Validation of Global Moderate-Resolution LAI Products: A Framework Proposed Within the CEOS Land Product Validation Subgroup

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***Abstract*—Initiated in 1984, the Committee Earth Observing Satellites' Working Group on Calibration and Validation (CEOS WGCV) pursues activities to coordinate, standardize and advance calibration and validation of civilian satellites and their data. One subgroup of CEOS WGCV, Land Product Validation (LPV), was established in 2000 to define standard validation guidelines and protocols and to foster data and information exchange relevant to the validation of land products. Since then, a number of leaf area index (LAI) products have become available to the science community at both global and regional extents. Having multiple global LAI products and multiple, disparate validation activities related to these products presents the opportunity to realize efficiency through international collaboration. So the LPV subgroup established an international LAI intercomparison validation activity. This paper describes the main components of this international validation effort. The paper documents the current participants, their ground LAI measurements and scaling techniques, and the metadata and infrastructure established to share data. The paper concludes by describing plans for sharing both field data and high-resolution LAI products from each site. Many considerations of this global LAI intercomparison can apply to other products, and this paper presents a framework for such collaboration.**

***Index Terms*—Committee on Earth Observing Satellites (CEOS), leaf area index (LAI), validation.**

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I. Background

A. Committee on Earth Observing Satellite's Land Product Validation Subgroup

The Committee Earth Observing Satellites' Working Group on Calibration and Validation (CEOS WGCV) was initiated in 1984 to pursue activities to coordinate, standardize, and advance calibration and validation of civilian Earth-observing satellites and their data. Five subgroups comprise the implementation arm of the WGCV. One subgroup, Land Product Validation (LPV) [1], was established in 2000 to define standard guidelines and protocols, and to foster data and information exchange relevant to the validation of land products. The subgroup's emphasis since its inception has been to provide a validation service for the Global Terrestrial Observation System (GTOS) [2]. This implies a focus on the terrestrial "Essential Climate Variables" of GTOS; which lists a number of critical products including leaf area index (LAI) [3]. Global LAI products provide key information on the exchange of energy, mass (e.g., water and CO_2), and momentum flux between Earth's surface and the atmosphere. LAI is utilized in most ecosystem productivity models and global models of climate, hydrology, and biogeochemistry [4]–[10]. LAI has been defined as the total leaf area (one-sided) in relation to the ground [11], or more specifically, as the one-sided green leaf area per unit ground area, in broadleaf canopies, and as the projected needle leaf area in coniferous canopies [12]. More generally, this can also be expressed as the total foliage surface area per unit of horizontally projected ground surface area [13]. However, for the CEOS LAI Intercomparison, needle leaf area is taken to be half of the total foliage surface area [14]. This definition has been adopted because it conforms to the reference "ground truth" LAI measured by optical instruments such as LAI-2000 and TRAC, which are the most commonly used validation instruments.

As various CEOS members each produce their own global LAI maps, characterization of each product's uncertainty—i.e., validation—becomes increasingly important for users to determine the most appropriate product, or combination of products, to use for their applications. CEOS defines validation as the process of assessing the quality of the data products derived from system outputs by independent means [15]. The LPV subgroup addresses the validation of specific products through topical meetings focused on opportunities for international collaboration to support the validation of those products. Much of LPV's initial guidance grew out of the experience gained through NASA' Earth Observing System (EOS) validation program [16], initiated in the 1990s; working to expand that effort internationally. To date, topical meetings have addressed albedo, land cover, LAI, and fire disturbance [1].

The motivation for organizing international validation collaboration is based on two premises. First, if different space agencies are producing similar satellite products, field validation efforts for one agency's product can also be used to validate another's. Second, making the most use of field validation data sets requires both detailed documentation and open access to those data. The first premise provides the impetus for CEOS members to participate in the activity. The second premise presents a need that is being met by the efforts of LPV. This paper presents LPV's collaborative efforts on LAI validation. The framework for collaboration on LAI products presented here can also be applied to other global products.

B. International LAI Intercomparison Effort

In the past five years, multiple LAI products have become available to the science community at both global and regional extents. The Moderate Resolution Imaging Spectroradiometer (MODIS) LAI product is produced every eight days globally at 1-km spatial resolution [17]. The MODIS record began in early 2000 and continues to present [18]. The MODIS approach was in part pioneered by the Advanced Very High Resolution Radiometer (AVHRR) LAI product developed by the same investigators [19]. The 16 km-resolution monthly AVHRR product was derived from an improved Pathfinder normalized difference vegeation index (NDVI) data set (1981 to 2001) [20]–[23]. The French Space Agency (CESBIO/CNES) has produced an LAI product from the PoLarization and Directionality of the Earth's Reflectances (POLDER)-2 sensor [24], [25]. The European Space Agency is supporting the GLOBCARBON project aimed at producing global fields of LAI (among other products) from the VEGETATION, Medium Resolution Image Spectrometer Instrument (MERIS), Advanced Along Track Scanning Radiometer (AATSR), and AVHRR sensors. Finally, the Carbon Cycle and Change in Land Observational Products from an Ensemble of Satellites (CYCLOPES) [26] program from the European Commission has developed preliminary biophysical products [including LAI and fraction of absorbed photosynthetically active radiation (fAPAR)] using multiple sensors. In addition to the global initiatives, regional LAI products have also been developed. For example, the Canada Centre for Remote Sensing (CCRS) has been producing standard LAI products over Canada since 1998 and is now performing a reanalysis back to 1985 using the AVHRR sensors [27]–[29].

