

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

Jeffrey T. Morisette, Frédéric Baret, Jeffrey L. Privette, Ranga B. Myneni, Jaime E. Nickeson, Sébastien Garrigues, Nikolay V. Shabanov, Marie Weiss, Richard A. Fernandes, Sylvain G. Leblanc, Margaret Kalacska, G. Arturo Sánchez-Azofeifa, Michael Chubey, Benoit Rivard, Pauline Stenberg, Miina Rautiainen, Pekka Voipio, Terhikki Manninen, Andrew N. Pilant, Timothy E. Lewis, John S. Iames, Roberto Colombo, Michele Meroni, Lorenzo Busetto, Warren B. Cohen, David P. Turner, Eric D. Warner, G. W. Petersen, Guenter Seufert, and Robert Cook

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 com-

munity 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.

Manuscript received February 4, 2005; revised May 26, 2006. This work was supported in part by the National Aeronautics and Space Administration under Grants EOS/03-0408-0637 and NNG04GK24G, in part by the Academy of Finland under Grant 47615, and in part by the Technology Development Centre (TEKES) of Finland under Grant AO423.

J. T. Morisette and J. L. Privette are with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: jeff.morisette@nasa.gov).

F. Baret and M. Weiss are with the Institut Scientifique de Recherche Agronomique Climat Sol et Environnement (INRA-CSE) Agroparc, 84914 Avignon, France.

R. B. Myneni and N. V. Shabanov are with Boston University, Boston, MA 02215 USA.

J. E. Nickeson is with Science Systems and Applications, Incorporated, Lanham, MD 20706 USA.

S. Garrigues is with the University of Maryland, Earth System Science Interdisciplinary Center, College Park, MD 20742 USA.

R. A. Fernandes and S. G. Leblanc are with the Canada Centre for Remote Sensing, Ottawa, ON K1A 0Y7, Canada.

M. Kalacska, G. A. Sánchez-Azofeifa, M. Chubey, and B. Rivard are with the Earth Observation Systems Laboratory (EOSL), Earth and Atmospheric Sciences Department, University of Alberta, Edmonton, AB T6G 2E3, Canada.

P. Stenberg and M. Rautiainen are with the Department of Forest Ecology, University of Helsinki, FIN-00014 Helsinki, Finland.

P. Voipio is with the Finnish Forest Research Institute, Suonenjoki Research Station, FIN-77600 Suonenjoki, Finland.

T. Manninen is with the Finnish Meteorological Institute, Research and Development, Earth Observation, Space Research, FIN-00191 Helsinki, Finland.

A. N. Pilant, T. E. Lewis, and J. S. Iames are with the U.S. Environmental Protection Agency, Research Triangle Park, NC 27711 USA.

R. Colombo, M. Meroni, and L. Busetto are with the Dipartimento di Scienze dell'Ambiente e del Territorio, Laboratorio Telerilevamento, Università Milano-Bicocca, 20126 Milano, Italy.

W. B. Cohen is with the Corvallis Forestry Sciences Laboratory, U.S. Department of Agriculture Forest Service, Corvallis, OR 97331 USA.

D. P. Turner is with Oregon State University, Corvallis, OR 97331 USA.

E. D. Warner and G. W. Petersen are with Pennsylvania State University, University Park, PA 16802 USA.

G. Seufert is with the Joint Research Center Institute for Environment and Sustainability, Climate Change Unit, 21-20 Ispra (VA), Italy.

R. Cook is with the Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA.

Digital Object Identifier 10.1109/TGRS.2006.872529

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 CO₂), 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’s 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 vegetation 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 prod-

ucts [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	3x3 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 south-eastern 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.

