrated multi-sensor aircraft sensing of the transect (44-45° N) with a comprehensive, field gathered, data-set (Spanner et al. 1994). The project relied on allometric equations for much of the field verification for leaf biomass quantification. Although some of dominant species described by the equations do not grow in California, many do, and these species are listed in Table 4-8.

Table 4-8. Regression constants for the allometric equation ln(Y) = a + b X of species that grow in California. Calculated from allometric relationships with X = DBH that were derived in the Oregon transect. Compiled from data in Spanner et al. (1990a).

Species	*a*	*b*	r^2
Abies procera	-4.87	2.17	0.99
Acer macrophyllum	-3.77	1.62	0.87
*Artemisia tridentata** (*b* = basal area in cm)	43.0	9×10^{-6}	0.68
Juniperus occidentalis	-4.23	1.56	0.99
Pinus ponderosa	-4.26	2.09	0.84
Tsuga heterophylla	-4.13	2.13	0.96
Tsuga mertensiana	-3.82	1.97	0.97

Two species that grow in California are the trembling alder *Populus tremuloides* which is found in the Sierra Nevada Mountains, and Monterey pine, *Pinus radiata,* which grows in coastal regions. Table 4-9 provides allometric data that could be used to obtain leafmass estimates for these species.

Table 4-9. Allometric equation constants for the allometric equation ln(Y) = a + b X for leafmass estimation from X = DBH. Data for *Pinus radiata* were obtained in New Zealand and *Populus tremuloides* data were obtained in north central Wisconsin (Geron and Ruark 1988).

Species	*a*	*b*	r^2
Pinus radiata	-2.36	1.45	0.62
Populus tremuloides	-4.34	1.87	0.97

A complete study of canopy characteristics was made of forest trees in Oregon as part of the OTTER project mentioned earlier (Section 4.4.1), using both field and allometric data (Table 4-10). Leafmasses had been previously estimated from allometric equations as described by

Gholz et al. (1979) and leaf surface area was calculated using surface area to dry weight ratios (cited in Peterson et al. 1987).

Table 4-10. Leafmasses, and leaf area index data for coniferous trees in the Oregon transect. (Peterson et al. 1987).

Vegetation Zone	Dominant Tree Species	Stand	Overstory LAI	Underst. LAI	Total LAI	% LAI of Understory	Foliage Biomass (kg/ha)	Average DBH (cm)	Average Basal Area (m^2/ha)	Average Stem Density (trees/ha)	Average Stand Height (m)	Coefficient of Variation (LAI%)	Raw Near IR/Red	ATM Corr. Near IR/Red
Western coast range,		9	15.4	0.71	16.1	5	22,890	34.7	114.6	1115	44.2	9.01	3.379	8.1
	Western hemlock - sitka spruce	11	11.1	2.31	13.4	17	16,690	58.6	99.1	283	46.2	19.63	3.036	9.102
Zone 1	Sitka spruce	10	5.7	3.15	8.8	37	9770	55.6	120.5	410	48.8	16.02	2.786	8.054
Interior coast range,	Douglas fir	8	5.0	1.31	6.3	20	9980	50.5	62.5	220	43.9	62.86	2.634	6.104
Zone 2	Grand fir, Western hemlock	18	4.0	0.87	4.8	18	8650	45.5	44.2	180	37.8	32.92	2.824	5.958
Low-elev. west Cascades, Zone 3	Douglas fir	13	6.5	3.19	9.7	33	12,160	34.0	59.7	505	39.1	19.69	2.828	7.173
		17	6.7	2.23	8.9	27	13,590	35.2	62.1	493	37.9	8.54	2.443	6.186
Mid-elev. west Cascades, Zone 4	Western hemlock, Douglas fir Pacific silver fir, noble fir	12	10.9	0.55	11.4	5	19,860	24.0	95.1	1390	29.1	15.53	3.450	9.260
High Cascades summit,	Lodgepole pine	6	5.2	1.73	6.9	26	10,900	13.2	52.6	2620	8.8		2.383	5.065
	Subalpine fir	7	3.9	1.28	5.1	25	10,410	12.7	44.6	2668	8.8	34.71	1.927	3.750
Zone 5	Mountain hemlock	16	4.5	1.05	5.5	10	13,720	23.0	59.4	1045	18.2	7.45	2.080	4.373
East slope	White fir	5	5.1	0.02	5.2	0.4	13,210	12.5	46.9	2370	24.2	14.19	1.396	4.975
Cascades, Zone 6	Douglas fir, white fir	4	5.4	0.02	5.4	0.4	12,350	18.7	56.5	1525	19.7	19.81	2.722	5.570
	Ponderosa pine, Douglas fir	3	3.1	0.04	3.2	1.2	9170	30.1	33.0	373	24.4	30.31	1.558	1.919
	Ponderosa pine	14	3.1	0.20	3.3	6	9520	15.4	34.9	1085	28.0	33.33	1.870	2.626
		15	2.8	0.15	3.0	5	8280	114	35.4	1761	20.6	34.67	1.759	2.375
Interior high desert,	Western juniper	1	0.6	0.05	0.6	8	4260	77.4"	22.4	265	12.4	13.33	0.8066	0.773
Zone 7		2	0.6	0.05	0.7	7	4790	124.2"	26.0	154	17.6	32.86	0.8174	0.787

Allometric equations were used in the development of a model for estimating biogenic isoprene emissions from forests in the eastern United States. (Geron et al. 1994, Geron et al. 1997). Genus, species and DBH parameters recorded in the U.S. Department of Agricuture's Eastwide Database (EWDB) were used to estimate foliar masses calculated from crown diameter with the following two equations:

$$\text{Crnwd} = 0.47 + 0.166\ \text{DBH} \tag{12}$$

Equation 12 was used to describe coniferous plants and excurrent (undivided main stem or trunk) broadleaf genera (e.g. *Populus*),

$$\text{Crnwd} = 1.13 + 0.205\text{DBH} \tag{13}$$

whereas equation 13 described deliquescent (repeated division into branches) broadleaf genera (e.g. *Quercus*). Once crown diameter had been estimated, LMD was calculated for component species of the model domain from published values of 1500 g m^{-2} for *Abies*, *Picea*, *Tsuga* and *Pseudotsuga* genera, 700 g m^{-2} for *Pinus* and other coniferous genera and, 375 g m^{-2} for deciduous stands (Geron et al. 1994).

4.7 ALLOMETRIC ESTIMATES OF LEAF AREA FOR CALIFORNIAN PLANT COMMUNITIES

Harvesting and sampling components of plant productivity is usually a time consuming undertaking, particularly in natural environments. Ecologists or silverculturalists attempt to maximize the number of independent variables that are recorded in a particular study site, to enable as much understanding of the productivity of a stand as possible. Thus, many of the previously mentioned leafmass productivity studies also included measurement of leaf area components or LAI. For example, leaf area and LAI estimates based on allometric relationships were calculated for a range of drought deciduous and evergreen trees and shrubs collected from Echo Valley, San Diego County, California, and are presented in Table 4-5 as reported by Mooney (1977).

4.8 ALLOMETRIC ESTIMATES OF LEAF AREA FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA

As described in section 4.7, allometric estimation of the leaf area of a natural or cultivated plant community may often be carried out concurrently with leafmass or productivity analysis. Table 4-10 shows leaf area and LAI estimates for forest trees of the Oregon transect region described by Peterson et al. (1987).

4.9 LEAFMASS DATA OF CALIFORNIAN PLANT COMMUNITIES OBTAINED THROUGH DIRECT MEASUREMENT METHODS

4.9.1 Leafmass Measurements of Chaparral Communities

As mentioned direct leafmass quantification methodology usually involves harvest of part or all of an entire tree or shrub. This is often the first step in dimension analysis or the allometric estimation of leafmass for a plant community. Tables 4-11, 4-12, and 4-13 present raw biometric data for common chaparral shrubs from three locations in California. These data of this type have potential value for leafmass estimation models for both validation and site/species specific input parameters, for example, LMD or SLW.

Table 4-11. Leafmass per canopy area (g m^{-2}) of chamise (*Adenostoma fasciculatum*) at the Echo Valley International Biological Program site San Diego County, California. (Mooney and Rundel 1979).

