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Worldwide Historical Estimates of Leaf Area Index, 1932–2000

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ABSTRACT

Scurlock, J. M. O., G. P. Asner, and S. T. Gower. 2001. Worldwide Historical Estimates of Leaf Area Index, 1932–2000. ORNL Technical Memorandum ORNL/TM-2001/268. Oak Ridge National Laboratory, Oak Ridge, Tenn.

Approximately 1000 published estimates of leaf area index (LAI) from nearly 400 unique field sites, covering the period 1932–2000, have been compiled into a single data set. LAI is a key parameter for global and regional models of biosphere/atmosphere exchange of carbon dioxide, water vapor, and other materials. It also plays an integral role in determining the energy balance of the land surface. This data set provides a benchmark of typical values and ranges of LAI for a variety of biomes and land cover types, in support of model development and validation of satellite-derived remote sensing estimates of LAI and other vegetation parameters. The LAI data are linked to a bibliography of over 300 original-source references.

These historic LAI data are mostly from natural and seminatural (managed) ecosystems, although some agricultural estimates are also included. Although methodologies for determining LAI have changed over the decades, it is useful to represent the inconsistencies (e.g., in maximum value reported for a particular biome) that are actually found in the scientific literature. Needleleaf (coniferous) forests are by far the most commonly measured biome/land cover types in this compilation, with 22% of the measurements from temperate evergreen needleleaf forests, and boreal evergreen needleleaf forests and crops the next most common (about 9% each). About 40% of the records in the data set were published in the past 10 years (1991–2000), with a further 20% collected between 1981 and 1990.

Mean LAI (± standard deviation), distributed between 15 biome/land cover classes, ranged from 1.31 ± 0.85 for deserts to 8.72 ± 4.32 for tree plantations, with evergreen forests (needleleaf and broadleaf) displaying the highest LAI among the natural terrestrial vegetation classes. We have identified statistical outliers in this data set, both globally and according to the different biome/land cover classes, but despite some decreases in mean LAI values reported, our overall conclusions remained the same.

This report documents the development of this data set, its contents, and its availability on the Internet from the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics. Caution is advised in using these data, which were collected using a wide range of methodologies and assumptions that may not allow comparisons among sites.

1. INTRODUCTION, TERMS OF REFERENCE, NEED FOR THIS DATA SET

Leaf area index (usually abbreviated to LAI or simply L) is broadly defined as the amount of leaf area in a vegetation canopy per unit land area. Like net primary productivity (NPP; e.g., Esser et al. 1997), LAI is a key structural characteristic of vegetation and land cover because of the role of green leaves in a wide range of biological and physical processes. Data on estimates of LAI worldwide are needed by the National Aeronautics and Space Administration (NASA) and related scientific communities investigating global change (e.g., Running and Coughlan 1988; Sellers and Schimel 1993). For example, information on typical values of LAI is required for scaling between leaf-level measurements of water vapor and CO_2 conductance and flux, and estimates of these conductances and fluxes for the total vegetation–atmosphere interface (McWilliam et al. 1993). Leaf area is an important determinant of photosynthetic carbon assimilation, so the estimation of LAI provides an indicator of growth potential (Barclay 1998). LAI is also a critical variable determining the energy balance of the land surface. However, despite an abundance of individual plot and stand-based studies, there appear to be very few comprehensive reviews of LAI data in the literature. Waring (1983) discussed LAI of forests as an index of growth and canopy light competition but did not tabulate data from previous studies. Gower et al. (1999) reviewed LAI estimation techniques but again did not summarize many previous data. Schulze (1982) also discussed leaf area and canopy light interception, and provided a review of 62 estimates of LAI from 12 vegetation biome types. Asner (1998) studied canopy reflectance variation using a compilation of 29 estimates from 20 vegetation types. However, neither of these two latter studies was sufficiently comprehensive to allow for broad determinations of the range and properties of LAI values by biome, whether globally or through time.

The User Working Group of the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (ORNL) (DAAC) recommended in 1998 that the DAAC should obtain and archive vegetation data to support NASA's Earth Observing System (EOS) Land Validation activities. In particular, field data such as estimates of LAI are required to support validation of the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor on the Terra satellite, launched in December 2000. Data are needed for a variety of vegetation and land cover types (e.g., grasslands and different types of mature forests) from multiple plots over an extended period of time. Such a compilation of historical LAI data can therefore provide expected values and ranges of LAI for broad spatial coverage. These data also contribute toward the DAAC's collection of regional and global data on vegetation, soils, climate, and hydrology to support NASA's Earth Science Enterprise activities on terrestrial ecosystem modeling.

Other related parameters, measured for the same plots or study sites, were also considered desirable by a number of advisers and reviewers of this data compilation. These included the time course (phenology) of LAI, or at least the time of year of measurement (given as month or Julian date), fPAR (fraction of photosynthetically active radiation intercepted by the canopy), albedo, fractional vegetation cover, crown allometry, leaf area density distribution within the canopy, and leaf/soil/canopy spectra. Norman and Campbell (1989) characterize LAI as just one of a number of parameters that describe canopy structure. Ideally, comprehensive metadata should accompany LAI data, such as details of methodology (direct or indirect estimation, type of instrument used, direct or diffuse radiation conditions in the case of optical methods, etc.). Unfortunately the authors found that most of these parameters and metadata are only rarely reported in the historic literature. However, at a future date it may be possible to compile a subset of the LAI data reported here for those more intensively measured and reported study sites for which additional detailed metadata and ancillary variables are available.

2. SIMPLE DEFINITION AND TYPICAL VALUES OF LAI

LAI may be described most simply as:

$$\text{LAI} = s/G$$

where *s* is the functional (green) leaf area of the canopy standing on ground area *G* (terminology after Beadle 1993). Because both *s* and *G* are normally measured as areas (m^2), LAI is dimensionless, although it is sometimes presented in units of m^2/m^2.

Most commonly *s* is measured as the projected area (e.g., after placing a sampled leaf on a horizontal surface). However, LAI may be more precisely defined in a number of different ways (see Section 3). For example, leaf area may be measured as the total surface area of leaves in a canopy. This will be equal to 2*s* for flat leaves and greater than 2*s* for needle-shaped and succulent leaves and photosynthetic stems. Care should be taken when making comparisons between LAI determinations that may not necessarily use the same methodology or even the same definition of LAI (Chen and Black 1992; Beadle 1993).

LAI is the major factor determining the amount of light intercepted by the plant canopy, but it varies greatly with species and canopy structure. Under optimum conditions for growth, its value for a closed canopy is related to the ability of the lower leaves in the canopy to intercept sufficient light to maintain a positive carbon balance (regardless of whether they are of the same stem, the same species, or competing/coexisting species). In general, the highest values reported previously for LAI are for particular coniferous canopies (in some cases LAI is greater than 15, although this is partly a function of how LAI is defined and measured—see Section 3). Beadle (1993) reported that maxima between 6 and 8 are typically observed for deciduous forest and between 2 and 4 for annual crops. Schulze (1982) found that typical projected LAI for most biomes (apart from desert and tundra) ranged from about 3 to 19, the highest values being reported for boreal coniferous forest. Many types of vegetation react to stress in the environment by producing canopies with lower LAI. Thus the LAI of a particular plot compared with typical values for such a biome/land cover type may provide an indicator of stresses, such as drought, flooding, nutrient deficiency, excessive heat or cold, as well as disease, herbivory, etc.