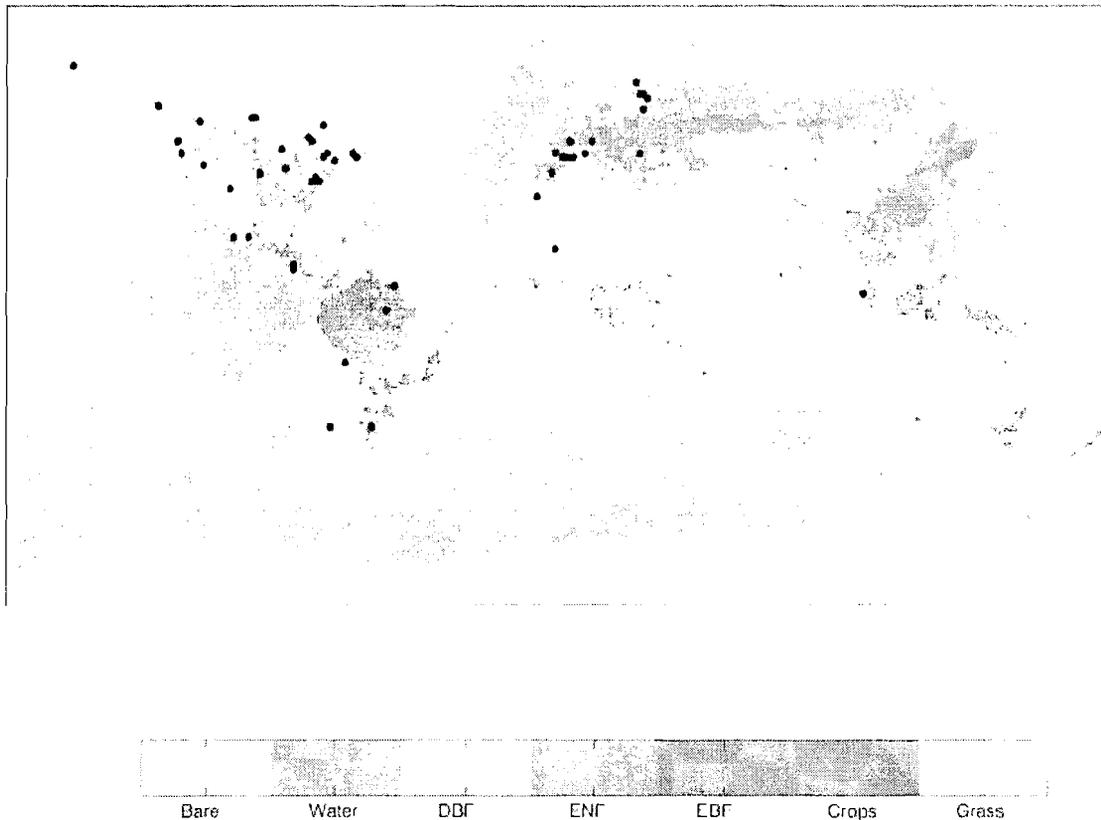


Fig. 1. Map of sites covered by the groups represented in this paper (given on a global map of dominant surface types in each $1^\circ \times 1^\circ$ cell (bare soil, water bodies, deciduous broadleaf forest, evergreen needleleaf forest, evergreen broadleaf forest, crops, grass) [87].

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 fraction measurements. The following four optical instruments are currently

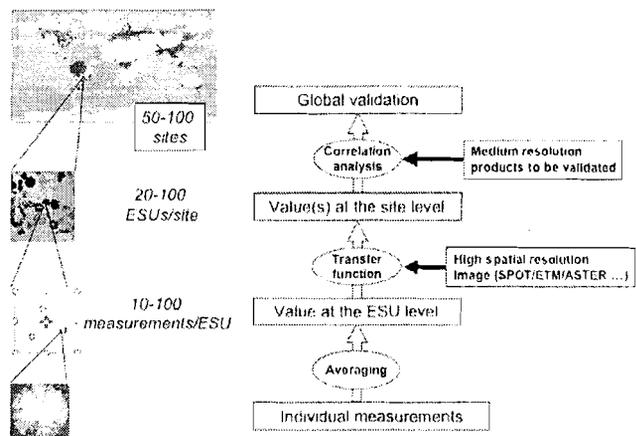


Fig. 2. General global land product validation procedure applied to LAI.

used by the groups in this intercomparison activity (the order here does not imply any preference or degree of accuracy):

- 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 appraised 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 corre-

lation 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 $0.32 \text{ m}^2/\text{m}^2$. 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 $150 \times 150 \text{ km}$ (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 ($\sim 30 \text{ m}$). 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