Species	Total plant biomass per area of canopy (g m^{-2})	LMD (g m^{-2})
Adenostoma fasciculatum	2127.0	360

Table 4-12. Summary of measurements for chaparral species at Echo Valley (Miller et al. 1977). Measurements are totals for individuals of the selected species. Our calculated values for LMD are also presented.

Species	Height (m)	Crown Diameter (m)	Crown Area (m^2)	Crown volume (m^3)	Leafmass (g)	Calculated LMD ($g\ m^{-2}$)
Ceanothus greggii	1.10	0.40	0.13	0.14	97.0	750
	0.71	0.35	0.10	0.07	12.0	120
Adenostoma fasciculatum	0.40	0.25	0.05	0.012	-	-
	0.54	0.15	0.018	0.001	-	-
	0.95	0.93	0.67	0.63	-	-
Heteromeles arbutifolia	1.79	0.75	0.45	0.80	79.0	180
Arctostaphylos glauca	1.05	1.00	0.78	0.82	215.0	280

Table 4-13. Specific leafmass and leafmass per area of canopy of a scrub oak (*Quercus dumosa*) dominated site in Bear Valley, San Diego, California (Kummerow and Mangan 1981). Our calculated values for LMD are also presented.

Species	Leaf dry weight (g)	Canopy area (m^2)	LMD ($g\ m^{-2}$)
Quercus dumosa	528	4.06	130
	335	5.56	65
Ceanothus greggii	430	0.94	460
	1,000	0.81	1,200
Adenostoma fasciculatum	1,784	2.56	700
Cercocarpus betuloides	128	0.37	350
Eriogonum fasciculatum	336	1.41	240

On a ground area basis, the overall LMD of all species in 140 m^2 of mixed chaparral at Echo Valley was 440 g m^{-2}. In 70 m^2 of chamise chaparral the mean LMD of all the species present was 310 g m^{-2} (Miller 1981).

4.9.2 Urban Trees

Leafmass per unit area of crown projection (g m^{-2}) for a deciduous broadleaf forest in the eastern U.S. was taken as 375 g m^{-2} in Geron et al. (1994). In a model evaluation for southeastern U.S. bottomland forests, leafmass per unit ground area for a closed-canopy forest was estimated to be 416 g m^{-2} using a litterfall method (Geron et al. 1997).

As seen in Table 4.14, LMD for the trees from urban landscapes in Bakersfield, CA, ranged from 150 to 3200 with a mean of 940 g m^{-2} (Winer et al. 1998), higher than LMD reported for forests. Although the smaller trees, such as the purpleleaf plums (Nos. 1-4, 10-13) had LMD's of the same order of magnitude as the forest (Geron et al. 1997), the columnar trees (Nos. 5-8) had values ranging from 1200-3200 g m^{-2}, about three to eight times higher than found in the forest. Larger trees, such as the eucalyptus (No. 14) and blackwood acacia (No. 18) had values of 2080 and 2600 g m^{-2}, respectively. The Modesto ash (No. 15), the fruitless mulberry (No. 16) and the sweetgum (No. 17) had values of 630, 990, and 720 g m^{-2}, respectively, about 50 - 100 % higher than the forest situation of Geron et al. (1997).

These results indicate the potential of urban trees to contain relatively more leafmass than trees in a continuous canopy environment. Lack of nearby competition for light and availability of water and nutrients (many urban residents add fertilizer nutrients to turf and landscape areas) may allow trees to contain many more leaves, with more corresponding leafmass, than trees in forested situations.

Table 4.14. Comparison of leafmass per unit area, of crown projection for urban shade trees as presented in Winer et al. (1998).

Tree No	Crown diameter (m)	Crown projection (m^2)	Measured leafmass (g)	LMD ($g\ m^{-2}$)
1996 trees				
1	3.0	7.3	4330	590
2	2.7	5.9	4110	700
3	4.0	12	6850	560
4	3.4	8.8	5390	610
5	2.1	3.6	4320	1200
6	2.7	5.9	8020	1400
7	1.8	2.6	5200	2000
8	3.0	7.3	23200	3200
9	2.4	4.7	3200	680
1997 Trees				
10	4.6	17	2560	150
11	2.6	5.4	1960	360
12	4.6	16	4350	260
13	4.6	16	3340	200
14	7.4	43	89600	2100
15	8.6	58	36500	630
16	10.4	85	84700	990
17	3.8	11	8010	720
18	5.4	23	61000	2600
19	2.6	5.3	1530	290
20	4.4	15	2920	190
21	3.2	8.2	1680	200

4.10 LEAFMASS DATA FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA OBTAINED THROUGH DIRECT METHODS

The development of BHC emissions inventories (Lamb et al. 1987, Guenther et al. 1994, Geron et al. 1994, and Guenther et al. 1995) have used direct leafmass values from some common sources. Table 4-17, for example, gives leafmass values reported by Lieth and Whittaker (1975) that were used in the emissions inventory of Lamb et al. (1987). For further explanation see section 4.13.

4.11 LEAF AREA DATA FOR CALIFORNIAN PLANT COMMUNITIES OBTAINED THROUGH DIRECT METHODS

The study of Winer and co-workers compared measured leaf areas of two plants to calculated values. All the leaves of one tree No. 7, the *Eucalyptus grandis*, were measured with a leaf area meter as described in section 3.2.6. The value for total leaf area for this tree calculated using LA = SLA x LM was 44 m^2, 94% of the measured leaf area of 47 m^2. The crown projection of the tree was 2.6 m^2 with a corresponding LAI of 17.9, higher than expected for shade trees; however, columnar tree forms, such as this *Eucalyptus* (height of 14 m, radius of 1.8 m) may have a higher LAI than broader forms, such as ellipsoids or spheres, containing the same volume.

All leaves of a *Rhus ovata* (sugar bush) shrub, a plant with a form approximated by a rectangular prism, were removed, measured for leaf area, dried, and weighed (Winer et al. 1998). The plant measured 2.4 x 2.4 x 1.8 m in length, width, and height, respectively, with a calculated volume of 11 m^3. The measured leafmass of 14,400 g was multiplied by the experimentally determined factor of 3.1×10^{-3} m^2 g^{-1} for this species to give a calculated leaf area of 45 m^2, which was 96 % of the measured leaf area of 47 m^2. Thus, the leaf areas that were calculated by using leafmass and SLW for these two urban species were within 6 % of the measured. Using the measured leaf area and projected area of crown coverage the LAI for this *Rhus ovata* shrub was 7.6.

Leaf area indices are not easily measured in chaparral plant communities, in which most plants contain many small leaves, often appressed to the stems. Ratios of leaf area : leaf weight were used to convert from leaf dry weight to leaf area in a study of chaparral shrubs at Echo Valley, California (Table 4-15). Values of 0.22 to 1.09 were lower than those suggested by Lieth (Table 4-16) (Miller 1981).

Table 4-15. Calculated LAI of communities on the pole facing slopes and ridgetops at Echo Valley California. From Miller (1981)

Species	LAI (m^2 m^{-2}) April 1978	May 1979
Quercus dumosa	0.52	0.32
Arctostaphylos glauca	1.09	1.04
	0.52	- -
Ceanothus gregii	0.63	0.90
	0.49	- -
Adenostoma fasciculatum	0.22	- -

4.12 LEAF AREA DATA FOR PLANT COMMUNITIES OUTSIDE CALIFORNIA OBTAINED THROUGH DIRECT METHODS

Leaf area data from many sources has been compiled for many of the worlds community types by Lieth and Whittaker (1975). of which a proportion was gathered by direct measurement (Table 4-16).

Table 4-16. Leaf area index data for selected important global plant communities (Lieth and Whittaker, 1975).

Vegetation Unit	LAI or assimilating surface (m^2 m^{-2})
Tropical rain forest	6 - 17
Raingreen forest	6 - 10
Summergreen forest	3 - 12
Chaparral	4 - 12
Warm temperate mixed forest	5 - 14
Boreal forest	7 - 15
Woodland	4
Tundra	0.5 - 1.3
Tropical grassland	1 - 5
Temperate grassland	5 - 16
Cultivated land / annual crops	4 - 12
Swamp and marsh	11 - 23

4.13 INTEGRATED LEAFMASS ESTIMATES FOR PLANT COMMUNITIES

A bottom-up model, integrating land-use and landcover maps with leafmass constants and BHC emission rates, was used to create comprehensive emissions inventories such as those of Lamb et al. (1987), Guenther et al. (1994), Geron et al. (1994) and Benjamin et al. (1998).