It is important to note that LAI measured for large sample plots, satellite image pixels, or model grid cells (typically from one hectare to many square kilometers in size) comprises the average of a range of point values of LAI, often including different species and canopy types, as well as bare ground. In general, therefore, such area-weighted LAI values may be expected to display lower maximum values and lower variance than point measurements.

3. COMMON METHODS OF DETERMINING LAI

According to Barclay (1998), there are at least five common measures of LAI, which partly reflect the different purposes for which LAI is determined (determination of vegetation growth, estimation of potential physiological activity, study of light attenuation under plant canopies, etc.). The four most common of these are defined.

Definition (1): Total LAI is based on the total outside area of the leaves, taking leaf shape into account, per unit area of horizontal land below the canopy.

Definition (2): One-sided LAI is usually defined as half the total LAI, even if the two sides of the leaves are not symmetrical.

Definition (3): Horizontally projected LAI is the area of "shadow" that would be cast by each leaf in the canopy with a light source at infinite distance and perpendicular to it, summed up for all leaves in the canopy.

Definition (4): Inclined projected LAI, or "silhouette" LAI, represents the projected area of leaves taking into account individual leaf inclinations. An additional fifth definition, according to Barclay (1998), is a variation on this approach, counting overlapping leaf areas only once.

Most published values of LAI appear to use definition (2) or definition (3), with an increasing number of definition (4) in the recent literature (Barclay 1998). Definition (1) is relatively rarely used (see discussion following description of methodologies). Definition (2) suffers from the problem that the meaning of "one-sided" is unclear for coniferous needles, highly clumped foliage, or rolled leaves (Chen and Black 1992). Chen and Black (1992) suggest that the LAI of non-flat leaves should be defined as half the total intercepting area per unit ground area, and that definition (3) should be abandoned. LAI according to definition (2) may exceed LAI according to definition (3) by a factor ranging from 1.28 (hemi-circular cylinders representing conifer needles), through 1.57 (representing cylindrical green branches) to 2.0 (spheres or square bars representing highly clumped shoots and some spruce needles) (Chen and Cihlar 1996). Regrettably, many individual reports of LAI in the literature fail to provide any details of the LAI definition assumed, and a significant fraction do not even describe the methodology used.

Methodologies for ground-based estimation of LAI include

(A) destructive harvesting and direct determination of one-sided leaf area, using squared grid paper, weighing of paper replicates, or an optically based automatic area measurement system;

(B) collection and weighing of total leaf litterfall, converted to leaf area by determining specific leaf area (leaf area/leaf mass) for sub-samples;

(C) allometry (based on simple physical dimensions, such as stem diameter at breast height), using species-specific or stand-specific relationships based on detailed destructive measurement of a sub-sample of leaves, branches, or whole individuals;

(D) indirect contact methods, such as plumb lines and inclined point quadrats;

(E) indirect noncontact methods, such as the Decagon Ceptometer (Decagon Devices, Inc., Pullman, Washington), the LICOR LAI-2000 (Li-Cor, Inc., Lincoln, Nebraska), and analysis of hemispheric photographs.

Methodologies (A) and (B) are commonly used in conjunction with definition (2) of LAI, whereas methodologies (D) and (E) are used with definitions (3) and (4), respectively. Methodology (C) may be used with any of the LAI definitions, including definition (1), depending upon the details of the calibration of the allometric equations. Whereas all of these methodologies may be used for forest canopies, (A) tends to be the most common for grasslands and crops, and (D) or (C) for irregularly shaped canopies, such as shrublands. In many cases, the choice of methodology is a matter of ease of use in a particular field situation.

The user of LAI data should note that almost all of these methodologies are subject to limitations, such as sampling error (small plots, etc.) for direct determination and non-random leaf distribution and inclination in the case of the indirect methods. For example, specific leaf area in an experimental stand of sweetgum (*Liquidambar styraciflua*) may vary by a factor of more than two between sun and shade leaves, making it difficult to use an annual average value for the determination of LAI by methodology (B) above (Norby et al. 2001; Norby, R. J., Oak Ridge National Laboratory, personal communication, July 2001). The wide range of leaf turnover times, from less than 12 months to about 6 years, may also present problems for this methodology. Some knowledge of the dynamics of leaf area production and abscission is really required to estimate LAI (Norby, R. J., Oak Ridge National Laboratory, and S. T. Gower, University of Wisconsin-Madison, personal communication, July 2001). Leaf spatial distribution, leaf angle distribution, and the contribution of non-photosynthetic tissue to light attenuation are all complicating factors in methodology (E), the optical determination of LAI, which was originally developed for crop canopies (Chen 1996). Strictly speaking, this methodology estimates "plant area index" (sometimes abbreviated to PAI), which includes projected stem area as well as leaves. For certain types of vegetation, instruments such as the LAI-2000 have also been found to systematically underestimate LAI compared with other methodologies (Deblonde et al. 1994; Kucharik et al. 1998; Gower et al. 1999).

Seasonal time of measurement is also an important consideration; even for evergreen canopies, there may be an important difference between annual maximum LAI and the average LAI during the growing season. LAI phenology tends to be overlooked in much of the literature.

The complexity of the radiation environment in many types of natural vegetation canopies also contributes to uncertainties in satellite-based LAI estimates, and errors in ground-based estimation of LAI only compound this problem (Chen and Cihlar 1996). However, a number of correcting factors may be applied to such indirect estimates to improve their accuracy and their comparability to direct measurement of LAI (Chen et al. 1997; Kucharik et al. 1998). The optimum strategy for collecting extensive "ground truth" LAI in the future may be to use a combination of several indirect optical methods, corrected and calibrated against a more limited number of direct estimates of LAI (Chen and Cihlar 1995).

4. COMPILING THE DATA

The process of compiling data of this kind includes identifying sites and sources of data; acquiring the data, metadata (information about the data), and other documentation; performing quality assessment checks; reformatting the data; and writing documentation for the entire data set. The data and documentation are then reviewed before final release to public access. Some of the initial steps in this process may be already complete for a portion of the data set, but other records may require entering anew.

The sites included in this data set represent mostly natural or seminatural ecosystems; however, some data from crops are included for comparison, and intensively managed pastures and tree plantations have been flagged where possible to distinguish them from natural or seminatural (minimally managed) grasslands and forests. As far as possible, the minimum criteria for inclusion of data in this compilation were the following:

- a geographical or place-name reference to the site of measurement (data related to vegetation types only were not considered)
- at least some ancillary data on vegetation type, stand age, etc., and preferably other physiological parameters such as aboveground NPP, etc.
- a citation to the source of the data

Where the geographical coordinates of the experimental site were not included in the original literature, coordinates were selected from national or regional maps, based upon site descriptions. A variety of published maps, road atlases, online maps, and online nationwide mapping software was used for this purpose.