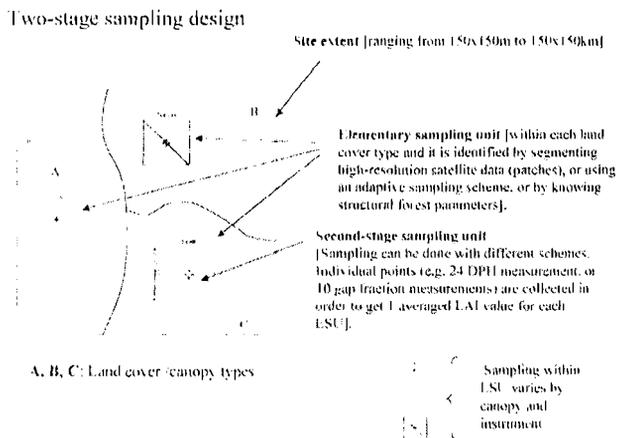


Fig. 3. Diagram representing two-stage sampling designs. Sampling design specification will depend on land cover class and measurement device. Design A correspond to low canopies of crops and grassland. Design B utilizes a transect required by the TRAC instrument, and design C is for forest canopies.

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 adaptive 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 multi-spectral 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 Big-Foot 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 (~ 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 needle-leaf 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 needle-leaf 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

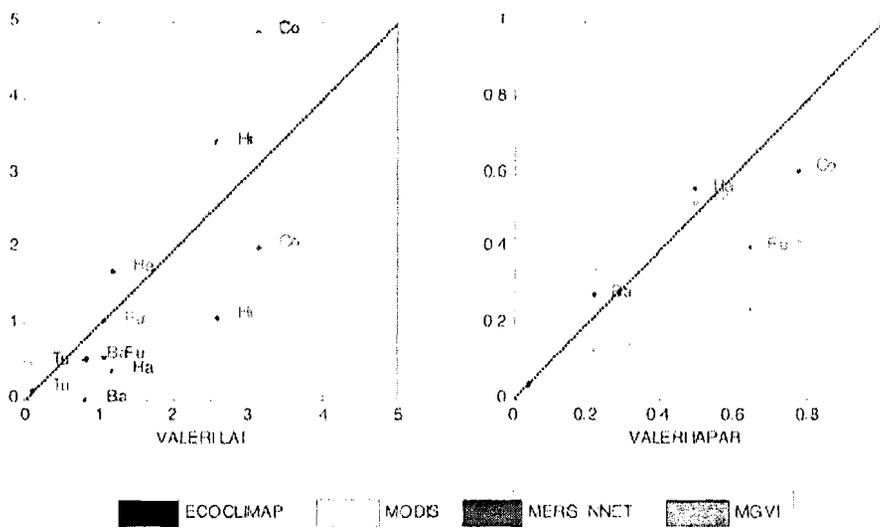


Fig. 4. Comparison between the ground-measured LAI and FAPAR values to the corresponding satellite products. It includes ECOCLIMAP, MODIS (1-km Collection 4, eight-day composite), and MERIS TOA algorithm. Several VALERI sites are used, including Haouz (Ha), Barrax (Ba), Turco (Tu), Fundulca (Fu), Concepcion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

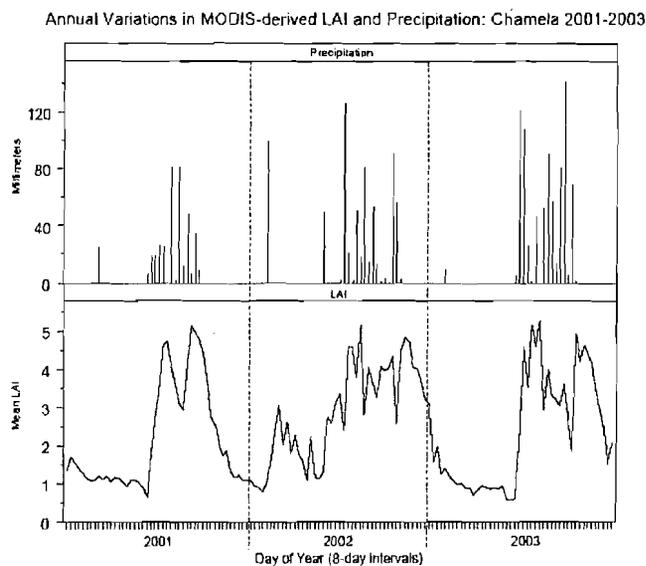


Fig. 5. Three-year time series for MODIS-LAI data derived for Chamela, Mexico. Inconsistencies observed in the wet periods can be attributed to cloud contamination and two algorithm pathways [19] of the MODIS LAI product.

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 measurement
- 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.