Landcover and plant community databases used in these models include: 1) the U.S. Forest Service (USFS) Eastwide Forest Inventory Database (EFID) (Geron et al. 1994), 2) a gridded landcover database covering the contiguous United States compiled by the EROS Data Center (Guenther et al. 1994), and 3) approximate biome composition values derived from the literature (Lamb et al. 1987). The (GAP) databases have been suggested as sources of landcover for California. Multiplying the surface area of each landcover class by LMD results in an estimate of leafmass. The above inventories have used leafmass constants from a variety of literature sources. For example, Lamb et al. (1987) used data provided by Lieth and Whittaker (1975) to calculate leafmass values (kg ha^{-1}) for five vegetation classifications and fifteen agricultural crop types (Table 4-17).

Lieth and Whittaker (1975) is the historical antecedent for many subsequent leaf biomass calculations and derivations. This source publication details a range of biomass data published by various authors who used 1) harvest methods (Table 4-17), 2) estimative ratios, 3) allometric methods (Table 4-18), and 3) dimension analysis (Table 4-19) to quantify leafmass, often on a continental or global scale.

Table 4-17. Net primary productivity and biomass values of plant components for selected communities obtained by harvest methods (Whittaker and Marks (1975), cited in Lieth and Whittaker (1975)).

Communities and species	Total (g/m^2/year)	Stem and branch wood (%)	Leaves and twigs (%)	Fruit and flower (%)	Root system: Rhizomes (%)	Root system: Roots (%)	Reference
Wheat	294	—	53.0	29.4	17.6		Filzer (1951)
Barley	242	—	46.6	35.5	17.9		Filzer (1951)
Zea mays (maize, high-yield)	1935	16.8	17.1	61.4	4.6		Lieth (1968)
Helianthus annuus (sunflower)	3213	37.5	17.6	36.0	8.9		Lieth (1968)
Arctic tundra, all species							Rodin and Bazilevich (1967)
Biomass (g/m^2)	500	10	20	—	70.		
Production	100	2	28	—	70.		
Populus (7-year-old poplars)							Lieth, Osswald, and Martens (1965)
Biomass (g/m^2)	467	61.2	18.8	—	20.0		
Production	226	48.6	36.7	—	14.7		
Blanket bog							Forrest (1971)
Biomass (g/m^2)							
Calluna vulgaris	1547	28.4	19.4	—	—	52.2	
Eriophorum vaginatum	482	—	72.2	0.2	11.2	16.4	
Empetrum and others	93	28	18	—	—	(54)	
Sphagnum, other bryophytes	103	—	100	—	—	—	
Lichens	43	—	100	—	—	—	
Total:	2268	20.5	35.8	0.1	43.6		
Net production							
Calluna vulgaris	351	10.8	37.0	—	52.2		
Eriophorum vaginatum	221	—	78.2	1.4	8.6	11.8	
Empetrum and others	26	12	38	—	—	(50)	
Sphagnum, other bryophytes	47	—	100	—	—	—	
Lichens	3	—	100	—	—	—	
Total:	648	6.3	56.0	0.5	37.2		

Table 4-18. Mean biometric values of some temperate tree species based on sample harvests at three locations (see footnote of table), (Whittaker and Marks (1975), cited in Lieth and Whittaker (1975)).

1 Forest stand measurements	2 Pygmy conifer oak scrub, mature SCM-52	3 Pine–oak woodland, mature SCM-51	4 Oak–pine forest, young BNL-60	5 Mixed deciduous forest, young HB-71	6 Cove forest, mature GSM-23	7 Tulip poplar forest, young GSM-22	8 Spruce–fir forest, mature GSM-29
Stems (> 1 cm/0.1 ha)	57	278	185	129	145	182	84
Canopy height (m)	3	10	9	20	36	27	25
Weighted mean tree height (m)	2.7	7.5	7.6	16.9	34.0	22.4	21.3
Weighted mean tree age (years)	65	46	43.3	124	222	29	161
Stem basal area, m^2/ha	4.3	26.0	15.6	26.3	54.2	34.2	55.6
Mean wood radial increment (mm/year)	0.28	0.39	0.86	1.12	0.73	2.28	0.96
Basal area increment (m^2/ha/year)	0.034	0.238	0.356	0.464	0.445	1.325	0.54
Stem volume, m^3/ha	9.5	99.4	75.4	194	720	310	650
Stem-wood volume (m^3/ha)	7.1	76.1	59.4	176	650	275	590
Parabolic volume estimate (m^3/ha)	6.6	97.8	70	204	851	346	547
Estimated volume increment (cm^3/m^2/year)	4.6	66.2	159	379	547	1444	534
Biomass accumulation ratio (g/g)	10.1	25.5	7.7	14.4	45.6	9.1	34.7
Stem-surface area (m^2/m^2)	0.03	0.27	0.30	0.41	0.6	0.6	0.6
Conic stem-wood surface	0.02	0.17	0.21	0.34	0.50	0.51	0.52
Branch-surface estimate (m^2/m^2)	0.26	1.7	1.2	1.98	1.6	2.2	—
Leaf-area ratio (m^2/m^2)	2.0	3.7	3.8	6.1	6.2	7.4	14.8
Chlorophyll in leaves (g/m^2)	1.0	1.8	1.9	2.4	2.2	2.1	3.0
Light penetration (%)							
Through trees	91.2	42.7	13.0	—	0.9	0.9	3.8
shrubs	12.7	34.2	6.0	—	0.8	0.7	2.6
herbs	12.7	34.0	5.9	—	0.2	0.7	1.4
Aboveground biomass (dry g/m^2)							
Trees	1530	11,350	6403	16,085	50,000	22,000	34,000
Shrubs	341	17	158	15	7	2	96
Herbs	3.1	3.4	2.2	4	38	1.5	22
Thallophytes	4.4	0.2	tr.	tr.	20	4.9	40
Tree percentage:							
stem wood	46.5	54.1	54.8	65.0	77.4	73.5	76.3
stem bark	12.7	15.5	12.7	6.8	7.0	6.9	7.8
branches	31.4	24.6	24.6	26.3	14.8	17.7	11.9
leaves and twigs	9.4	5.8	7.9	1.9	0.8	1.9	4.0
Aboveground net productivity (dry g/m^2/year)							
Trees	65	435	796	898	1050	2400	980
Shrubs	117	6.7	61	4.3	1.5	7	22
Tree percentage:							
stem wood	10.1	17.3	18.7	28.5	38.1	42.0	38.0
stem bark	2.6	4.6	3.3	3.0	4.5	5.1	4.4
branches	19.3	20.7	24.3	29.7	19.7	26.2	18.1
leaves and twigs	61.8	54.0	50.9	35.7	35.5	22.1	36.9
fruits	6.2	3.4	2.8	3.1	2.2	4.6	2.6

The abbreviations, for example SCM-52, refer to the sample location as follows: Santa Catalina Mountains, Arizona (SCM-52), Brookhaven National Laboratory, New York (BNL-60), Hubbard Brook, New Haven (HB-71) and Great Smoky Mountains, Tennesee (GSM-23).

Table 4-18 (above) provides a comprehensive analysis of a range of biometric dimensions (including tree biomass g m^{-2}) for the temperate forest types listed. For use in BHC emissions inventories, the relevant values are the total dry tree biomass and the percentage of the tree dry weight that is composed of oLMDer leaves and a component described as currently growing leaves and twigs.

Table 4-19. Summary descriptions of seven temperate-zone forests and woodlands. The Brookhaven and Hubbard Brook values are based on intensive studies; the Santa Catalina samples used aboveground dimension analysis and the Smokies samples are based on estimative ratios and regression analysis. (Whittaker and Marks (1975), cited in Lieth and Whittaker (1975)).