The LAI data described here were compiled by the authors. Gower contributed a substantial data set with LAI, NPP, and references for about 700 sites. About 200 records of LAI, with references, were already available at the ORNL DAAC as a by-product of preparing the "Osnabruck" data set on NPP (Esser et al. 1997). Asner provided a data set and references for about 80 recent LAI measurements from his own work and other studies. Additional records were added as further citations and published tables of data came to light during the data compilation and quality-assurance process.

After elimination of duplicate data and doubtful or incomplete records, the data were condensed into a table of 1008 unique records from 339 known field sites (geographical coordinates available), with a further 69 records for which coordinates could not be estimated (i.e., about 400 locations). Each record represents a unique value reported for a particular vegetation type, treatment, or vegetation condition (maximum LAI, minimum LAI) at an individual study site. The vast majority of records (98%) have been matched to a bibliography of over 300 original literature references, which forms a useful resource in its own right.

5. DATA QUALITY ASSESSMENT

Criteria for consistency in the data included the use of common systems of names, units, etc., including names of countries and assignment of biome/land cover to a consistent set of 15 classes, in addition to the original biome designation, where available. These 15 classes (Table 1) are based upon those developed for the Ecosystem Model-Data Intercomparison workshops under the auspices of the Global Primary Production Data Initiative (Olson et al. 2001; Scurlock et al. 1999). They represent a compromise between biome and land cover classes that are meaningful to ecologists, ecosystem modelers and users of satellite remote sensing data. By sorting and re-sorting the table of records in order of each variable, it was possible to check for out-of-range values and to cross-check many suspect records against the original primary literature. Geographical coordinates were converted to decimal degrees (ddd.dd), and mapped using Geographical Information System software to check for erroneous coordinates located in water bodies or other unlikely areas.

Table 1. Biome/land cover classes based upon the Ecosystem Model-Data Intercomparison (Olson et al. 2001) and acronyms that appear in this data set

Biome/land cover	Acronym or terminology used
Tundra, circumpolar and alpine	Tundra
Deserts	Desert
Wetlands, temperate and tropical	Wetland
Grasslands, temperate and tropical	Grassland
Crops, temperate and tropical	Crops
Shrubland, heath or Mediterranean-type vegetation	Shrub
Plantations (managed forests); temperate deciduous broadleaf, temperate evergreen needleleaf, and tropical deciduous broadleaf	Plantation
Forest, boreal deciduous broadleaf	Forest/BoDBL
Forest, boreal evergreen needleleaf	Forest/BoENL
Forest, boreal/temperate deciduous needleleaf	Forest/BoTeDNL
Forest, temperate deciduous broadleaf	Forest/TeDBL
Forest, temperate evergreen needleleaf	Forest/TeENL
Forest, temperate evergreen broadleaf	Forest/TeEBL
Forest, tropical deciduous broadleaf	Forest/TrDBL
Forest, tropical evergreen broadleaf	Forest/TrEBL

6. DATA FORMAT

The LAI data set includes column headings, such as site name, country, latitude, longitude, LAI, and many supporting variables, not all of which are available for all records (Table 2). The publicly available data consist of a large downloadable spreadsheet table (in several user-friendly proprietary formats). The bibliography of more than 300 original-source references is available as an accompanying file. References may be matched to the data records using the author name combined with the year of publication; our experience is that only the first four characters of the author name are usually required.

Table 2. List of column headings in the LAI data set, in the order in which they occur in the data file

Variable	Definition
Sitename	Unique common name for study site, where reported
Country	Country of study
Latitude	Latitude (decimal degrees) to two decimal places (south is negative by convention)
Longitude	Longitude (decimal degrees) to two decimal places (west is negative by convention)
LAI	Leaf area index, as reported (m^2/m^2 or dimensionless)
Time of measurement	Season, month, occasionally exact date
Year_LAI	Year of original study, where reported (otherwise assumed to be equal to Year_pub)
Methodology/remarks	Methodologies: A – destructive harvest B – litterfall C – allometry D – point quadrat/plumb line E – Indirect noncontact (LAI-2000 or other) X – unknown Remarks where additional information given
Biome	Biome/land cover type, as reported
Biomecover	Biome/land cover type assigned to one of 15 classes (see Table 1)
Dominant species	Major species/genus/family, where reported
Author	Name of first author of original reference
Year_pub	Year of publication
ANPP	Aboveground net primary productivity (g/m^2/year dry matter)
BNPP	Belowground net primary productivity (g/m^2/year dry matter)
TNPP	Total net primary productivity (ANPP + BNPP) (g/m^2/year dry matter)
Elevation	Elevation of study site in meters, as reported
Age	Age of vegetation stand in years (mostly reported for forests)
Remarks/original source	Additional remarks about peculiarities of the study; references to previous or related studies

7. EXPLORATION AND ANALYSIS OF THE DATA

To characterize the LAI data set, we present summary statistics, examine the relationship between LAI and NPP, extract data for a selected set of satellite remote sensing validation sites, and conduct a prototype outlier analysis.

The distribution of the LAI measurement sites is reasonably representative of vegetation/land cover worldwide in terms of their geographical scope (Fig. 1), although it should be noted that over 40% of the records are from the United States and 15% from Japan (Table 3). Almost two-thirds of the records (62%) may be identified by study site name, and only 7% lack precise geographical coordinates. About half the records are dominated by 15 common plant genera, mostly forest trees such as pines (11% of all records), although several crop genera are represented here (Table 4).

Mean values of LAI (± standard deviation), distributed between 15 biome/land cover classes, ranged from 1.31 ± 0.85 for deserts to 8.72 ± 4.32 for tree plantations, with evergreen forests (needleleaf and broadleaf) displaying the highest LAI among the natural vegetation classes (Fig. 2).

Needleleaf (coniferous) forests are by far the most commonly measured biome/land cover types in this compilation, with 22% of the measurements from temperate evergreen needleleaf forests, and boreal evergreen needleleaf forests and crops the next most common (about 9% each).

The earliest LAI record in the data set is from 1932 and the latest from 2000. When the data are plotted by decade of publication, there is a noticeable increase in the number of records (indicative of more intensive periods of study) and a decline in the mean measured value by decade (Fig. 3). The latter may reflect the tendency toward indirect methodologies for estimation of LAI (which are thought to underestimate “true” LAI for some types of canopy—see Section 3) and away from direct measurement and allometry (where small errors may propogate and result in significant overestimation of LAI). About 40% of the records in the data set were published in the past 10 years (1991–2000), with a further 20% collected between 1981 and 1990.

Possible systematic biases in LAI estimates with different methodologies were explored by plotting the subset of data from the best-documented decade (1991–2000) according to methodology given (Fig. 4). Almost half the measurements for this decade were obtained by Methodology C (allometric equations), but apart from the possibility that Methodology B (litterfall) tends to result in higher LAI estimates, there were no obvious differences between methodologies.