These global LAI products and multiple, disparate validation activities related to these products present the opportunity to realize efficiency through international collaboration. The LPV group convened workshops in 1998 and 2001 on LAI products [30], [31]. These initial workshops established an international effort for global LAI product validation through an LAI intercomparison activity. A third workshop in 2004 [32] further advanced this effort and brought together the groups represented here.

Each of the nine groups currently involved in this effort has their own particular interest in quantifying the accuracy of LAI products. Some are explicitly funded to provide a validation service to an agency producing an LAI product. Others are more interested in using the global products for their needs or region. The LAI team at Boston University (BU) is responsible for the development of the NASA EOS LAI products [18]. They rely on validation activities to check the accuracy of their product and to guide refinement of their algorithms. The Validation of LAnd European Remote sensing Instruments (VALERI) [33] group, supported mainly by CNES and the Institut National de Recherche Agronomique (INRA), has focused on the development of an effective methodology to generate high spatial resolution maps of biophysical variables from satellites and the use of those maps for the validation of moderate-resolution global products. VALERI is closely integrated with the objectives of the CEOS LPV subgroup and is working to establish the uncertainty of global products for international initiatives such as the Integrated Global Observing System (IGOS) [34], GTOS [34], [35], and International Geosphere-Biosphere Program (IGBP) [36]. The BigFoot project [37] grew out of a prototype effort to characterize the Long Term Ecological Research (LTER) sites across the U.S., and expanded to help validate MODIS LAI, land cover and net primary productivity products at nine flux tower sites [38]. CCRS, in conjunction with the University of Toronto, has produced LAI maps of Canada [27], [28]. An integral component in the production of these maps has been an assessment of their accuracy. CCRS has invested in validation through its dataset of over 250 consistently surveyed forest and shrub LAI plots [39] within ten study areas [27], [28] located to sample a variety of forest types across Canada. The ten study areas have provided CCRS with an understanding of how the global LAI products can be used in concert with their own regional product [40]. The University of Alberta is conducting tropical forest studies aiming to relate remotely sensed data to ecological characteristics. Their LAI work is aimed at estimating field LAI and relating these to high-resolution (1–30 m) satellite imagery for dry and moist tropical forest sites [41]–[44]. Scientists at the U.S. Environmental Protection Agency's (EPA) Office of Research and Development have initiated LAI validation activities to quantify the uncertainty of the MODIS LAI product as a dynamic, spatially explicit input to models for atmospheric deposition, biogenic emissions, and

TABLE I
GROUP SUMMARY OF VALIDATION COMPONENTS FOR THE GROUPS CURRENTLY PARTICIPATING IN THE CEOS LAI INTERCOMPARISON

Group	Field instruments	Conversion of PAI to LAI	Understory correction	Site extent	Sampling scheme	High resolution imagery	Transfer function	Accuracy of high-resolution LAI map	Sensors used
Boston University	LAI-2000	No	Yes	various: from 5 x 5 km to 10 x 10 km	Two-stage	Landsat ETM+ (future: ASTER)	Parametric regression [56, 66] fine-res. MODIS algorithm. [56, 95]	derived from regression equations	MODIS
VALERI	LAI-2000 DHP	No	Yes	3×3 km	Two-stage	Landsat ETM+ SPOT HRVIR/HRG (future: ASTER)	Parametric regression Kriging [74]	cross validation and Kriged variance	MODIS VEGETATION MERIS POLDER AVHRR
BigFoot	LAI-2000 Allometry destructive meas.	No	No	5 x 5 km	Two-stage	Landsat ETM+ (future: ASTER)	reduced major axis regression [38]	cross validation [75]	MODIS
CCRS	LAI-2000 TRAC DHP	species-based conversion factors	No	10 x 10km 150 x 150km	Two-stage	Landsat TM/ETM+	Parametric regression [27, 40, 76]	derived from regression equations.	VEGETATION MODIS POLDER
University of Alberta	LAI-2000 DHP litter traps	using DHP from dry season and calibration from leaf litter and specific leaf area data	No	10x10 km	Two-stage	Landsat ETM+, Hyperion IKONOS/Quickbird	Parametric & Non-parametric regression, Bayesian Network and neural network [42, 43]	Calibration for dry forest [41]	MODIS
US EPA	DHP TRAC	No	Yes on 2 sites	1x1 to 2x2 km	Two-stage	Landsat ETM+, IKONOS	Parametric regression	NA	MODIS
Italy	LAI-2000 DHP destructive meas.	No	Yes	from 250x250m to 1x1 km	Two-stage	Landsat ETM+ Hyperspectral Airborne	Model inversion Parametric regression [96]	derived from regression equations	MODIS
Finland	LAI-2000	No	No	1km x1km (2 sites) 3km x 3km (2 sites)	One-stage Two-stage	Landsat ETM+ SPOT HRVIR	Parametric regression [46]	derived from regression equations	MODIS
Penn State	LAI-2000 ACCUPAR	No	No	1.6 x 1.6 km	One-stage	ASTER	work in progress	NA	MODIS