1 Mean dimension	2 *Acer spicatum*	3 *Quercus alba*	4 *Acer saccharum*	5 *Quercus robur*	6 *Pinus rigida*	7 *Picea rubens*
Location	HB	BNL	HB	LS	BNL	HB
Number of trees in sample	15	15	14	11	15	15
Breast-height diameter (cm)	4.8	9.3	25.9	43.5	15.2	14.5
Height (m)	6.3	7.3	17.9	19.7	8.9	9.1
Age (years)	24	33	72	149	41	87
Bark thickness, breast height (mm)	1.6	5.67	6.3	16.4	12.05	2.8
Wood radial increment (mm/year)	0.53	0.64	1.13	1.59	1.08	0.72
Stem volume (dm^3)	11.7	42.1	780	1490	125.1	144
Parabolic volume estimate (dm^3)	10.5	40.7	980	1235	114.1	152
Stem-wood volume increment (dm^3/year)	0.48	1.41	12.9	24.2	3.41	4.41
Estimated volume increment (dm^3/year)	0.31	1.00	13.2	19.5	2.10	2.74
Stem surface (m^2)	0.72	1.60	10.16	—	3.17	3.29
Conic stem surface estimate (m^2)	0.59	1.26	9.14	—	2.33	2.62
Aboveground biomass (dry kg)	8.7	36.6	703	987.8	85.5	87.5
stem wood (%)	54.1	54.6	59.6	64.6	54.3	57.0
stem bark	8.0	17.1	7.5	7.3	12.3	8.0
branches	35.0	20.2	31.4	25.7	22.3	27.8
older leaves	—	—	—	—	5.9	6.3
curr. twigs and leaves	2.9	7.9	1.5	2.4	5.2	0.8
Aboveground production (dry kg/year)	0.86	4.9	30.9	42.6	9.84	3.38
stem wood (%)	27.2	15.4	26.3	28.5	18.6	53.0
stem bark	4.2	4.8	3.3	1.9	4.6	6.3
branches	38.0	24.4	33.6	21.2	23.0	14.2
curr. twigs and leaves	29.1	51.6	35.6	48.4	49.5	22.6
fruits	1.5	3.4	1.2	—	4.1	3.9
Biomass accumulation ratio	10.2	6.9	22.8	23.2	8.7	25.8
Aboveground production ratio to:						
Estim. vol. increment (g/cm^3)	2.77	4.91	2.33	2.18	4.68	1.23
Leaf-blade area (g/m^2)	175	216	177	111	155	56

* Based on sets of sample trees at Hubbard Brook, New Hampshire (HB, Whittaker *et al.* 1974), Brookhaven National Laboratory, New York (BNL, Whittaker and Woodwell 1968), and Linnebjer, Sweden (LS, Andersson 1970, 1971). The samples include two sets of small deciduous trees (columns [2] and [3]), two of small conifers ([6] and [7]), and two of medium-sized deciduous trees ([4] and [5]). Some contrasts between the *Pinus rigida* and *Picea rubens* samples reflect the growth of the former in full sunlight in and above the canopy of small oaks versus growth of the latter in the shade beneath a deciduous canopy.

Lamb et al. (1987) integrated the foliage biomass data from Table 4-19, above (and additional biomass data from the National Academy of Sciences, 1975), with approximate biome composition values when calculating vegetation biomass estimates for the continental United States (Table 4-20).

Table 4-20. Vegetation biomass estimates (g m^{-2}) for the five vegetation classifications and fifteen agricultural crop types used for constructing a national BHC emissions inventory (Lamb et al. 1993).

Type	Emission category			
	Deciduous			Coniferous
Natural vegetation	High isoprene	Low isoprene	No isoprene	
Oak forest	1850	600	600	700
Other deciduous forest	600	1850	900	1350
Coniferous forest	390	260	260	5590
Scrubland	300	450	2100	150
Grassland	250	375	375	500

Agricultural crops	Yield (1000 Mt)	Area harvested (1000 ha)	Dry biomass/ economic yield	Biomass density (Mt ha^{-1})
1 Corn	266,822	31,460	1.9	16.1
2 Hay	118,642	24,388	1.1	5.4
3 Alfalfa	67,858	10,471	—	32.5
4 Soybeans	46,885	24,851	3.9	7.4
5 Wheat	43,669	21,892	3.7	7.4
6 Sorghum	21,433	5377	—	31.8
7 Potatoes	13,639	475	0.6	17.2
8 Barley	9137	3536	5.0	12.9
9 Oats	7258	3989	4.1	7.5
10 Rice	6003	1200	—	10.5
11 Cotton	2329	5131	3.5	1.6
12 Peanuts	1608	567	2.6	7.4
13 Tobacco	857	383	2.2	4.9
14 Rye	189	107	—	24.3
Miscellaneous crops	25,772			

The above leafmass estimates and the primary source data used to derive the values, have been used in many other BHC emissions inventories (Lamb et al. 1993; Geron et al. 1994, Geron et al. 1995). Other sources of foliar density have been used to establish BHC emissions inventories. For example, Guenther et al. (1994) derived a range of LMD values for the range of species contained within six broad woodland landscapes in the contiguous United States (Table 4-21). This data set was developed using the 1.1-km resolution land-cover database compiled by Loveland and coworkers (1991) at the EROS Data Center (EDC). The EDC database contains a total of 167 land-cover types of which 91 contain woodlands that could be categorized into the six broad categories used below. The method of Guenther et al. (1994) used the integrated vegetation index (IVI) reported by Loveland et al. (1991) as a coefficient for estimating the NPP of each woodland type. The estimates of NPP associated with each land-cover category were then used to interpolate between the upper and lower bound estimates of LMD reported by Box (1981) (shown in Table 4-22), for each of the six forest categories (Table 4-21). Using this method, Guenther et al. (1994), went on to complete a more specific BHC emissions survey of a range of tree species that grow in eastern Georgia and western Alabama. The total LMD for these woodlands have been summed here to 370 g m^{-2} for the species surveyed in eastern Georgia and 480 g m^{-2} for those of western Alabama.

Table 4-21. Foliar mass ranges estimated by Guenther et al. (1994) and the percentage of land area covered by each forest type based on a total area 3.8 x 10^6 km^2 of tree-covered surface area in the contiguous USA (Based on Loveland et al. 1991 cited in Guenther et al. 1994).

Forest category	Cover (%)	LMD (g m^{-2})
Deciduous forest	11	300-500
Coniferous forest	15	400-800
Mixed forest	29	300-700
Wetland forest	1	350-600
Scrub woods	12	200-350
Mixed woods/crop	32	600-1000
All	100	200-1000

Box (1981) details foliar biomass data for some major vegetation categories of the world. The estimates are based on a map of vegetation distribution patterns and components of net primary production reported by Lieth and Box (1972), cited in Box (1981). The map was made from a fairly small data set in which annual NPP and biomass components were related to the most important climatic determinants of a region, mainly mean annual temperature and average annual precipitation. A correlation model for components of NPP (leaf area, foliar mass etc.) was developed using harvest data which was then extrapolated using a large climatic data base. Table 4-20 shows the value ranges for the biomass components covered by the model. Input data was published primarily by the International Biological Program (IBP) cited in the National Academy of Science report (1975) as well as other sources (Box, 1981).

Table 4-22. Production and biomass ranges for world vegetation types. The values are a summary of data reported by many authors primarily through the International Biological Program (Box, 1981).

	Net Primary Productivity ($g/m^2/yr$)	Standing Biomass (kg/m^2)	Leaf Area Index (m^2/m^2)	Leaf Biomass (kg/m^2)
Tropical Rainforest	1000-3500	6-80	6-16	0.2-2.0
Raingreen Forest	1000-3000	6-60	5-10	0.3-1.5
Warm Temperate Forest	600-2500	6-100	5-14	0.5-1.4
Mediterranean Forest/Woodland	500-1500	6-50	4-12	0.4-1.2
Summergreen Forest	500-2500	6-60	3-12	0.2-0.8
Temperate Rainforest	600-2000	20-200	6-40	0.7-2.5
Boreal Forest	400-1500	6-40	7-15	0.5-1.3
Woodlands	300-1000	2-20	1-6	0.1-0.5
Tropical Savanna	200-2000	0.2-15	1-8	0.1-2.0
Temperate Grassland	200-1500	0.2-5.0	1-10	0.1-1.0
Semi-desert Scrub	10-250	0.1-4.0	0.1-2.0	0.02-1.0
Tundra & Alpine	10-400	0.1-3.0	0.5-3.0	0.01-1.0
Deserts (extreme)	0-10	-	-	-
Cultivated Land	100-4000	0.4-12.0	1-10	0.1-1.0
Swamp and Marsh	800-6000	3-50	5-14	0.5-1.5
Freshwater Bodies	100-1500	-	-	-

5.0 SUMMARY TABLES

Table 5-1. Leafmass density data (g m^{-2}) of plant communities available for modeling biogenic hydrocarbon emissions from Californian landscapes.