The relationship between aboveground net primary productivity (ANPP) and LAI was investigated for a subset of the data for which both parameters were available (excluding LAI greater than 10 to avoid all-sided estimates from coniferous forests and other outliers and also excluding outliers with ANPP greater than 4000 g/m2/year). As might be expected, a modest but demonstrable correlation ($r^2 = 0.33$) was found between these two vegetation parameters (Fig. 5).

One possible application of the data set is shown in Table 5, where historic LAI estimates have been selected for their proximity and similarity to the NASA Land Validation sites (and other validation sites) used for calibrating satellite remote sensing of vegetation by NASA’s Earth Observing System and other non-USA programs.

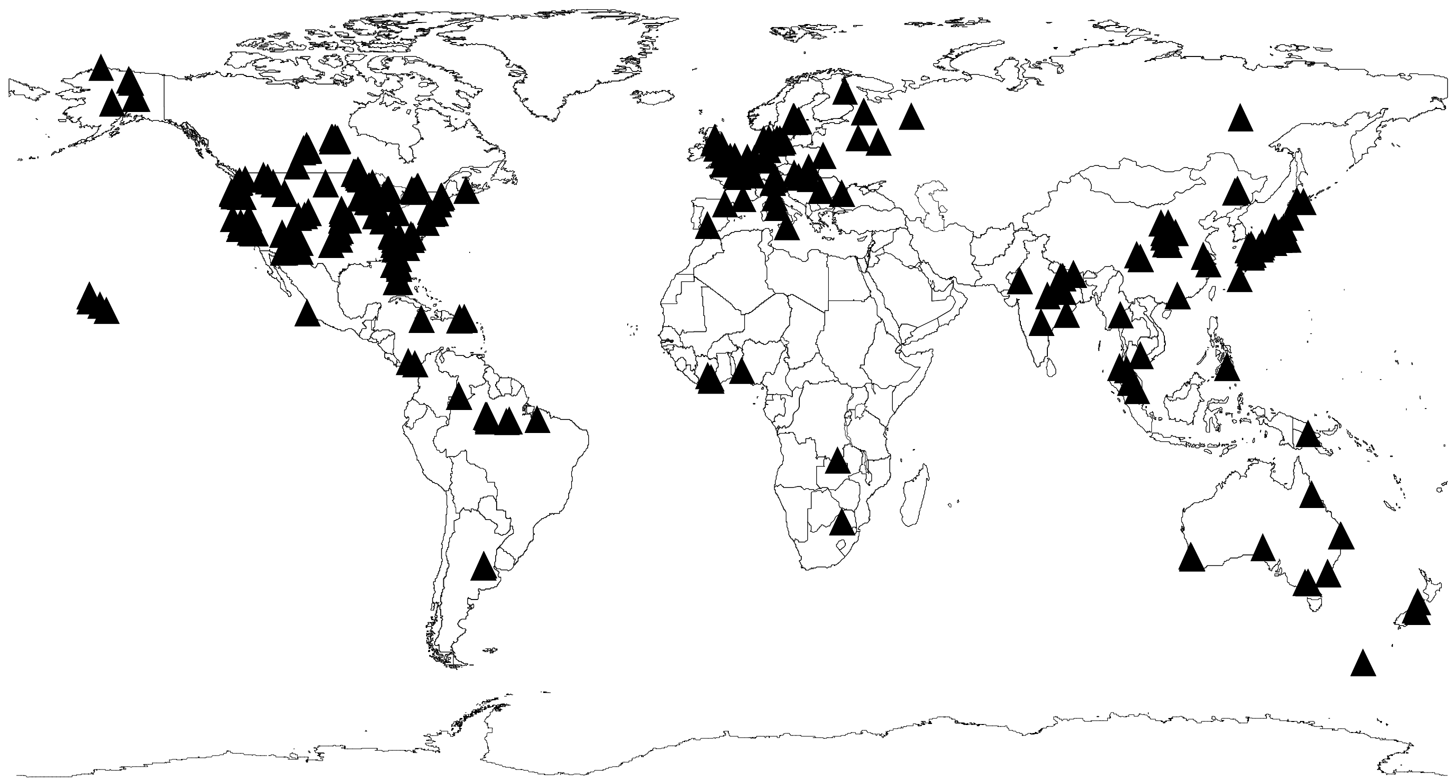

Fig. 1. Global map of study sites in the LAI data set. Not all sites are discernible because of overlapping symbols.

Table 3. Frequency of LAI estimates for countries with more than 10 records

Country	Frequency	Percent
Australia	43	4.3
Brazil	21	2.1
Canada	58	5.8
China	28	2.8
France	17	1.7
India	32	3.2
Japan	153	15.2
New Zealand	14	1.4
Nepal	11	1.1
Puerto Rico	13	1.3
Russia	22	2.2
Sweden	15	1.5
U.K.	63	6.3
U.S.A.	417	41.4
Venezuela	10	1.0
Others	91	9.0

Table 4. Frequency of LAI records by dominant genus

Genus	Frequency	Percent
Acer	14	1.4
Cryptomeria	13	1.3
Eucalyptus	23	2.3
Fagus	16	1.6
Helianthus	17	1.7
Metrosideros	17	1.7
Picea	71	7.0
Pinus	111	11.0
Populus	48	4.8
Pseudotsuga	18	1.8
Quercus	50	5.0
Shorea	14	1.4
Triticum	19	1.9
Vicia	10	1.0
Zea	15	1.5
Others	223	22.1
Genus not reported	329	32.6
Total	1008	100.0