ACKNOWLEDGMENT

Funding for the coordinated LPV effort came, in part, from NASA's Terrestrial Ecology program, D. Wickland program manager. The University of Alberta contributors thank the generous financial support of the Canadian International Development Agency, the National Geographic Society, the InterAmerican Institute for Global Change, Palo Verde National Park, Santa Rosa National Park, the SEMARNAT-CONACYT in Mexico, and the Tinker Foundation. The contributors from Finland wish to thank the financial support from the Technology Development Centre (TEKES) and the Academy of Finland. The authors thank D. Wickland for the continued support of the MODIS validation infrastructure. Additionally, the authors thank J. Calvo-Alvarado, M. Quesada, T. Caelli, E. Gonzalez, and D. Janzen for their collaboration. The VALERI group thanks very much CNES for its constant support since 2000, hoping that the support will increase with additional European contributors. The contributors from Finland wish to thank H. Smolander, Head of Suonenjoki Research Station of the Finnish Forest Research Institute, for support and collaboration. Penn State would like to thank R. Birk, Director of the NASA Applied Science Branch, and E. Scheffner, Director of the NASA REASON Program, for their support.

REFERENCES

- [1] CEOS LPV [Online]. Available: <http://landval.gsfc.nasa.gov/LPVs/>
- [2] GTOS [Online]. Available: <http://www.fao.org/gtos/>
- [3] WMO, "Implementation plan for the global observing system for climate in support of the UNFCCC," U.N. Environment Programme Int. Council, Geneva, Switzerland, GCOS - 92, WMO/TD 1219, 2004.
- [4] G. B. Bonan, "The land surface climatology of the NCAR land surface model coupled to the NCAR community climate model," *J. Clim.*, vol. 11, pp. 1307-1326, 1998.
- [5] R. E. Dickinson, A. Henderson-Sellers, P. J. Kennedy, and M. F. Wilson, "Biosphere-atmosphere transfer scheme (BATS) for the NCAR CCM," NCAR Res., Boulder, CO, NCAR/TN-275-STR, 1986.
- [6] J. M. Melillo, A. D. McGuire, D. W. Kicklighter, B. Moore, C. J. Vorostmatry, and A. L. Schloss, "Global climate change and terrestrial net primary productivity," *Nature*, vol. 363, pp. 234-240, 1993.
- [7] S. W. Running and J. C. Coughlan, "A general model of forest ecosystem processes for regional applications," *Ecol. Model.*, vol. 42, pp. 124-154, 1988.
- [8] P. J. Sellers, D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collo, and L. Bounoua, "A revised land surface parameterization (SIB2) for atmospheric GCM's. Part I: Model formulation," *J. Clim.*, vol. 9, pp. 676-705, 1996.
- [9] P. J. Sellers, R. E. Dickinson, D. A. Randall, A. K. Betts, F. G. Hall, J. A. Berry, G. J. Collatz, A. S. Denning, H. A. Mooney, C. A. Nobre, N. Sato, C. B. Field, and A. Henderson-Sellers, "Modeling the exchanges of energy, water, and carbon between continents and the atmosphere," *Science*, vol. 275, no. 5299, pp. 502-509, 1997.
- [10] C. Potter, S. Klooster, V. Genovesi, and R. Myneni, "Satellite data help predict terrestrial carbon sinks," *EOS*, vol. 84, no. 46, pp. 502-508, 2003.
- [11] FAO Definition of LAI [Online]. Available: http://www.fao.org/gtos/tems/variable_show.jsp?VARIABLE_ID=80
- [12] R. B. Myneni, S. Hoffman, Y. Knyazikhin, J. L. Privette, J. Glassy, Y. Tian, Y. Wang, X. Song, Y. Zhang, G. R. Smith, A. Lotsch, M. Friedl, J. T. Morisette, P. Votava, R. R. Nemani, and S. W. Running, "Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data," *Remote Sens. Environ.*, vol. 83, pp. 214-231, 2002.
- [13] J. M. Chen and T. A. Black, "Defining leaf area index for nonflat leaves," *Plant, Cell Environ.*, vol. 15, pp. 421-429, 1992.
- [14] A. R. G. Lang, "Cauchy's theorems and estimation of surface areas of leaves, needles and branches," in *Crop Structure and Light Microclimate. Characterization and Applications*, C. Varlet-Grancher, R. Bonhomme, and H. Sinoquet, Eds. Paris, France: INRA, 1993.
- [15] C. Justice, A. Belward, J. Morisette, P. Lewis, J. Privette, and F. Baret, "Developments in the 'validation' of satellite sensor products for the study of land surface," *Int. J. Remote Sens.*, vol. 21, no. 17, pp. 3383-3390, 2000.
- [16] J. T. Morisette, J. L. Privette, and C. O. Justice, "A framework for the validation of MODIS land products," *Remote Sens. Environ.*, vol. 83, no. 1-2, pp. 77-96, 2002.
- [17] MODIS LAI [Online]. Available: <http://cliveg.bu.edu/modismisr/laifpar/laifpar.html>