Community Type	Location	LMD (g m^{-2})	Reference
Deciduous forest	Eastern Georgia	371	Guenther et al. (1994)
	Western Alabama	479	Guenther et al. (1994)
	Contiguous USA	300-500	Guenther et al. (1994)
	Global estimate	200-800	Box (1981)
	New Hampshire	305	Lieth and Whittaker
	Japan	270-390	(1975)
	Unspecified	260	N.A.S. (1975)
	Atlanta, Georgia	470	N.A.S. (1975)
	Contiguous USA	470	Geron et al. (1995)
	Eastern United States	470	Lamb et al. (1993)
	Southeastern	375	Lamb et al. (1987)
	bottomland forest	416	Geron et al. (1994)
	Japan	200-300	Geron et al. (1997)
			Parker (1995)
Coniferous forest	Unspecified	1040	Golley (1972)
	Oregon transect	828-2289	Peterson et al (1987)
	Atlanta, Georgia	650	Geron et al (1995)
	Contiguous USA	650	Lamb et al (1987, 1993)
	Global estimate	500-1300	Box (1981)
	Eastern United States	1500	Geron et al (1994)
	Japan	900-1500	Parker (1995)
Deciduous conifers	Japan	200-300	Parker (1995)
Pine forest	Unspecified	640	N.A.S. (1975)
	Oregon transect	828-1090	Peterson et al (1987)
	Castelporziano, Spain	600-900	Seufert et al (1997)
	Eastern United States	700	Geron et al (1994)
	Japan	500-600	Parker (1995)
Oak woodland	Atlanta, Georgia	375	Geron et al (1995)
	Contiguous USA	375	Lamb et al (1987, 1993)
	Castelporziano, Spain	338-600	Seufert et al (1997)
	Global	100-500	Box (1981)

Table 5-1. (Continued)

Community Type	Location	LMD ($g\ m^{-2}$)	Reference
Scrubland			
– Chaparral, Evergreen	California	503	Mooney (1977)
	Chile	348	Mooney (1977)
– Drought deciduous	California	1133	Mooney (1977)
– Coastal sage	California	34	Gray and Schlesinger
– Scrub Oak (range)	California	11-1523	(1981)
(mean)	California	490	Kummerow and Mangan
	Atlanta, Georgia	435	(1981)
	Contiguous USA	435	Geron et al (1995)
	Castelporziano, Spain	612-788	Lamb et al (1987, 1993)
– Semi-desert	Global	20-100	Seufert et al.(1997)
– Mixed chaparral	California	440	Box (1981)
– Chamise chaparral	California	310	Miller (1981)
			Miller (1981)
Grassland	Atlanta, Georgia	150	Geron et al (1995)
	Contiguous USA	150	Lamb et al (1987, 1993)
	Global	100-500	Box (1981)
Agricultural crops	Contiguous USA (	490-3250	Geron et al. (1995) Lamb et al. (1987, 1993)
	Global	100-1000	Box (1981)
Urban Trees	California	150-3200	Winer et al. (1998)
Evergreen broadleaf	Global	700-2500	Box (1981)
	Japan	700-1100	Parker (1995)
Desert	Oregon high desert	426-479	Peterson et al (1987)
Tropical forests	Thailand	380-820	
	Puerto Rico	540-810	N.A.S. (1975)
	Brazil	910	N.A.S. (1975)
	Panama	350-1130	N.A.S. (1975)

Table 5-2. Leaf area density data (g m^{-2}) for plant communities.

Scientific Name	Location	LMD (g m^{-2})	Reference
Conifers			
Abies concolor	Oregon transect	1235-1321	Peterson et al. (1987)
Abies grandis	Oregon transect	865	Peterson et al. (1987)
Abies spp.	Japan	990-1600	N.A.S. (1975)
Chamaecyparis obtusa	Japan	1400	N.A.S. (1975)
Cryptomeria japonica	Japan	1960	N.A.S. (1975)
Juniperus occidentalis	Oregon transect	426-479	Peterson et al. (1987)
Picea sitcensis	Oregon transect	977-1669	Peterson et al. (1987)
Pinus contorta	Oregon transect	1090	Peterson et al. (1987)
Pinus ponderosa	Oregon transect	828-952	Peterson et al. (1987)
Pinus spp.	Japan	500-600	Box (1981)
Pseudotsuga menzeisii	Oregon transect	998-1986	Peterson et al. (1987)
Tsuga heterophylla	Oregon transect	1986-2289	Peterson et al. (1987)
Broadleaf deciduous			
Alnus spp.	Japan	280	N.A.S. (1975)
Betula spp.	Japan	220	N.A.S. (1975)
Fagus crenata	Japan	380	N.A.S. (1975)
Populus spp	Japan	380	N.A.S. (1975)
Broadleaf evergreen			
Acacia spp.	Japan	570	N.A.S. (1975)
Cyclobalanopsis myrsinaefolia	Japan	880	N.A.S. (1975)
Chaparral / Mediterranean			
Adenostoma fasciculatum	California	290	Mooney (1977)
Adenostoma fasciculatum	California	272	Kummerow and Mangan (1981)
Arctostaphylos glauca	California	934	Mooney (1977)
Arctostaphylos glauca	California	276	Miller et al. (1977)
Artemisia californica	California	51	Gray and Schlesinger (1981)
Artemisia californica	California	64	Mooney (1977)
Ceanothus greggii	California	595	Mooney (1977)
Ceanothus greggii	California	746	Miller et al. (1977)
Ceanothus greggii	California	120	Miller et al. (1977)
Ceanothus greggii	California	1523	Kummerow and Mangan (1981)
Ceanothus greggii	California	495	Kummerow and Mangan (1981)

Table 5-2. (Continued)

Scientific Name	Location	LMD ($g\ m^{-2}$)	Reference
<u>Chaparral / Mediterranean (cont.)</u>			
Ceanothus leucodermis	California	294	Mooney (1977)
Cercocarpus betuloides	California	935	Kummerow and Mangan (1981)
Encelia californica	California	45	Mooney (1977)
Eriogonum parvifolium	California	20	Gray and Schlesinger (1981)
Eriogonum fasciculatum	California	168	Kummerow and Mangan (1981)
Eriophyllum confertiflorum	California	2.5	Gray and Schlesinger (1981)
Heteromeles arbutifolia	California	638	Mooney (1977)
Heteromeles arbutifolia	California	175	Miller et al. (1977)
Quercus agrifolia	California	462	Mooney (1977)
Quercus dumosa	California	349	Mooney (1977)
Quercus dumosa	California	32	Kummerow and Mangan (1981)
Quercus dumosa	California	11	Kummerow and Mangan (1981)
Quercus petraea	Castelporziano, Spain	160	Lenz et al. (1997)
Quercus pubescens	Castelporziano, Spain	92	Lenz et al. (1997)
Quercus phylliraeoides	Japan	860	N.A.S. (1975)
Rhus ovata	California	460	Mooney (1977)
Salvia mellifera	California	230	Mooney (1977)
Salvia leucophylla	California	230	Gray and Schlesinger (1981)
Yucca whipplei	California	33	Gray and Schlesinger (1981)

6.0 SUMMARY AND CONCLUSIONS

Leafmass data may be gathered through direct measurement methods, allometric measurement methods or indirect measurement methods, in order of precision. However with increased precision comes additional cost in time and labour.

6.1 DIRECT MEASUREMENTS OF LEAFMASS DENSITY

Leafmass is most accurately determined by a direct measurement method; specifically, harvesting all the leaves of a tree crown or plant canopy and measuring the total dry weight. This method is extremely time-consuming and labor-intensive, and for this reason very little direct leafmass or leaf area data has been collected for a majority of the plants in the SCOS97-NARSTO modeling domain, a situation which is confounded by the lack of economically significant species that grow within. We believe this report has collated most of the leafmass data that has been collected through direct harvest methods which is currently available for natural arid-zone California species.