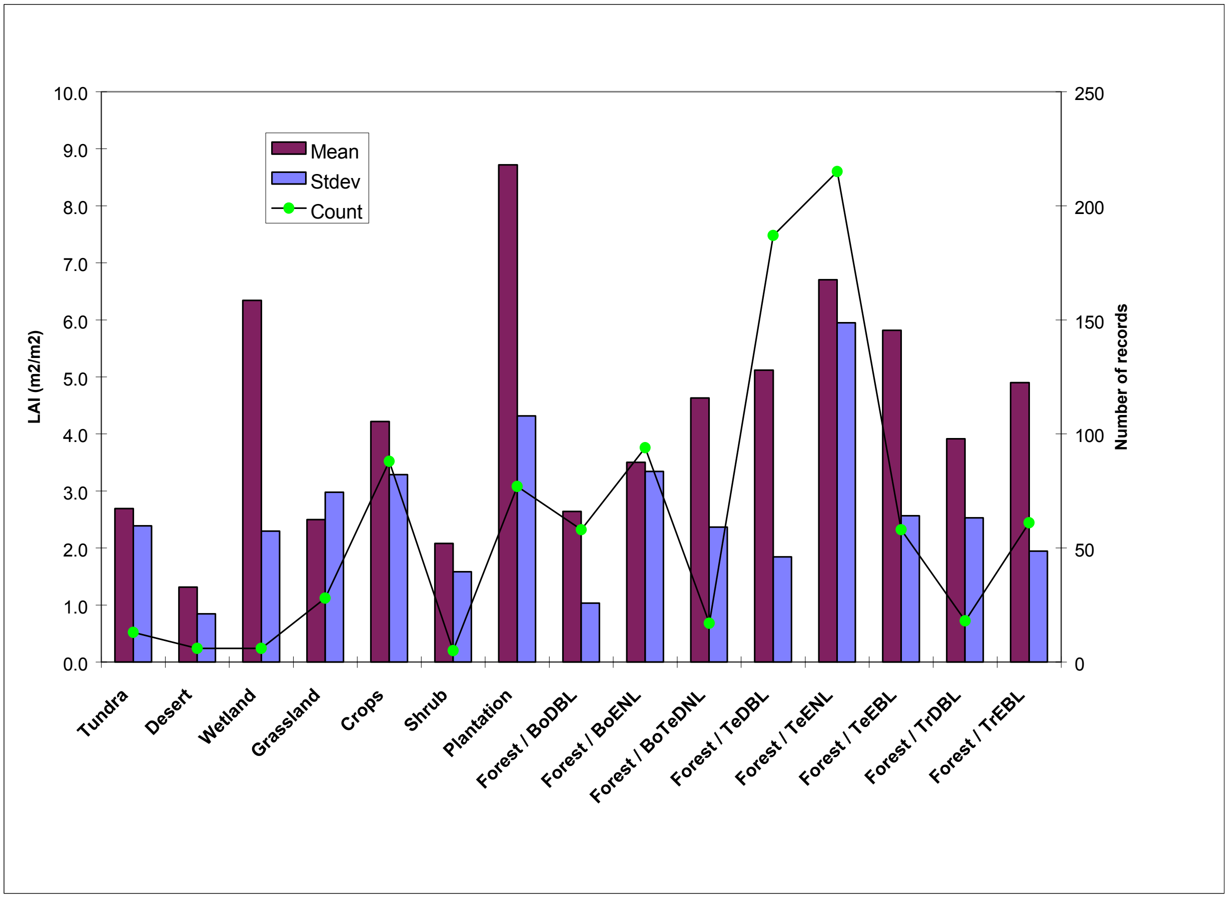

Fig. 2. Distribution of approximately 1000 historical estimates of LAI, summarized by biome/cover type. See Table 1(b) for explanation of abbreviated biome names.

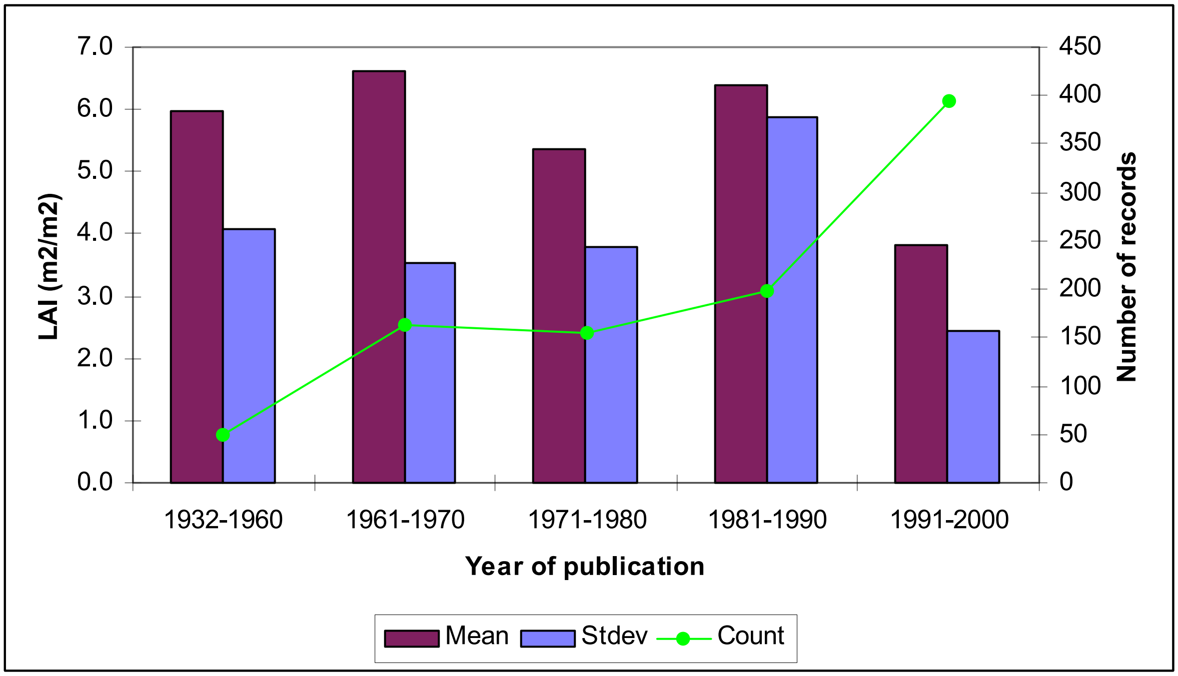

Fig. 3. Distribution of reported LAI values, classified by decade of publication.