- [18] W. Yang, D. Huang, B. Tan, J. C. Stroeve, N. V. Shabanov, Y. Knyazikhin, R. R. Nemani, and R. B. Myneni, "Analysis of leaf area index and fraction vegetation absorbed PAR products from the Terra MODIS sensor: 2000–2004," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1829–1842, Jul. 2006.
- [19] R. B. Myneni, R. R. Nemani, and S. W. Running, "Estimation of global leaf area index and absorbed par using radiative transfer models," *IEEE Trans. Geosci. Remote Sens.*, vol. 35, no. 6, pp. 1380–1393, Nov. 1997.
- [20] AVHRR [Online]. Available: <http://edc.usgs.gov/products/satellite/avhrr.html>
- [21] AVHRR LAI [Online]. Available: <http://cliveg.hu.edu/modismisr/>
- [22] AVHRR LAI [Online]. Available: http://www.ccrs.nrcan.gc.ca/ccrs/com/rsnews/2802/2802ra5_e.html
- [23] AVHRR Pathfinder NDVI [Online]. Available: http://daac.gsfc.nasa.gov/guides/GSFC/guide/avhrr_dataset_gd.html
- [24] J. L. Roujard and R. Lacaze, "Global mapping of vegetation parameters from POLDER multiangular measurements for studies of surface-atmosphere interactions: A pragmatic method and validation," *J. Geophys. Res.*, vol. 107, no. D12, p. 4150, Jun. 2002.
- [25] CNES POLDER-2 LAI [Online]. Available: http://smc.cnes.fr/POLDER/A_produits_scie.htm
- [26] CYCLOPS [Online]. Available: <http://www.avignon.inra.fr/cyclopes/public/home.htm>
- [27] J. M. Chen, G. Pavlic, L. Brown, J. Cihlar, S. G. Leblanc, H. P. White, R. J. Hall, D. Peddle, D. J. King, J. A. Trofymow, E. Swift, J. Van der Sanden, and P. Pellikka, "Validation of Canada-wide leaf area index maps using ground measurements and high and moderate resolution satellite imagery," *Remote Sens. Environ.*, vol. 80, pp. 165–184, 2002.
- [28] R. A. Fernandes, C. Butson, S. G. Leblanc, and R. Latifovic, "Landsat-5 and Landsat-7 ETM+ based accuracy assessment of leaf area index products for Canada derived from SPOT-4 VEGETATION data," *Can. J. Remote Sens.*, vol. 29, no. 2, pp. 241–258, 2003.
- [29] CCRS Vegetation Products [Online]. Available: http://www.ccrs.nrcan.gc.ca/ccrs/rd/apps/landcov/veg/emveg_e.html
- [30] J. L. Privette, J. T. Morisette, F. Baret, S. T. Gower, and R. B. Myneni, "Summary of the international workshop on LAI product validation," *Earth Obs.*, vol. 13, no. 3, pp. 18–22, Jul./Aug. 2001.
- [31] J. L. Privette, J. T. Morisette, R. Myneni, and C. Justice, "Global validation of EOS LAI and FPAR products," *Earth Obs.*, vol. 10, no. 6, pp. 39–42, Nov./Dec. 1998.
- [32] J. T. Morisette and J. L. Privette, "Summary of the 3rd International Workshop on LAI Product Validation," *Earth Obs.*, vol. 16, no. 5, pp. 28–31, Sep./Oct. 2004.
- [33] VALERI [Online]. Available: <http://www.avignon.inra.fr/valeri/>
- [34] J. Cihlar, S. Denning, F. Ahern, O. Arino, A. Belward, F. Bretherton, W. Cramer, G. Dedieu, C. Field, R. Francey, R. Gommès, J. Gosz, K. Hibbard, T. Igarashi, P. Kabat, R. Olson, S. Plummer, I. Rasool, M. Raupach, R. Scholes, J. Townshend, R. Valentini, and D. Wiekland, "IGOS-P carbon cycle observation theme: Terrestrial and atmospheric components," UNESCO, Paris, France, GTOS Rep. 25, 2001.
- [35] O. W. Heal, J.-C. Menaut, and W. L. Steffen, "Toward a Global Terrestrial Observing System (GTOS): Detecting and monitoring change in terrestrial ecosystems," UNESCO, Paris, France, MAB Dig. 14 and IGBP Global Change Rep. 26.