As reported, one of the few whole plant leafmass quantification studies attempted within the region was that of Winer and co-workers (1998). The LMD for twenty-one trees from urban landscapes in Bakersfield, CA, ranged from 150 to 3200 with a mean of 940 g m^{-2}, higher LMD values than those reported for forests, indicating the potential of urban trees to contain relatively more leafmass than trees in a continuous canopy environment.

Variations of direct leafmass measurement methods include the use of quadrats or the collection of seasonal leaf litter. For example, three-dimensional quadrats were used by Winer et al. (1998) in a slightly modified version of the stratified-clip to quantify the leafmass of urban trees. Samples were clipped from the contents of an open cube with a volume of 1 ft^3. Ten sampling locations within the crown were chosen based on a three digit random sampling system (Winer et al. 1998). This system did not give leafmass constants that were as representative of tree crowns as the 1 m^3 frames used in earlier studies of Winer and co-workers (Winer et al. 1983, Miller and Winer 1984).

Leafmass estimation by collecting and weighing the annual fall of leaves as litter assumes knowledge of the ratio of litter fall to total biomass production (Lieth and Whittaker, 1975). Litter fall estimates were used by Geron et al. (1997) to validate indirect estimates of species composition and foliar mass in southeastern bottomland deciduous forests. Twenty-six 45 cm diameter litter traps were placed 7.5 m from each plot center normal to the transect azimuth. Leaf litter was collected every two weeks, dried, separated and weighed (Geron et al. 1997). Results from leaf litter analysis provided an accurate determination of specific leaf area (cm^2 g^{-1}) and by multiplying this by SLW, total LAI was calculated. Using this method Geron et al. (1997) estimated a total LAI for a southeastern bottomland deciduous forest of 5.2 m^2 m^{-2}, which was in good agreement with LAI measurements of 4.4 - 5.9 made by measuring light interception with an LAI 2000 (LiCor, Inc.) canopy analyzer instrument. LAI values were used (Equation 2) to calculate leafmass.

6.2 ALLOMETRIC EQUATIONS FOR LEAFMASS DENSITY ESTIMATION

Leafmass estimates of some BHC emissions inventories (Lamb et al. 1993, Geron et al. 1994, Lenz et al. 1997, Geron et al. 1997) have utilized allometric equations to estimate leafmass (as a dependent variable) based on stem diameter (as an independent variable). Often, leafmass estimates from allometric equations are site and species-specific, largely influenced by an environmental component. There is to date, however, an obvious scarcity of allometric equations available to describe the leafmass for species of the SCOS97-NARSTO domain. Due to the size of the region and the large number of species present in the study area, it is not feasible to obtain allometric relationships for each species within each biome. In some cases it may be possible to adjust an environmental component such as water balance, mean annual temperature or minimum winter temperature, so allometric equations developed for plants in another location could be used for plants of the same species or genus that grow in the SCOS97-NARSTO domain. For example, Gholz (1982) studied a range of climatic predictors for correcting the equation Y = a + b X, for Y = LAI, Y = biomass or Y = NPP of trees in the Oregon transect. The best predictor over the range of environments tested was winter low temperature. Water balance, the difference of potential evaporation to rainfall (considered to be the most important variable of growth) was expected to provide an accurate correction factor for Y but did not work well over the range of environments. This was due mainly to an outlier entered by one environment, the sub-alpine region, an effect that distorted the fit. With this point removed, water balance provided the best correction factor for LAI (r^2= 0.99), biomass (r^2= 0.95) and NPP (r^2= 0.91). Until more certainty can be attributed to environmental correction algorithms, non-specific allometric equations would probably not provide sufficient precision for leafmass estimates used to compile BHC emissions models. However, site and species-specific relationships that have been developed have unquestionable value for validating species-specific LMD estimates derived from remote sources.

6.3 INDIRECT MEASUREMENTS OF LEAFMASS DENSITY

Indirect methods that incorporate remote sensing imagery appear to hold the most potential for estimating leafmasses of plants for the SCOS97-NARSTO modeling domain. These methods may be used to either 1) directly estimate the leafmass of plant crowns based on vegetation indices calculated from spectral reflectance, or 2) calculate leafmasses from spectrally derived estimates of LAI integrated with species-specific SLW. The vegetation index that appears to be most accurate for use in arid environments is the NDVI.

At present, the relationships between NDVI and canopy structure, photosynthetic fluxes or net primary productivity (NPP) appear to be most consistent in uniform vegetation. Relatively few studies have compared NDVI to canopy structure and PAR absorption in natural landscapes with vegetation of differing growth habit and phenology that may be exposed to seasonal or chronic stresses (Gamon et al. 1995). However, mounting evidence indicates that the NDVI may be useful in cases where plants are separated and foliar characteristics are unpredictable, such as in desert communities with low (< 1) overall LAI values (Gamon et al. 1995). Earlier work indicated that application of NDVI was confounded in these environment types due to unpredictable soil reflectance properties (Asrar et al. 1992). However, recently developed radiative-transfer models and correction algorithms capture quite well the primary effects of differing illumination and viewing conditions on the reflectance of discontinuous vegetation covers and should improve canopy estimates in Californian communities (Wu and Strahler 1994, Nikolov 1997a). Also, advancing remote sensing technologies are expected to improve pixel resolution, and thus reduce background effects which are especially important in arid region plant communities (Ustin et al. 1986). The description of leafmass by NDVI at low canopy densities (LAI ≈ 2) may be well suited to future study of California's vegetation since the

NDVI is extremely sensitive to changes in canopy cover when the cover is low, but does not clearly distinguish between values relating to crown structure (such as leafmass) when the index ranges from 20 – 100 % of full scale (Gamon et al. 1995). However, the method may not be suited for use in the SCOS97-NARSTO domain until the direct quantification of leafmass using NDVI has been better established for arid environments.

6.4 LEAFMASS ESTIMATES USING THE VOLUMETRIC METHOD

Another possible approach suggested for leafmass quantification on a regional basis would be to use the volumetric method. An aereal coverage map of plant species could be converted into foliar volume by multiplying with canopy height, and further converted to leafmass through multiplying by the appropriate leafmass constant (g m^{-3}) (Winer et al. 1983, Horie et al. 1991, Karlik and Winer 1998). Use of the volumetric method has three main practical disadvantages when applied to the semi-arid shrublands of the SCOS97-NARSTO domain: 1) The lack of available species-specific leafmass constants 2) difficulty in developing leafmass constants for land cover with non-uniform canopy structure, and 3) difficulty in estimating plant height or crown volumes from spectral reflectance data.

6.5 ESTIMATING LMD FROM LAI VALUES OBTAINED USING NDVI

With present capabilities, the NDVI is possibly best utilized through the conversion of LAI estimates to LMD using experimentally determined SLW values (Equation 2). Where possible we have presented these data for California chaparral plants. For example, for *Quercus petraea* and *Q. pubescens,* the LMD values (Table 4-2) were calculated as 160 and 92 g m^{-2}, respectively. There is a scarcity of SLW data for natural California species, although SLW data for more than 60 species were experimentally determined by Winer et al. (1998) and a compilation of SLW data is being prepared by Nowak (1998). Gathering data for SLW requires a somewhat less intensive sampling procedure than for measuring leafmass constants.

Gamon et al. (1995) posit that NDVI may be well suited to leaf area estimations in environments where canopy coverage of ground surface is less than 100 %. This position was supported in a recent study in which a simple radiative transfer model that showed NDVI to be sensitive to changes in the fractional cover until canopy closure was reached, beyond which a further increase in LAI resulted in an additional small, asymptotic increase in NDVI (Ripley and Carlson, 1997). Indeed, one criticism of the NDVI is that its sensitivity to changes in LAI weakens with increasing LAI beyond a threshold value, which is thought to be ~ 2-3 for agricultural monocultures and ~ 7-8 for coniferous canopies (Peterson et al. 1987), which approximately correspond to canopy closure. The upper threshold is indicated by a flattening of the asymptotic shape that is characteristic of LAI vs. NDVI curves (see Figure 4-6). Although many of California's natural landscapes display LAI values that fall within these thresholds, it is possible to correct for saturation of the NDVI by scaling the index to correspond to the values for bare soil (LAI = 0) and a surface with vegetative cover of 100 percent (Carlson and Ripley 1997). This may be necessary in areas of sporadic ground cover.