air quality forecasting. The EPA has focused efforts in the southeastern U.S. where they have measured LAI at six forested sites in the Albemarle–Pamlico Basin of North Carolina and Virginia during each growing season between May 2001 and October 2004. The University of Milano-Bicocca, Italy, is involved in part of the long-term Kyoto Experiment, a Joint Research Center Institute for Environment and Sustainability (JRC-IES) research project included in the framework of the CARBOEUROPE [45] cluster of projects aimed to understand and quantify the carbon balance at the European level. The University of Milano-Bicocca group is collecting LAI and fAPAR field measurements, in the context of CARBOEUROPE, in order to develop local relationships between canopy properties and carbon exchanges and to validate moderate-resolution remote sensing products at a total of 13 sites (two short-rotation poplar forests and 11 traditional poplar plantation sites, characterized by LAIs ranging between 0.3 to 4.0). The University of Helsinki effort is working to develop more accurate LAI estimation methodologies for boreal regions, focusing on the clumped structure of these conifer-dominated forests [46], [47]. The Finnish sites are dominated by Scots pine (*Pinus sylvestris* L.) at Ruokolahti, Hirsikangas, and Rovaniemi, and by Norway spruce (*Picea abies* (L.) Karst.) at Suonenjoki [48]–[50]. Penn State's Office for Remote Sensing of Earth Resources is integrating MODIS LAI and albedo products into the EPIC crop model [51] for estimating corn and rice yields and to test the sensitivity of the modeling to the MODIS land, soils, and weather inputs. The validation component of this research will span three growing seasons, 2005–2007, within corn and soybean fields in the central U.S. and rice fields in China. A summary of the characteristics of each group's work is given in Table I. The list of sites represented in this paper are listed at [52] and shown in Fig. 1.

C. General Framework for Collaboration on the Validation of Global Products

The four main components of international validation efforts are as follows:

1) an organizational entity;
2) the willingness of participants to improve the consistency between methods and results;
3) a mechanism for sharing the data along with a description of the procedure used;
4) the synthesis of data and results into global accuracy statements.

For the CEOS LAI intercomparison activity, LPV is serving as the organizing entity. Through the LPV's topical meetings on LAI [30]–[32], a general validation procedure has emerged [38], [53]. The main objective of this paper is to document the methods currently used by the LAI intercomparison activity participants, including ground LAI measurements and scaling techniques, and the metadata and infrastructure established to share data. The paper concludes by describing the plans for sharing both field data and high-resolution LAI products from each site.

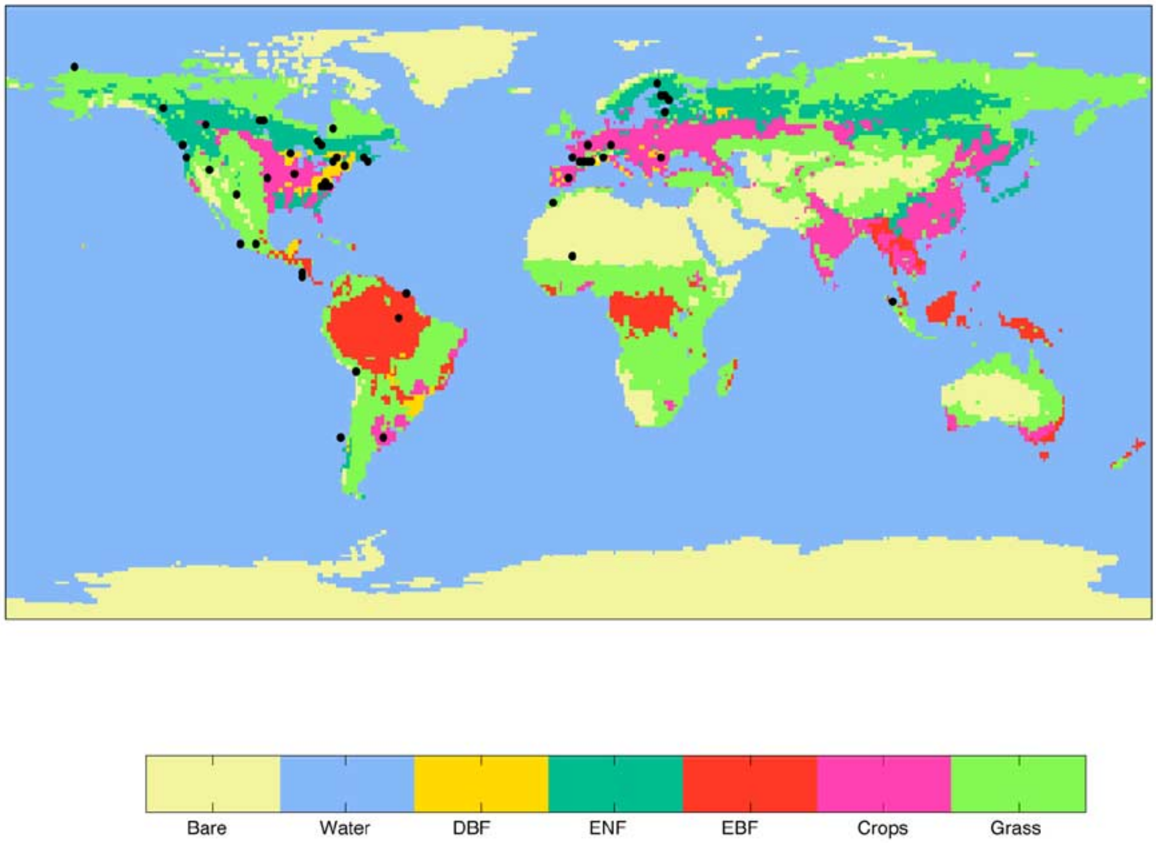

Fig. 1. Map of sites covered by the groups represented in this paper (given on a global map of dominant surface types in each $1^\circ \times 1^\circ$ cell (bare soil, water bodies, deciduous broadleaf forest, evergreen needleleaf forest, evergreen broadleaf forest, crops, grass) [87].