- [36] A. S. Belward, J. E. Estes, T. Loveland, J. Scepán, A. Strahler, J. Townshend, and C. Justice, "The IGBP-DIS global 1 km land cover data set: A project overview," *Photogramm. Eng. Remote Sens.*, vol. 65, no. 9, pp. 1013–1020, 1999.
- [37] The BigFoot Program [Online]. Available: <http://www.fsl.orst.edu/larse/bigfoot/index.html>
- [38] W. B. Cohen, T. K. Maier-sperger, D. P. Turner, W. D. Ritts, D. Pflugmacher, R. E. Kennedy, A. Kirschbaum, S. W. Running, M. Costa, and S. T. Gower, "MODIS land cover and LAI Collection 4 product quality across nine sites in the Western Hemisphere," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1843–1857, Jul. 2006.
- [39] S. G. Leblanc and R. A. Fernandes, "A dataset of in-situ LAI estimates across Canada based on optical measurement methods," Natural Resources Canada Earth Sciences Sector Groundwater Programme, Ottawa, ON, Canada, 2004.
- [40] R. A. Abuelgasim, R. A. Fernandes, and S. G. Leblanc, "Evaluation of national and global LAI products derived from optical remote sensing instruments over Canada," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1872–1884, Jul. 2006.
- [41] M. Kalacska, J. C. Calvo-Alvarado, and G. A. Sanchez-Azofeifa, "Calibration and assessment of seasonal changes in leaf area index of a tropical dry forest in different stages of succession," *Tree Physiol.*, vol. 25, pp. 733–744, 2005.
- [42] M. Kalacska, G. A. Sanchez-Azofeifa, T. Caelli, B. Rivard, and B. Boerlage, "Estimating leaf area index from satellite imagery using Bayesian networks," *IEEE Trans. Geosci. Remote Sens.*, vol. 43, no. 8, pp. 1866–1873, Aug. 2005.
- [43] M. Kalacska, G. A. Sanchez-Azofeifa, B. Rivard, J. C. Calvo-Alvarado, A. R. P. Journet, J. P. Arroyo-Mora, and D. Ortiz-Ortiz, "Leaf area index measurements in a tropical moist forest: A case study from Costa Rica," *Remote Sens. Environ.*, vol. 91, pp. 134–152, 2004.
- [44] M. Kalacska, G. A. Sanchez-Azofeifa, J. C. Calvo-Alvarado, B. Rivard, and M. Quesada, "Effects of season and successional stage on leaf area index and spectral vegetation indices in three Mesoamerican tropical dry forests," *Biotropica*, vol. 37, pp. 486–496, 2005.
- [45] CARBOEUROPE [Online]. Available: <http://www.bgc-jena.mpg.de/public/carbocur/>
- [46] P. Stenberg, M. Rautiainen, T. Manninen, P. Voipio, and H. Smolander, "Reduced simple ratio better than NDVI for estimating LAI in Finnish pine and spruce stands," *Silva Fennica*, vol. 38, no. 1, pp. 3–14, 2004.
- [47] J. I. Peltoniemi, S. Kaasalainen, J. Näränen, M. Rautiainen, P. Stenberg, H. Smolander, S. Smolander, and P. Voipio, "BRDF measurement of understory vegetation in pine forests: Dwarf shrubs, lichen, and moss," *Remote Sens. Environ.*, vol. 94, pp. 343–354, 2005.
- [48] H. Smolander, P. Stenberg, and S. Linder, "Dependence of light interception efficiency of scots pine shoots on structural parameters," *Tree Physiol.*, vol. 14, pp. 971–980, 1994.
- [49] S. Palmroth, P. Stenberg, S. Smolander, P. Voipio, and H. Smolander, "Fertilization has little effect on light interception efficiency of Picea abies shoots," *Tree Physiol.*, vol. 22, pp. 1185–1192, 2002.
- [50] P. Stenberg, T. Nilson, S. Smolander, and P. Voipio, "Gap fraction based estimation of LAI in scots pine stands subjected to experimental removal of branches and stems," *Can. J. Remote Sens.*, vol. 29, pp. 363–370, 2003.