6.6 VALIDATING LEAFMASS ESTIMATIONS

As seen in the flow diagrams (Figures 2-1, 2-2) the value attributed to leafmass for a given biome has a primary influence on the magnitude of calculated emissions and the accuracy of a BHC emissions inventory. In turn, the method used to calculate LMD has an effect on the calculation of leafmass. To implement remote sensing methods for inventorying BHC emissions with confidence, additional field measurements of leafmass, LAI and LMD are necessary. Values for LMD gathered from previous studies provide benchmark data for some of California's plant communities and individual plant species. The uncertainties associated with the data should be considered on a case-by-case basis. In general, the range of LMD values for a plant species or community is within an order of magnitude and often within a factor of two. Obviously, a complete species- or site-specific description of LMD is not available for California at this time. However, methods are available by which LMD estimates for California landscapes can be generated.

7.0 RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 BACKGROUND

As discussed in Winer et al. (1998), quantitative descriptions of leafmasses and spatial allocation of both leafmasses and plant species identities remain weak links in the development of BHC emission inventories. We recommend measurements of leafmasses of plant species and in plant communities, prioritized according to potential emissions of BHC compounds. These measurements should be accompanied by field validation of the GAP GIS database, or other GIS database selected for integration into ARB models.

A portion of field measurements should be accomplished via direct measurement methods, including whole-plant harvest of key specimens or within key plant communities. An example is oak savanna, for which limited field measurements are planned during 1999 as part of a related ARB-funded project. Whole-plant measurements should be accompanied by parallel development of allometric and indirect measurement methods to assess relatedness and utility of these alternative approaches. For example, measurements should be made of biophysical parameters, such as DBH, for development and testing of allometric equations. Ground-based indirect measurement methods for estimating LAI should also accompany whole tree harvest, to explore, investigate and refine these methods for rapid development of field data, especially for use in plant communities of similar structure and composition but in different geographic areas.

Field measurements should be accompanied by parallel development of leafmass and LD values derived from high altitude remote sensing methods, such as those related to the NDVI, which should then be compared to understand precision, accuracy, and uncertainty of estimates derived from such methods. We recommend assessment of both empirical and analytical models for LD which are based NDVI and ultimately upon remote sensing imagery.

7.2 SPECIFIC RECOMMENDATIONS

- Developing taxonomic frameworks based on reported values for estimating LD derived from sampling, including developing quantitative data regarding the precision and accuracy of LD methods for plants in the natural communities.
- Developing quantitative data for leafmass and LD of selected oak species in a natural environment through whole-tree harvest and exploration of indirect measurement methods, e.g. light interception, for estimation of foliar mass of trees and comparison of calculated leafmass to whole-tree leaf removal. We regard oak communities as a high priority for research because of their potential impact upon BHC inventories.
- Further evaluation of LD for urban trees through whole-plant harvest, and concurrent development of LD relationships based upon ground-based indirect measurement methods such as light interception. Validated use of rapid, indirect measurement methods would make field surveys of urban plants all the more feasible and cost-effective because of time savings.
- Explore the utility of structural class estimates for both urban trees and plants found in California's natural communities. A larger dataset is needed, including additional species, to better understand potential use of structural class values to describe leafmasses and LD. Structural class values were generally too low as compared to whole-tree values for urban trees (Winer et al. 1998, Karlik and Winer 1998).

8.0 REFERENCES

Asrar, G., M. Fuchs, E. T. Kanemasu, and J. L. Hatfield. 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron. J. 76: 300-306.

Asrar, G., R. B. Myneni and B. J. Choudhury. 1992. Spatial heterogeneity in vegetation canopies and remote sensing of absorbed photosynthetically active radiation: a modeling study. Remote Sensing Environ. 41: 85-103.

Basham-May, A. M., J. E. Pinder III, and G. C. Kroh. 1997. A comparison of Landsat Thematic mapper and SPOT multi-spectral imagery for the classification of shrub and meadow vegetation in northern California U.S.A. Int. J. Remote Sensing 18:3719-3728.

Barbour, M. G., J. H. Burk and W. D. Pitts. 1980. *Terrestrial plant ecology*. The Benjamin/Cummings Publishing Company, Inc, Menlo Plark Ca.

Baulies, X. and X. Pons. 1995. Approach to forest inventory and mapping by means of multi-spectral airborne data. Int. J. Remote Sensing 16: 61-80.

Benjamin, M. T., M. Sudol, D. Vorsatz and A. M. Winer. 1997. A spatially and temporally resloved biogenic hydrocarbon emissions inventory for the California South Coast Air Basin. Atmos. Environ. 31: 3087-3100.

Benjamin, M. T., A. M. Winer, J. Karlik, S. Campbell, B. Jackson, and A. Lashgari. 1998. Assembling a biogenic hydrocarbon emissions inventory for the SCOS97-NARSTO modeling domain. 91st Annual Meeting of Air and Waste Management Association, San Diego, CA, June 14-18. Paper No. 98-A621.

Box, E. O. 1981. Foliar biomass: data base of the international biological program and other sources. *In* Bufalini, J. J. and R. R. Arnts (eds). *Atmospheric biogenic hydrocarbons Vol. 1. Emissions*. Ann Arbor Science. Ann Arbor, Michigan

Camillo, P. 1987. A canopy reflectance model based on an analytical solution of the multiple scattering equation. Remote Sensing Environ. 23:453-477.

Campbell, G. S. and J. M. Norman. 1989. The description and measurement of plant canopy structure. *In* Russell, G., B. Marshall and P. G. Jarvis (eds). *Plant Canopies: Their Growth Form and Function*. Cambridge University Press, Cambridge.

Carlson, T. N. and D. A Ripley. 1997. On the relation between NDVI, fractional vegetation cover and leaf area index. Remote Sensing Environ. 62: 241-252.

Elliot, K. J., and Clinton, B. D. 1993. Equations for estimating biomass of herbaceous and woody vegetation in early-successional Southern Appalachian pine-hardwood forests. USDA Southeastern forest experiment station research note SE-365.

Fassnacht, K. S., S. T. Gower, M. D. MacKenzie, E. V. Nordheim and T. M. Lillesand. 1997. Estimating the leaf area index of north central Wisconsin forests using the Landsat Thematic Mapper. Remote Sensing Environ. 61:229-245.

Franklin, J. and D. L. Turner. 1992. The application of the geometric optical canopy reflectance model to semiarid shrub vegetation. IEEE Trans. Geosci. Remote Sens. GE-30: 293-301.

Gacka-Grzesikiewicz, E. 1980. Assimilation surface of urban green areas. Ekol. Pol. 28: 493-523.

Gamon, J. A., C. B. Field, M. L. Goulden, K. L. Griffin, A. E. Hartley, G. Joel, J. Penuelas and R. Valentini. 1995. Relationships between NDVI, canopy structure and photosynthesis in three Californian vegetation types. Ecol. Appl. 5:28-41.

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

Geron, C. D., A. B. Guenther and T. E. Pierce. 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. J. Geophys. Res. 99:12,773-12,791.

Geron, C. D., T. E. Pierce and A. B. Guenther. 1995. Reassessment of biogenic volatile organic compound emissions in the Atlanta area. Atmos. Environ. 29: 1569-1578.

Geron, C. D., D. Nie, R. A. Arnts, T. D. Sharkey, E. L. Singsaas, P. J. Vanderveer, A. Guenther, J. E. Sickles II and T. E. Kleindienst. 1997. Biogenic isoprene emission: Model evaluation in a southeastern United States bottomland deciduous forest. J. Geophys. Res. 102: 18,889-18,901.

Gholz, H. L. 1982. Environmental limits on aboveground net primary production, Leaf area, and biomass in vegetation zones of the Pacific Northwest. Ecology 63: 469-481.

Gray, J. T. and W. H. Schlesinger. 1981. Biomass production and litterfall in the coastal sage scrub of sourthern california. Amer. J. Bot. 68: 24-33.