II. Bottom-Up Approach for Global Validation From Field Measurements

We present the LAI intercomparison activity as a "bottom-up" approach (i.e., from local field-level measurement to global comparison with satellite-derived LAI products). The following are the main considerations:

1) methods and instruments used to collect the field-reference LAI data;
2) measurement extent and sampling scheme at each site;
3) integration of field data with high-resolution imagery;
4) methods to compare high-resolution product with moderate-resolution product;
5) network of sites available for field validation.

Fig. 2 shows the relationship between these steps. Here we present more detail on the first three steps. As this paper focuses on establishing the intercomparison framework, it is important to document the fixed components. However, using the field data that have been collected, future efforts will address synthesis studies which can both provide details on, and explore different methods related to, the last two steps.

A. Field Reference LAI Measurements

LAI can be measured directly by destructive methods, or indirectly via allometric relationships. However, these are both quite time consuming, and cannot be applied routinely to multiple locations. For this reason, the nine groups mainly used noncontact indirect methods to estimate LAI from gap faction measurements. The following four optical instruments are currently used by the groups in this intercomparison activity (the order here does not imply any preference or degree of accuracy):

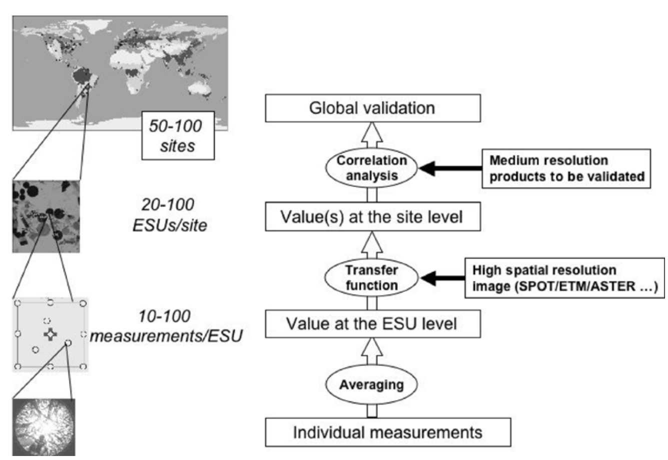

Fig. 2. General global land product validation procedure applied to LAI.

- LAI-2000 Plant Canopy Analyzer (Li-Cor Inc., Lincoln, NE) [54];
- cameras equipped for digital hemispherical photography (DHP) [55];
- AccuPAR Linear Par Ceptometer (Decagon, Inc., Pullman, WA);
- Tracing Radiation and Architecture of Canopies (TRAC) instrument (3rd Wave Engineering, ON, Canada) [56], [57].

Some groups are using a single type of instrument, while others are combining instruments. Within the VALERI group, field measurements are generally performed using gap fraction measurements either based on the LAI-2000 instrument or DHP, depending mainly upon vegetation type [55]. BigFoot's LAI was derived from LAI-2000 along with allometry and direct harvest. Their methodology varied by date and vegetation type [58]–[60]. For the University of Alberta sites, LAI was estimated using the LAI-2000 combined with DHP. In this study litter traps were also used at one of the dry forest sites [41]. Measurements with the LAI-2000 in Finland were complemented with relascope sampling [61] at the center of each plot. The CCRS and the EPA [62] groups used a combined LAI-2000/TRAC or DHP/TRAC method for *in situ* LAI measurements. At the Italian forest plantation sites, field measurements included the LAI-2000, DHP, and destructive sampling [63].

The use of gap fraction and gap size distribution to estimate LAI depends upon light measurements within the canopy that are influenced by site, species, and leaf characteristics. The many issues associated with the use of different optical methods to determine LAI, such as illumination and clumping are covered in detail in [64]. Sampling and footprint issues are well covered in [55], where the influences are site homogeneity, canopy and sampling device used. Weiss *et al.* [55] also discusses the issue of nongreen elements, which are particular issues in forested sites, where the woody contribution using optical methods can be significant. CCRS used conversion factors to correct for this, and have documented these factors, as well as the instruments and processing applied, in the CCRS LAI database [39]. For the University of Alberta's three dry-forest sites, dry season hemispherical photographs were used to estimate the contribution of the wood area index. The combination of wood area index and litter traps [41] allowed for a calibration of the LAI values from the LAI-2000 measurements. The Italian group apprised the magnitude of stem and branch contributions by using gap fraction measurements collected during leaf-off conditions. Understory LAI can significantly impact vegetation indexes (VI) commonly used to generate fine-resolution LAI maps. Several studies proposed to explicitly include measurement of the understory component. The BU team utilized the reduced simple ratio (RSR) [65] to reduce the impact of understory on the correlation between vegetation indexes and overstory LAI [66]. Understory LAI was quantified in Italy and Finland (Hirsikangas site) through measurements of the total LAI (positioning the sensor at ground level) and the overstory LAI (positioned just above the understory vegetation) [63]. A similar approach was applied in the forest sites sampled by the VALERI group using upward-looking and downward-looking DHP to characterize the overstory and understory LAI, respectively. At the EPA's Appomattox and Hertford sites, complete understory removal was performed on each 100×100 m quadrant [67]. A comparison of pre- and post-removal IKONOS imagery at Hertford showed a 3.5% decrease in NDVI ($p < 0.05$) after understory removal.