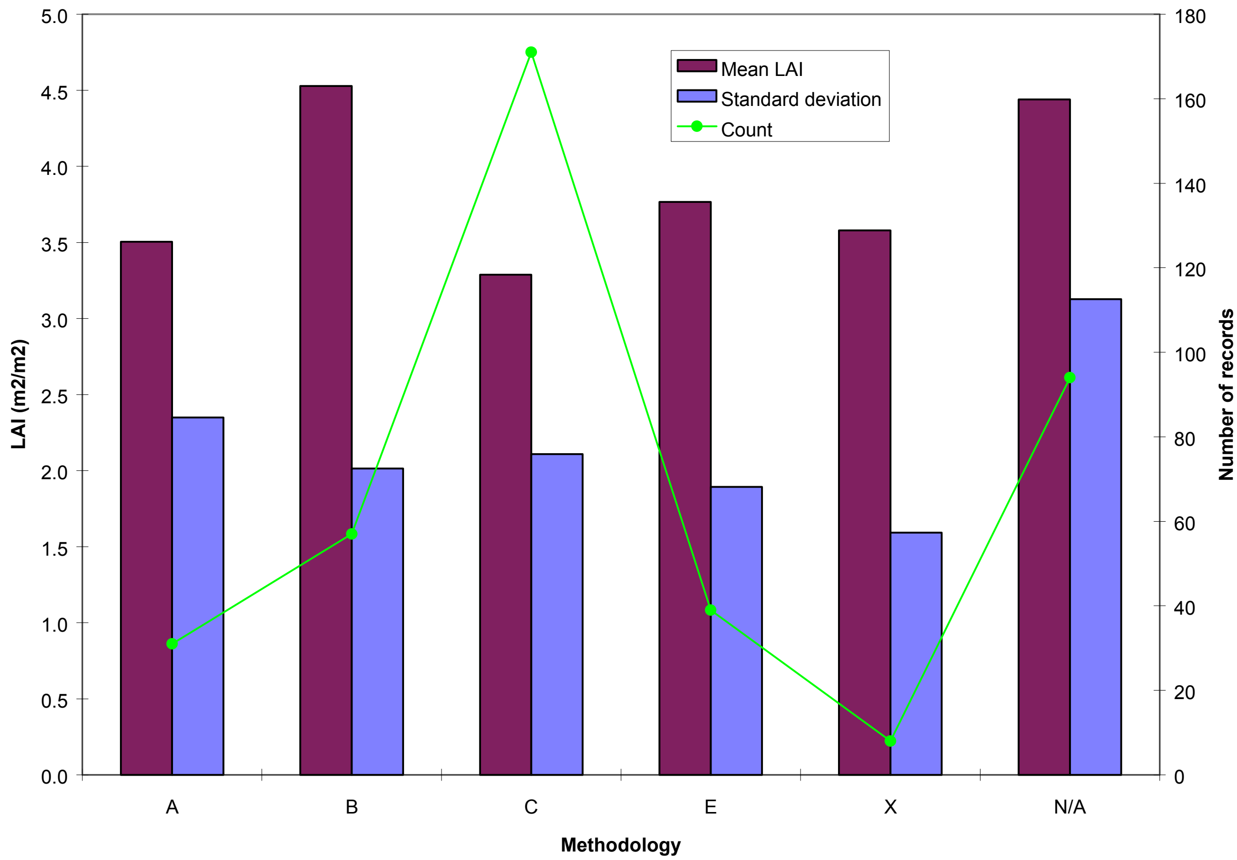

Fig. 4. Distribution of LAI data published in the decade 1991–2000, plotted by estimation methodology. Where a combination of methods was used, only the principal method is tallied. A, Destructive harvest; B, Litterfall; C, Allometry; E, Indirect noncontact (LAI-2000 or other); X, Unknown (i.e., literature was checked and method was not specified); N/A, Not available (i.e., literature was not available for checking).

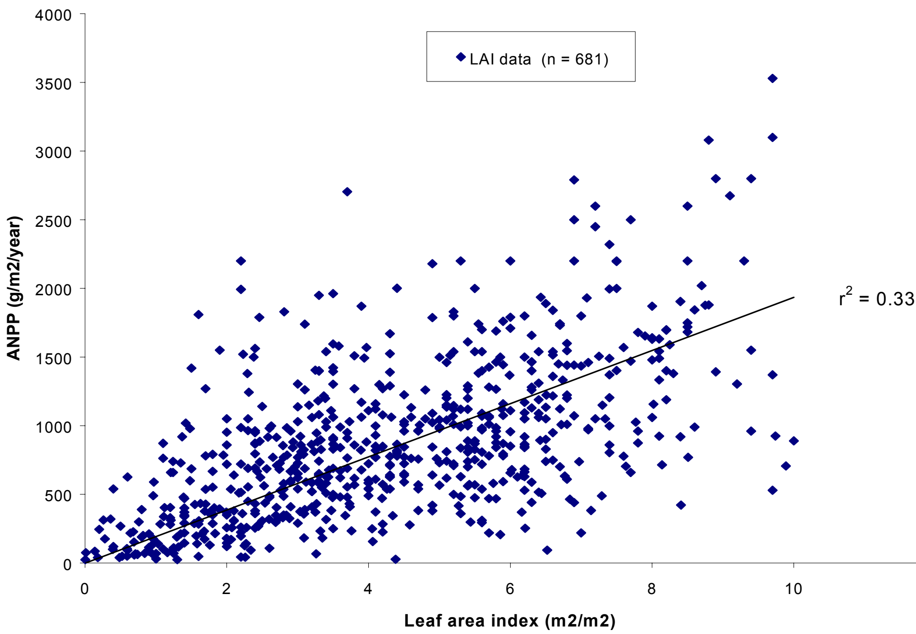

Fig. 5. ANPP as a function of LAI for a subset of the data for which both parameters were available.

As a further data-checking exercise, a common statistical outlier analysis was used to determine LAI data values that were unlikely to be accurately reported, either in measurement or in recording of the data (Sokal and Rohlf 1981). The interquartile range (IQR) approach is a non-parametric analytical method that identifies outliers via a detailed statistical determination of a data distribution. The data were first ranked from lowest numerical value to highest, and the median and quartiles of the data set were determined. Statistical outliers were then defined as those data values that lie beyond an "inner fence," which is defined by

$$x < F_1 + 1.5(IQR) \qquad \text{or} \qquad x > F_3 - 1.5(IQR),$$

where F_1 and F_3 are the first and third quartiles
and $IQR = F_3 - F_1$.

The outlier analysis indicated that a total of 53 statistically improbable values occurred throughout the entire data set (Table 6). The global mean LAI value was subsequently decreased from 5.23 to 4.51 following the outlier analysis. More importantly, the global maximum LAI value fell from 47.0 to 12.1 (or 15.0, when biomes were considered individually). Of the 15 biomes, 6 had no statistical outliers, partly because of the conservative nature of the IQR method (Sokal and Rohlf 1981). Other more aggressive approaches, such as Grubbs' Method (Grubbs 1969) could have produced additional outliers for flagging or potential removal from the data set.

Several biomes had statistical outliers that, when removed, resulted in significant changes in mean, minimum, and maximum LAI values (Table 6). The boreal and temperate deciduous broadleaf biomes showed notable decreases in maximum LAI values following the analysis, although the mean values for these biomes were not significantly changed. In contrast, the IQR analysis removed three outliers from the grassland biome data set, which resulted in a drastic decrease of the maximum reported LAI value from 15.4 to 5.0 and a subsequent decrease in mean LAI from 2.5 to 1.7 (Table 6). Likewise, the temperate evergreen needleleaf biome experienced a drop in maximum LAI from 47.0 to 15.0 and a fall in mean LAI from 6.70 to 5.47. Overall, the IQR outlier analysis served mostly to remove very high LAI values, which occasionally led to decreases in the mean LAI value reported for a biome.

Table 5. Extended list of land validation sites for satellite remote sensing, matched to nearest sites from the Worldwide Historical LAI data set (this study)

Cross-referencing was possible for 29 out of the list of 40 sites, in many cases for the same type of biome/vegetation cover. List of sites based on NASA Earth Observing System (EOS) LAI Meeting, Frascati, Italy, June 2001.