Guenther, A., C. N. Hewitt, D. Erickson, R. Fall, C. Geron, T. Graedel, P. Harley, L. Klinger, M. Lerdau, W. A. McKay, T. Pierce, B. Scholes, R. Steinbrecher, R. Tallamraju, J. Taylor and P. Zimmerman. 1995. A global model of natural volatile organic compound emissions. J. Geophys. Res. 100: 8873-8892.

Guenther, A., P. Zimmerman and M. Wildermuth. 1994. Natural volatile organic compound emission rate estimates for U.S. woodland landscapes. Atmos. Environ. 28: 1197-1210.

Horie, Y., S. Sidawi. and R. Ellefsen. 1991. Inventory of leaf biomass and emission factors for vegetation in California's south coast air basin. South Coast Air Quality Management District Contract No. 90163. 132 pp.

Howard, J. A. 1991 *Remote sensing of forest resources: theory and application.* Chapman and Hall, London.

Karlik, J. and A. M. Winer. 1998 Comparison of calculated and measured leafmasses of urban trees. Ecol. Appl. In press.

Kittredge, J. 1944. Estimation of the amount of foliage of trees and stands. J. For. 42:168-176.

Kummerow, J. and R. Mangan. 1981. Root systems in Quercus dumosa Nutt. dominated chaparral in southern California. Acta ecologica / Ecologia plantarum 2: 177-188.

Lamb, B., A. Guenther, D. Gay and H. Westberg. 1987. A national inventory of biogenic hydrocarbon emissions. Atmos. Environ. 21: 1695-1705.

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

Law, B. E. 1995. Estimation of leaf area index and light intercepted by shrubs from digital videography. Remote Sensing Environ. 51: 276-280.

Law, B. E. and R. H. Waring. 1994a. Remote sensing of leaf area index and radiation intercepted by understory vegetation. Ecol. Appl. 4: 272-279.

Law, B. E. and R. H. Waring. 1994b. Combining remote sensing and climatic data to estimate net primary production across Oregon. Ecol. Appl. 4: 717-728.

Lenz, R., T. Selige and G. Seufert. 1997. Scaling up the biogenic emmissions from test sites at Castelporziano. Atmos. Environ. 31:(s1)239-250.

Lieth, H., and R. H. Whittaker (eds). 1975. *Primary productivity of the biosphere.* Springer-Verlag, New York.

Li X. and A. H. Strahler. 1985. Geometric-Optical modeling of a conifer forest canopy. IEEE GE-23: 705- 721.

Loveland, T. R. J. W. Merchant, D. O. Ohlen and J. F. Brown. 1991. Development of a land-cover characteristics database for the conterminous U. S. Photogram. Eng. Remote Sensing. 57: 1453-1463.

Miller, P. C. and E. Ng. 1977. Root:shoot biomass ratios in shrubs in southern California and central Chile. Madrono 24: 215-223.

Miller, P. C. 1981. Light and energy environments of chaparral and matorral in southern California and central Chile. *In* N. S. Margaris and H. A. Mooney (eds): *Components of productivity of mediterranean-climate regions basic and applied aspects*. 1981 Dr W. Junk Publishers, The Hague.

Miller, P. R. and A. M. Winer. 1984. Composition and dominance in Los Angeles Basin urban vegetation. Urban Ecol. 8: 29-54.

Mooney, H. A. 1977. *Convergent evolution in Chile and California: Mediterranean climate ecosystems*. Dowden, Hutchinson and Ross INC. Stroudsburg, PA.

Mooney, H. A. and P. W. Rundel. 1979. Nutrient relations of the evergreen shrub *Adenostoma fasciculatum* in the California chaparral. Bot. Gaz. 140: 109-113.

Myneni, R. B., B. D. Ganapol and G. Asrar. 1992. Remote Sensing of Vegetation Canopy Photosynthetic and stomatal conductance efficiencies. Rem. Sens. Environ. 42:217-238.

National Acadamy of Science. 1975. Productivity of world ecosystems: Proceedings of a Symposium, presented 31 Aug-1 Sept., 1972. Seattle. WA. International Biological Program.

Nemani, R. R., and S. W. Running. 1989. Estimation of regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data. J. App. Meteorol. 28:276-284.

Nikolov, N. T. 1997a. Modeling spatial distribution of leaf area index, canopy conductance to ozone, and fluxes of CO_2, O_3 and latent heat at the San Joaquin Valley (CA). Progress Report (Revised) of February 1997.

Nikolov, N.T. 1997b. Mathematical modeling of seasonal biogeophysical interactions in forest ecosystems. Ph.D. Dissertation, Colorado State University, Fort Collins, CO.

Nicholson, S. A. 1975. Foliage biomass in temperate tree species. The American Midland Naturalist 93: 44-52.

Nowak, D. J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. For. Sci. 42: 504-507.

Nowak, D.J. 1998. Personal Communication.

Parker, G. G. 1995. Structure and microclimate of forest canopies. *In* Lowman M. D. and N. M. Nadkarni (eds). *Forest Canopies*. Academic Press, San Diego.

Peterson, D. L., M. A. Spanner, S. W. Running and K. T. Teuber. 1987. Relationship of thematic mapper simulator data to leaf area index of temperate coniferous forests. Remote Sensing Environ. 22: 323-341.

Roberts, D. A., M. Gardner, R. Church, S. Ustin, G. Scheer, and R. O. Green. 1996. Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. Draft manuscript.

Running S. W., R. R. Nemani, D. L. Peterson, L. E. Band, D. F. Potts, L. L. Pierce and M. A. Spanner. 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. Ecology, 70: 1090-1101

Schlesinger, W. H. and D. S. Gill. 1980. Biomass, production, and changes in the availability of light, water, and nutrients during the development of pure stands of the Chaparral shrub *Ceanothus magacarpus*, after fire. Ecology 61: 781-789.

Schlesinger, W. H. and D. S. Gill. 1978. Demographic studies of the chaparral *shrub Ceanothus megacarpus* in the Santa Ynez Mountains, California. Ecology 59: 1256-1263.

Spanner, M. A., L. L. Pierce, D. L. Peterson and S. W. Running. 1990a The seasonality of AVHRR data of the temperate coniferous forests: relationship with leaf area index. Int. J. Remote Sens. 8: 95-111.

Spanner, M. A., L. L. Pierce, D. L. Peterson, and S. W. Running. 1990b. Remote sensing of temperate coniferous forest leaf area index : The influence of canopy closure, understory vegetation and background reflectance. Int. J. Remote Sens. 11: 95-111.

Spanner, M., L. Johnson, J. Miller, R. McCreight, J. Freemantle, J. Runyon, and P. Gong. 1994. Remote sensing of seasonal leaf area index across the Oregon transect. Ecological applications 4: 258-271.

Suefert, G. (ed). 1997. BEMA: A European commission project on biogenic emissions in the Mediterranean area. Atmos. Environ. 31: (s1)1-260.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing Environ. 8: 127-150.

Ustin, S. L., J. B. Adams, C. D. Elvidge, M. Rejmanek, B. N. Rock, M. O. Smith, R. W. Thomas, and R. A. Woodward. 1986. Thematic mapper studies of semiarid shrub communities. Bioscience 36: 446-452.

Wu, Y., and A. H. Strahler. 1994 Remote estimation of crown size, stand density, and biomass on the Oregon transect. Ecological applications 4: 299-312.

Winer, A. M., D. R. Fitz and P. R. Miller. 1983. Investigation of the role of natural hydrocarbons in photochemical smog formation in California. Final report to the California Air Resources Board, Contract No. A0-056-32, 267 pp.

Winer, A. M., L. Chinkin, J. Arey, R. Atkinson, J. Adams and J. Karlik. 1995. Critical evaluation of a biogenic emission system for photochemical grid modeling in California. Final report to the California Air Resources Board, Contract No. 93-725, 234 pp.

Winer, A. M., J. Karlik, J. Arey and J. Chung. 1998. Biogenic hydrocarbon inventories for California: Generation of essential databases. Draft final report to the California Air Resources Board, Contract No. 95-309, 234 pp.

Whittaker R. H. and P. L. Marks. 1975. Methods of assessing terrestrial productivity. *In* Lieth, H., and R. H. Whittaker (eds). *Primary Productivity of the Biosphere*. Springer-Verlag, New York.