Validation of LAI from gap fraction measurements was performed using direct measurements, destructive sampling or allometric relationships. Kalacska [41] found a strong linear correlation between LAI-2000 measurements and litter traps in a dry tropical forest. The Italian group has found LAI derived from destructive sampling was always greater than the LAI computed from LAI-2000 [63]. This difference is suspected to be due to the observed clumping at crown level. The LAI-2000 and destructive LAI estimates have a strong linear relationship, with an RMSE of 0.32 m^2/m^2. Within the VALERI group, LAI derived from allometric relationships were compared to those derived from LAI-2000: over the Järvselja Estonia site in 2000 [68], a relatively good agreement is found, except in relatively inhomogeneous situations; conversely, over the Nezer site in France, the LAI-2000 was providing biased estimates of LAI, while DHP was providing better and unbiased estimates [69].

There have also been comparisons between results from multiple optical instruments. CCRS has found that DHP-based LAI estimates are well correlated with LAI-2000 and TRAC-based estimates although there is an offset likely related to a combination of multiple-scattering effects [70] and the resolution of the DHP instruments [71]. The DHP processing approach developed at CCRS was compared to the CAN_EYE software [72] that the VALERI group developed using images acquired for the VALERI Larose Forest site in Ottawa, Canada. Effective LAI values differed by less than 5%, though clumping estimates differed by up to 20% for some plots. This suggests that intercomparison of clumping corrections for optically based *in situ* LAI estimates should be investigated further as Jonckheere *et al.* [64] also concluded that clumping was the greatest error influence in the indirect estimation of LAI.

B. Site Extent and Sampling Schemes

The smallest site extent is defined as the minimum area compatible with the resolution of the satellite product to be validated. Given the current moderate-resolution LAI products, a minimum size is approximately 1 km^2, although this size is perhaps too small, considering the point spread function and geolocation uncertainties of these sensors. However, if a site is located in a relatively homogeneous area, these problems are certainly minimized. The largest extent investigated was 150×150 km (CCRS, Table I), allowing for an investigation of the variability of LAI within the sites.

The sampling scheme is mainly driven by the footprint associated with the field measurements as well as by the up-scaling process and imagery that will be used. Some groups are using geostatistical methods to scale up local measurements, which are generally performed over a relatively small site extent. Most groups are using high spatial resolution images, sometimes in combination with geostatistical methods, to scale up the local field measurements. The objective pursued by the sampling strategy will be to use elementary sampling units (ESU) to capture the variability across the site extent, and repeat measurements within the ESU to capture the variability within the high spatial resolution imagery ($\sim$ 30 m). Consensus among the participating groups is toward a two-stage nested sampling approach, as proposed by [73] (Fig. 3).

Validation studies must define the sampling scheme within the ESU (also called primary sampling units in [73]). Sampling within the ESU should consider the footprint of the field measurement and pixel size of the high-resolution image used in the

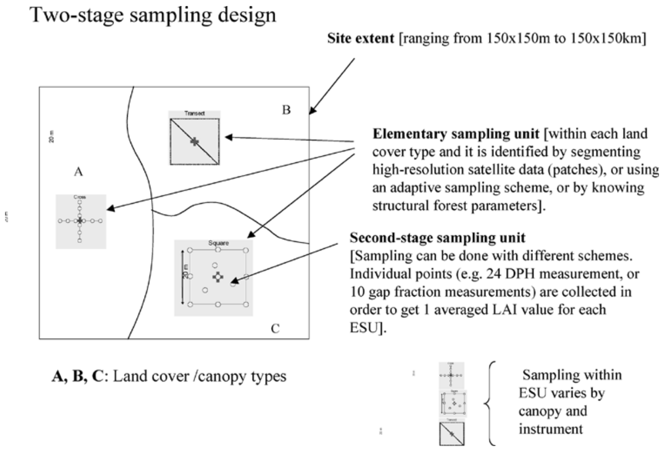

Fig. 3. Diagram representing two-stage sampling designs. Sampling design specification will depend on land cover class and measurement device. Design A correspond to low canopies of crops and grassland. Design B utilizes a transect required by the TRAC instrument, and design C is for forest canopies.

up-scaling process. For devices such as LAI-2000, DHP or AccuPAR, the extent of the ESU represents a small cluster of pixels [38], [42], [43], [74]. At the maximum, the ESU corresponds to a patch of a vegetation class [53], [66] or a plot of managed forest or crop (Italian group). For the TRAC instrument, the extent of the ESU is defined by the pattern of transects used (EPA and CCRS groups) [28]. The sampling scheme within each ESU is quite variable, generally based on a fixed pattern for the smallest extents (Fig. 3, class A), or on transects with TRAC (Fig. 3, class B), and a more or less random sampling for the largest extents, corresponding to patches of vegetation (Fig. 3, class C). The number of individual measurements largely depends on the extent of the ESU, and the height of the canopy. The minimum number is 5 (Bigfoot) and a maximum of 100 (University of Alberta), for small canopies.

Validation studies also need to define the distribution of the ESUs over the whole site. The ESUs are either based on the availability of a land cover map [18], on the use of a recent high spatial resolution image [38], or using an adaptative approach [74]. ESU placement is a compromise between spacing as close as possible for efficiency and yet far enough apart to avoid spatial autocorrelation or neighbor heterogeneity [38], [74]. The number depends on the extent of the site, its variability and the extent of the ESUs themselves.