Extended list of EOS land validation sites					Nearest historic LAI sites				
Validation site name	Country	Biome	Lat (dd)	Long (dd)	LAI site name	Biome/cover	Lat	Long	LAI historic
ARM/CART-Ponca City	OK, USA	Cropland	36.750	-97.083	ARM-CART, Ponca, OK	Cropland/wheat	36.75	-97.08	7.50
ARM/CART	OK, USA	Cropland	36.770	-97.130					
ARM/CART-Shilder	OK, USA		36.850	-96.683					
ARM/CART-SGP	OK, USA	Grass/crop	36.640	-97.500					
ARM/CART-Little Washita	OK, USA		34.960	-97.979	Johnson and Risser (1974)	Forest/TeDBL	35.25	-97.33	4.80
BARC/USDA-ARS	MD, USA	Crop/decid forest	39.030	-76.850	Georgetown, DE	Cropland/beans	38.70	-75.30	Range 0.90–2.50 (days 38–69)
Barton Bendish	UK	Cropland	52.617	0.527	Sutton Bonington	Wheat	52.83	-1.25	5.52 ± 1.42 (n = 5)
Bondville	IN, USA	Cropland	40.007	-88.291	Lincoln, NE Kansas	Wheat/soybean Wheat	40.48 39.15	-96.40 -96.62	2.70/3.20 (n = 2) 1.50/3.50 (n = 2)
BOREAS NSA	Canada	Conif forest	55.880	-98.481	BOREAS NSA	Forest/BoENL	55.75 –55.92	-97.69–99.03	3.08 ± 2.47 (n = 13)
BOREAS SSA	Canada	Conif forest	53.656	-105.323	BOREAS SSA	Forest/BoENL	53.59	-104.73–106.20	3.45 ± 3.21 (n = 6)
Brasschaat (De Inslag)	Belgium		51.300	4.517	Various	Forest/TeDBL	50.03 –50.18	4.35–5.23	6.00 ± 1.88 (n = 5)
Cascades/HJ Andrews	OR, USA	Conif forest	44.249	-122.180	Andrews Exp. Forest, OR	Forest /TeENL	44.25	-122.33	12.50
Cascades/Old Pine	OR, USA	Conif forest	44.499	-121.624	Oregon Gholz plot VI (pine)	Forest/TeENL	44.50	-121.50	7.00
Cascades/Young Pine	OR, USA	Conif forest	44.417	-121.567	OTTER Metolius control (pine)	Forest/TeENL	44.25	-121.75	0.80
Harvard Forest	MA, USA	Decid forest	42.538	-72.171	Asner (1998)	Forest/TeDBL	42.50	-72.20	3.20–5.50
Howland	ME, USA	Conif forest	45.200	-68.733					No sites; ± 1.0 degree lat

Table 5 (continued)

Extended list of EOS land validation sites					Nearest historic LAI sites				
Validation site name	Country	Biome	Lat (dd)	Long (dd)	LAI site name	Biome/cover	Lat	Long	LAI historic
Ji Parana/Jaru	Brazil	Trop BL forest	-10.083	-61.931					No sites; ± 1.00 degree lat
Jornada LTER	NM, USA	Shrub/ woodland	32.607	-106.870	Jornada LTER, NM	Grass/shrub	32.52	-106.80	Range 0.80–3.90
Jrvselja	Estonia	Boreal forest	58.260	27.300					No sites; ± 1.00 degree lat
Kejimkujik Park, Nova Scotia	Canada	Decid forest	44.500	-65.500	Fundy Model Forest	Forest/TeMXD	45.43	-65.31	8.60
Konza	KS, USA	Grassland	39.082	-96.560	Konza	Grassland	39.10	-96.61	0.30–3.50
Krasnoyarsk	Russia	Boreal forest	57.270	91.600					No sites; ± 1.00 degree lat
Landes	France	Conif forest	44.567	-1.033					No sites; ± 1.00 degree lat
Mali	Mali	Shrubland	15.333	-1.533					No sites; ± 1.00 degree lat
Mandalgobi	Mongolia	Grass/crop	45.995	106.327	Zhao (1994) [CHINA]	Forest/TeMXD	45.00	127.00	4.65 ± 2.01 (n = 8)
Maricopa	AZ, USA	Crop/decid forest	33.070	-111.970	Whittaker and Niering (1975)	Woodland	32.50	-111.00	2.22 ± 1.02 (n = 4)
					Whittaker and Niering (1975)	Forest/TeMXD	32.50	-111.00	10.88 ± 5.14 (n = 8)
Maun	Botswana	Woodland	-19.923	23.594					No sites; ± 1.00 degree lat
Mongu	Zambia	Woodland	-15.438	23.253					No sites; ± 1.00 degree lat
NTL LTER	WI, USA	Conif forest	45.946	-89.600	Price County, WI	Forest/TeENL	45.90	-90.20	2.40/3.10 (n = 2)
Okwa River	Botswana	Shrubland	-22.409	21.713					No sites; ± 1.0 degree lat
Pandamentanga	Botswana	Woodland	-18.655	25.500					No sites; ± 1.0 degree lat
Park Falls	WI, USA	Decid forest	45.946	-90.272	Fassnacht and Gower (1997)	Forest/TeDBL	45.70–46.10	88.90–90.20	5.70 ± 1.32 (n = 15)

Table 5 (continued)

Extended list of EOS land validation sites					Nearest historic LAI sites				
Validation site name	Country	Biome	Lat (dd)	Long (dd)	LAI site name	Biome/cover	Lat	Long	LAI historic
Podkamennaya	Russia	Boreal forest	61.500	92.500	Schulze et al. (1995)	Forest/BoDNL	60.85	128.27	1.03–5.70 (n = 3)
Romilly	France	Cropland	48.433	3.800	Fontainebleu	Forest/TeDBL	48.43	2.68	4.32 ± 2.20 (n = 5)
Ruokolahti	Finland	Conif forest	61.533	28.700	South Karelia	Forest/BoENL	62.00	34.00	3.06 ± 0.82 (n = 17)
SALSA San Pedro	AZ, USA	Shrub/ woodland	31.740	-109.850	Whittaker and Niering (1975)	Desert	32.50	-110.75	0.93 ± 0.46 (n = 4)
Sevilletta LTER	NM, USA	Grass/crop	34.344	-106.671	Sevilletta	Shrubland	34.35	-106.88	Range 0.80–1.90
Skukuza, Kruger N.P.	South Africa	Savanna	-25.020	31.497	Nylsvley	Grass/savanna	-24.60	28.70	0.78 ± 0.16 (n = 5)
Tapajos/Santarem	Brazil	Tropfor (primary)	-2.857	-54.960	Tapajos	Forest/TrEBL	-3.5	-55.3	Range 3.80–7.10
Tapajos/Santarem	Brazil	Tropfor (logged)	-3.017	-54.971					
Tapajos/Santarem	Brazil	Trop pasture	-3.020	-54.889	Tapajos	Pasture	-3.20	-54.60	Range 0.25–9.10
Tshane	Botswana	Savanna	-24.164	21.893					No sites; ± 1.00 degree lat
Uardry, NSW	Australia	Grass/crop	-34.390	145.300	Kioloa State Forest	Forest/TeEBL	-35.35	150.18	3.12 ± 1.00 (n = 13)
Virginia Coast Reserve	VA, USA	Crop/decid forest	37.500	-75.670					No sites; ± 1.00 degree lat
Walker Branch	TN, USA	Decid forest	35.958	-84.288	Walker Branch/Oak Ridge	Forest/TeDBL	35.96	-84.29	5.03 ± 0.12 (n = 3)
Watson Lake, Yukon	Canada	Conif forest	60.100	-128.800					No sites; ± 1.00 degree lat
Zotino	Russia	Boreal forest	61.000	90.000					No sites; ± 1.00 degree lat

Table 6. Statistical distribution of LAI by biome, for the original data compilation, and after removal of outliers following Inter-Quartile Range (IQR) statistical analysis

Of the original total of 1008 records, 77 were excluded from this analysis (e.g., because biome was not available). See Table 1(b) for biome acronyms.