C. Deriving LAI Maps From Field Data and High-Resolution Imagery

Once the field data have been collected and converted to green LAI values, the next step is to associate the measurements with the spectral values from high-resolution imagery. Establishing the relationship between the field-based LAI estimates and imagery is known as up-scaling. Methodology for up-scaling has evolved over the last five years and is now starting to stabilize. The up-scaling process is mainly based on the calibration of empirical transfer functions that establish a relationship between the average LAI values from each ESU and the multispectral values from a satellite or airborne image. Selection of the optimal transfer function is site-specific [75]. A summary of the groups' transfer functions and references are listed in Table I. The empirical relationships selected are usually based on linear regressions with vegetation indexes [28], or multiple linear regression with top-of-the-atmosphere or top-of-canopy reflectances when available [74]. Recent work on regression error models for transfer functions [76], [77] may help quantify the uncertainty in the LAI maps derived this way and the implications of comparing the high-resolution and moderate-resolution LAI surfaces.

Because of the empirical nature of the transfer functions used, atmospheric corrections are not mandatory if it is safe to assume the atmosphere characteristics are constant over the site. Atmospheric correction could be applied [78] if aerosol properties are available (such as those collected through AERONET; [79]). Where not available, atmospheric correction can still be accomplished based on empirical methods [80], [81]. Atmospheric correction allows intersite comparison of radiance or reflectance values and thus, intersite comparison of the transfer functions.

The most common high-resolution satellite sensors used here are the Enhanced Thematic Mapper plus (ETM+) on Landsat-7 [82], Thematic Mapper (TM) on Landsat-5 [83], SPOT High Resolution Visible InfraRed (HRVIR) on SPOT 4, and SPOT High Resolution Geometric (HRG) on SPOT 5 [84]. All groups used data from one of these sensors. Penn State plans to utilize the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor [85], [86]. BU, VALERI, and BigFoot also expect to utilize ASTER in future analyses. The high-resolution LAI maps derived from these sensors range from 15- to 30-m resolution, which is relatively consistent with the extent of the ESUs. The University of Alberta and EPA groups are utilizing ETM+ data as well as higher resolution ($\sim$ 1 m) imagery available from the IKONOS (Space Imaging, Thornton, CO) or Quickbird (DigitalGlobe, Longmont, CO) sensors.

D. Aggregation of High-Resolution LAI Maps to Match Moderate-Resolution Product

The comparison between the ground-based LAI maps with moderate-resolution products requires a consistent statistical support area. This apparently simple problem is quite complex if all the uncertainties and effects associated with the satellite products are accounted for. The following processing steps must be addressed prior to any comparisons.

Step 1) Project the satellite product and the LAI high-resolution map in the same coordinate system. It is preferable to maintain the projection system of the satellite product being validated as the reference projection. Spatial errors due to resampling imagery are relative to the image pixel size. Errors are reduced by reprojecting the high spatial resolution imagery to match the moderate-resolution product.

Step 2) Coregister the high spatial resolution LAI map to the moderate-resolution satellite product to reduce possible geometric errors. This can be achieved through correlation techniques. However, this generally requires images larger than the site extent to be able to exploit particular heterogeneities in the image as ground control points.

Step 3) Aggregation of the LAI map according to the apparent point spread function (PSF) of the satellite product. Satellite images are produced through of a series of processing steps, including resampling and temporal compositing. Each additional step makes it more difficult to track how the sensor PSF relates to the ultimate product "effective" PSF.

Steps 1) and 2) are fairly straightforward; however Step 3) is currently poorly addressed and is one of the reasons why it is generally difficult to validate moderate-resolution satellite products at their original resolution. This step would require a detailed knowledge of the sensor geometric characteristics as well as careful tracking of the processing to fully understand the spatially weighted ground area influencing a given pixel in the moderate-resolution imagery. More research in this area seems warranted.

E. Global Validation From the Network of Sites Available

Global validation is the final stage of this exercise and corresponds to the comparison between the aggregated high-resolution LAI map and the corresponding satellite product, achieved over an area as large as possible containing an ensemble of sites. The sites should represent the variability and range of LAI and canopy types as observed over the Earth's surface. The sites covered by the groups represented in the paper are listed in [52] and shown in Fig. 1. These sites were selected based on individual group motivation rather than a global statistical sampling design. However, [87] describes methods for evaluating the distribution of LAI validation sites with respect to the global distribution of biomes and indicates that the current set of CEOS LAI intercomparison sites need to be more proportionally representative of global land cover. A synthesis of field-observed LAI values, going back to 1981, are given in [88], which highlights the fact that many more field LAI measurements are available. More abundant data sources and groups could be incorporated in future efforts if they have the resources required to scale up measurements for comparison with the moderate-resolution products.

Now we present results of comparisons of high-resolution LAI maps with the global or regional moderate-resolution LAI products provided by some of the teams. The global moderate-resolution products being validated by the various groups are summarized in Table I

The BigFoot project compared their high-resolution LAI maps to the MODIS LAI product and considered both algorithm pathways [19] as well as the mean value across algorithm pathways. BigFoot found the LAI Collection 4 product to agree better with their high-resolution LAI maps than the earlier Collection 3 product. However, quality varied by algorithm pathway and cover/biome type. For low LAI, the estimates agreed fairly well, but higher MODIS and field-derived values were only weakly correlated. Seasonality in evergreen needleleaf forests appears exaggerated in the MODIS product and there are significant differences in LAI depending upon the algorithm pathway utilized. BigFoot found a large percentage of the MODIS LAI estimates were not from the main radiative transfer (RT) pathway [38] but were instead from the vegetation-index-based backup algorithm.

Boston University has validated the MODIS LAI product over six vegetation types, or biomes, and results have been reported in eight peer-reviewed publications [53]. MODIS LAI validation activities helped to identify anomalies in the Collection 3 product. Analysis of the Collection 3 MODIS LAI showed that the anomalies were due to three factors: 1) a mismatch between simulated and MODIS surface reflectances; 2) misclassification within the MODIS land cover product, which is an input to the LAI algorithm; and 3) limited precision of input MODIS surface reflectances [53]. Optimization of woody vegetation retrievals is an ongoing activity and will be implemented for Collection 5 processing which is to begin in 2006. Prototypes of Collection 5 LAI products in North America show an increase of about 20% to 30% in main RT algorithm retrieval rate and better agreement with field measurements over broadleaf forests [89]. Surface reflectances are highly contaminated by clouds and snow during the wintertime, which significantly limits the retrieval rate of the main RT algorithm and causes anomalous seasonality over needleleaf forests (similar effects are also seen in other MODIS land products; for example, NDVI and the enhanced vegetation index). Results from BU suggest that users should select LAI derived via the main RT algorithm and not the backup algorithm for application studies including validation.

CCRS [28] compared their Canada-wide LAI products derived from SPOT-VEGETATION (VGT) to Landsat-based LAI maps over eight scenes where *in situ* data were acquired. It was found that, in general, LAI estimates at 3 km-resolution agreed within one LAI unit (or 25% for LAI over 4), although some large outliers were found in areas with complex terrain and wetlands. Complex terrain corresponds to regions where both fine- and coarse-resolution reflectance estimates are difficult to correct for terrain-related bidirectional reflectance distribution function (BRDF). Wetland regions can induce differences in the infrared simple ratio (defined as the ratio of shortwave infrared to near-infrared bands [28]) between the dates of the fine- and coarse-resolution measurements. CCRS also recently compared the global POLDER (from June 1997) and MODIS Version 4 products with the CCRS regional SPOT VGT LAI maps over four forest sites [40]. They found that only the CCRS maps were typically within 25% of the up-scaled *in situ* maps. The MODIS LAI maps, in contrast, overestimated broadleaf and mixed-wood LAI by over 100% and were very weakly correlated with up-scaled reference LAI maps (correlation coefficients less than 0.25 for all sites evaluated).

The VALERI group has validated the products developed for MERIS and MODIS over the six sites sampled in 2000 (Fig. 4). Additionally, the climatological LAI values proposed by the ECOCLIMAP physiographic database [90] are also displayed. The comparison is achieved over a 3×3 km support area. The six sites show a range of ground-measured LAI values between almost 0.0 (Turco) up to 3.1 (Concepción). We note that there is a large scattering of values between products and with regard to the ground-derived LAI values for two evergreen needleleaf forest sites with the largest LAI values: Hirsikangas and Concepción.

Initial work at the University of Alberta focused on multitemporal MODIS LAI for the area defined by the Chamela/Cuixmala Biological Reserve, where a total of 29 field plots (60×60 m) are currently monitored (Fig. 5). Immediately apparent were wide fluctuations in LAI values, even between consecutive dates within the same season. Because these wide

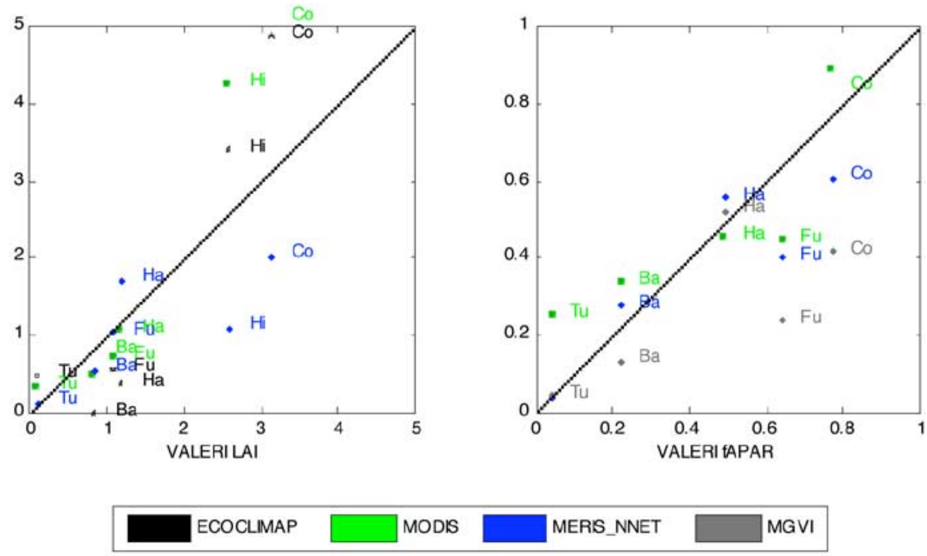

Fig. 4. Comparison between the ground-measured LAI and fAPAR values to the corresponding satellite products. It includes ECOCLIMAP, MODIS (1-km Collection 4, eight-day composite), and MERIS TOA algorithm. Several VALERI sites are used, including Haouz (Ha), Barrax (Ba), Turco (Tu), Fundulea (Fu), Concepcion (Co), and Hirsikangas (Hi).