	Original data					Data after IQR analysis				
Biome	Number of observations	Mean	Standard deviation	Min	Max	Number of outliers removed	Mean	Standard deviation	Min	Max
All	931	5.23	4.08	0.002	47.0	53	4.51	2.52	0.002	12.1
Forest / BoDBL	58	2.64	1.03	0.28	6.0	5	2.58	0.73	0.6	4.0
Forest / BoENL	94	3.50	3.34	0.48	21.6	8	2.65	1.31	0.48	6.21
Crops	88	4.22	3.29	0.2	20.3	5	3.62	2.06	0.2	8.7
Desert	6	1.31	0.85	0.59	2.84	0	1.31	0.85	0.59	2.84
Grassland	28	2.50	2.98	0.29	15.4	3	1.71	1.19	0.29	5.0
Plantation	77	8.72	4.32	1.55	18.0	0	8.72	4.32	1.55	18.0
Shrub	5	2.08	1.58	0.4	4.5	0	2.08	1.58	0.4	4.5
Forest / BoTeDNL	17	4.63	2.37	0.5	8.5	0	4.63	2.37	0.5	8.5
Forest / TeDBL	187	5.12	1.84	0.4	16.0	3	5.06	1.60	1.1	8.8
Forest / TeEBL	58	5.82	2.57	0.8	12.5	1	5.70	2.43	0.8	11.6
Forest / TeENL	215	6.70	5.95	0.002	47.0	16	5.47	3.37	0.002	15.0
Forest / TrDBL	18	3.92	2.53	0.6	8.9	0	3.92	2.53	0.6	8.9
Forest / TrEBL	61	4.90	1.95	1.48	12.3	1	4.78	1.70	1.48	8.0
Tundra	13	2.69	2.39	0.18	7.2	2	1.88	1.47	0.18	5.3
Wetlands	6	6.34	2.29	2.50	8.4	0	6.34	2.29	2.5	8.4

8. DISCUSSION

At the present time, about 1000 LAI records are available for an estimated 400 unique field sites, together with associated variables such as latitude/longitude, elevation, stand age, aboveground NPP, etc. This data compilation attained its target—it was originally estimated that around 1000 distinct LAI measurements worldwide might be available from the scientific literature—and a possible further 500 to 1000 data points have been identified by the authors. However, we are aware that certain kinds of biome/land cover types are under-represented in this data set—deserts, wetlands, and shrublands are particularly lacking, suggesting a need for directed field work in the future.

Modeling and EOS satellite product validation both require field measurements to constrain LAI values for different biomes (typical minimum and maximum values, phenology, etc.). The value of this kind of historical data set lies in providing realistic ranges by biome/land cover type for comparison with newly collected data. A data point for MODIS validation is better than nothing, even with imperfect ancillary information! (Running, S. W., University of Montana, personal communication, December 1998). Maximum values for point measurements are unlikely to be exceeded or even approached for spatially weighted LAI, which is what satellites and truly spatial models are measuring or modeling. As the size of the sample area increases, the range of LAI found for a particular biome or land cover type (particularly its maximum value) will decrease. Thus, large areas (1 km^2 or more) are unlikely to ever have LAI greater than 5, although LAI from field plots may exceed 8 or even 10 in some cases. Our global outlier analysis suggests that LAI values in excess of 12 do not appear to fit in this worldwide historical data set, a view which is supported by expert opinion (Waring, R. H., Oregon State University, personal communication, October 2001).

LAI in needleleaf canopies stands out from all other vegetation cover types—some of these include all-sided LAI, which is clearly a different parameter from one-sided broadleaf LAI—but even needleleaf projected LAI is not really the same thing. Older estimates of needleleaf LAI obtained using allometric equations tend to be biased by the larger, open-grown trees used to develop the relationships between foliage mass and tree diameter (Waring, R. H, Oregon State University, personal communication, October 2001). Indirect noncontact (optical) LAI estimates (e.g., LAI-2000) may be comparable with destructive harvesting or allometry for broadleaf canopies, but in needleleaf canopies it appears that a "clumping factor" also has to be taken into account (see Chen et al. 1997, Section 3). Such techniques estimate an "effective" LAI which may be an underestimate when foliage in the canopy is non-randomly distributed or clumped (Gower et al. 1999).

The vast majority of these field-based LAI data are from small sample plots (typically 0.2 ha in size or less, but many studies do not clearly report the number of samples or their spatial extent). Such data represent the LAI of individual canopies and/or canopy clusters. However, as the integrated area of the measurements increases, the reported LAI decreases because the fractional cover of the canopies becomes a contributing factor:

pixel or grid cell LAI, spatially weighted = plant LAI * fractional canopy cover

A small number of field studies have worked along homogenous transects, and a very few studies have actually addressed the issue of scaling-up. For example, the Bigfoot initiative (formerly MODLERS) is addressing the topic of scaling from point field measurements to the relatively coarse resolution of satellite products, by measuring and scaling-up LAI and other parameters for 5 km ∗ 5 km grids (based on 25-meter and 1000-meter cells) around four flux tower sites in North America.

9. DATA AVAILABILITY

9.1 ORNL DISTRIBUTED ACTIVE ARCHIVE CENTER FOR BIOGEOCHEMICAL DYNAMICS

The LAI data are maintained and distributed by the ORNL Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics (http://www.daac.ornl.gov). The DAAC provides information about the Earth's biogeochemical dynamics to the global-change research community, policymakers, educators, and the interested general public. The ORNL DAAC is part of the Earth Observing System Data and Information System Project of the National Aeronautics and Space Administration (NASA), which forms an integral part of NASA's contribution to the U.S. Global Change Research Program. For information about this data set and others, the DAAC User Services staff may be contacted at

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9.2 CAUTIONS IN USING THE DATA

Creating a single compilation of LAI data for this large number of sites required certain assumptions and conversions that may not be universally applicable to all sites. Some of the sites in this data set are agricultural sites, and others may represent natural systems with management treatments, such as fertilizer, irrigation, grazing, burning, or thinning. Where possible, we have tried to indicate uncertainties or unusual treatments. Detailed descriptions of the study sites, sampling methods, and the method of estimating LAI are available only in the original literature. Therefore the inclusion of points in this data set is no guarantee that the LAI values are strictly comparable. The data should be regarded as illustrating the range of LAI for natural and managed ecosystems worldwide. However, we anticipate that users may find this data set useful as an index to select more detailed LAI site data, or that they may select a subset of these data for their use. Users of this synthesis are strongly encouraged to check the primary literature prior to using these data.

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