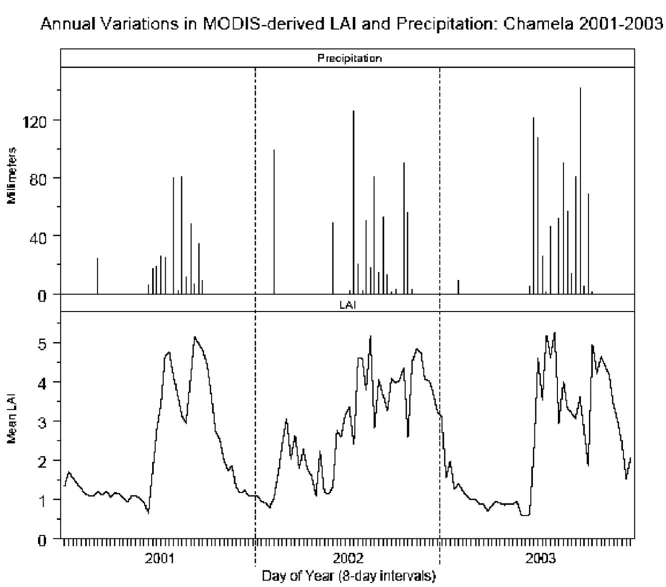

Fig. 5. Three-year time series for MODIS-LAI data derived for Chamela, Mexico. Inconsistencies observed in the wet periods can be attributed to cloud contamination and two algorithm pathways [19] of the MODIS LAI product.

fluctuations are unlikely, the observed drops in LAI values were attributed to changes in atmospheric conditions. The main algorithm likely failed in these cases due to cloud cover, thus triggering the VI-based backup algorithm. The same cloud cover that caused the main algorithm to fail would lead to low VI values; consequently, relatively low LAI values are output for these dates. Recent validation tests have reported a tendency for the main algorithm to fail more often in tropical locations due to relatively higher cloud cover over these areas, similar results were found in [12]. Future work by University of Alberta will compare MODIS time series for specific dates for which there are field-based LAI reference maps. Also, since tropical dry forests have been prone to misclassification in the past due to spectral similarities with pasture during the dry season [91], future work will investigate the accuracy of the MODIS biome map used as input into the LAI algorithm [53]. Currently, results from Finland are limited to the Ruokolahti and Hirsikangas sites, where the analysis was performed in cooperation with the BU team [66] and the VALERI group, respectively.

To synthesize these separate validation exercises, a data-sharing policy is required and organization of such a global data exchange was proposed at the CEOS LPV workshop [32]. The Oak Ridge National Laboratory's (ORNL) Distributed Active Archive Center for Biogeochemical Dynamics (DAAC) [92] will be utilized for data sharing. The ORNL DAAC will archive data, assist in the creation of metadata, and provide users with search tools to access registered data [93]. The groups agreed to share field measured LAI values as well as the resulting high-resolution LAI maps and details of the methods for their derivation. At the time of writing, field data and high-resolution maps from the BigFoot, BU, CCRS, VALERI, Finland, and Italy work had been submitted to ORNL DAAC, and other groups were in the process of making their data available, e.g., [94]. Table II provides a listing of the consensus metadata required for the LAI global validation activity.

III. Conclusion

The success of this global LAI validation effort is highly dependent upon the consistency the methods used to derive the high spatial resolution LAI maps. This paper synthesizes the *approaches* used by nine groups and sets the stage for future work on the synthesis of *results* and *accuracy statements* for global LAI products.

The descriptions of field validation procedures presented here, together with the data-sharing arrangements agreed to by the participants, provides the foundation for the global validation of medium-resolution satellite LAI products that will be addressed through future work organized under the CEOS LAI intercomparison activity.

TABLE II
METADATA REQUIREMENTS FOR LAI INTERCOMPARISON ACTIVITY

Required metadata for optical LAI field measurements:
-Latitude and Longitude of measurment
-Height of instrument during measurements
-Instrument(s) used (make, model)
-Instrument configuration (masks, rings, etc.)
-Significance of terrain/slope and if there has been any accounting for such
-Description of understory (including moss) component and if/how it been included in the LAI calculation
-Species (leaf-types, broadleaf or needle-leaf)
-Phenological state of vegetation
-Sky conditions
-Stem area considerations (i.e. note any adjustments for LAI vs PAI)
-Time of day (specify whether local or GMT time reported)
-Sampling strategy
-Post-processing of data
-Software used
-Operator ID (in case there are consistent biases by operator)
Required metadata for the high-resolution LAI surface maps:
-Full description of the high-resolution data used as input for the map (including sensor, acquisition time, solar and viewing geometry, and pre-processing step)
-Full description of geo-referencing information for the LAI surface
-Full description of, or reference for, any of the ground measurements used
-Significance of terrain/slope and if there has been any accounting for such
-Species (leaf-types)
-Description of understory (including moss) component and if/how it been included in the LAI calculation
-Description of transfer function connecting the map to the field data
Metadata required for destructive LAI measurements:
Due to the diverse approaches for destructive/allometric LAI estimation, there are no specific metadata requirements, but we request that the data providers thoroughly detail their sampling and measurement techniques so to allow full replication/understanding of the methods.

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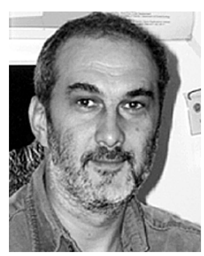

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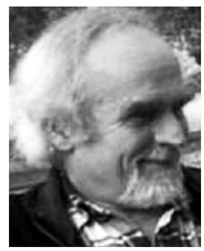

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