- [51] J. R. Williams, C. A. Jones, J. R. Kiniry, and D. A. Spanel, "The EPIC crop growth model," *Trans. ASAE*, vol. 32, pp. 497–511, 1989.
- [52] LAI Intercomparison Sites [Online]. Available: http://lpvs.gsfc.nasa.gov/BIO/LAI_intercomparison_sites.jpg
- [53] W. Yang, B. Tan, D. Huang, M. Rautiainen, N. V. Shabanov, Y. Wang, J. L. Privette, K. F. Huemmrich, R. Fensholt, I. Sandholt, M. Weiss, R. R. Nemani, Y. Knyazikhin, and R. B. Myneni, "MODIS leaf area index products: From validation to algorithm improvement," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1885–1898, Jul. 2006.
- [54] G. S. Campbell and J. M. Norman, "The description and measurements of plant canopy structure," in *Plant Canopies: Their Growth, Form and Function*, G. Russell, B. Marshall, and P. G. Jarvis, Eds. Cambridge, U.K.: Cambridge Univ. Press, 1990, pp. 1–19.
- [55] M. Weiss, F. Baret, G. J. Smith, I. Jonckheere, and P. Coppin, "Review of methods for *in situ* leaf area index determination, Part II: Estimation of LAI, errors and sampling," *Agricult. Forest Meteorol.*, vol. 121, pp. 37–53, 2004.
- [56] J. M. Chen, "Optically based methods for measuring seasonal variation in leaf area index of boreal conifer forests," *Agricult. Forest Meteorol.*, vol. 80, pp. 135–163, 1996.
- [57] S. G. Leblanc, "Correction to the plant canopy gap size analysis theory used by the tracing radiation and architecture of canopies (TRAC) instrument," *Appl. Opt.*, vol. 31, no. 36, pp. 7667–7670, 2002.
- [58] J. L. Campbell, S. Burrows, S. T. Gower, and W. B. Cohen, "BigFoot: Characterizing land cover, LAI, and NPP at the landscape scale for EOS/MODIS validation. Field Manual 2.1," Oak Ridge Nat. Lab., Oak Ridge, TN, Environ. Sci. Div. Pub. 4937, 1999.
- [59] S. T. Gower, C. J. Kucharik, and J. M. Norman, "Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems," *Remote Sens. Environ.*, vol. 70, pp. 29–51, 1999.
- [60] B. E. Law, D. Turner, J. Campbell, O. J. Sun, S. Van Tuyl, W. D. Ritts, and W. B. Cohen, "Disturbance and climate effects on carbon stocks and fluxes across western Oregon USA," *Global Change Biol.*, vol. 10, pp. 1429–1444, 2004.
- [61] T. E. Avery and H. E. Brukhart, *Forest Measurements*, 4th ed. New York: McGraw-Hill, 1997.
- [62] J. S. Iiames, A. N. Pilant, and T. E. Lewis, "In-situ estimates of forest LAI for MODIS data validation," in *Remote Sensing and GIS Accuracy Assessment*, R. S. Lunetta and J. G. Lyon, Eds. Boca Raton, FL: CRC, 2004, pp. 41–58.

- [63] R. Colombo, M. Boschetti, C. Giardino, M. Meroni, C. Panigada, L. Busetto, P. A. Brivio, C. M. Marino, and G. M. Seufert, "Osservazioni remote iperspettrali e multiangolari per la stima dei parametri biofisici della vegetazione: Parte I—Disegno dell'esperimento e analisi dei dati (Hyperspectral and multiview remote sensing observations for the estimation of vegetation biophysical parameters: Part I—Planning scheme and data collection)," *Rivista Ital. Telerilevamento*, vol. 24, pp. 5–13, 2002.
- [64] I. Jonckheere, S. Fleck, K. Nackaerts, B. Muys, P. Coppin, M. Weiss, and F. Baret, "Review of methods for *in situ* leaf area index determination Part I. Theories, sensors and hemispherical photography," *Agricult. Forest Meteorol.*, vol. 121, pp. 19–35, 2004.
- [65] L. Brown, J. M. Chen, S. G. Leblanc, and J. Cihlar, "A shortwave infrared modification to the simple ratio for LAI retrieval in boreal forests: An image and model analysis," *Remote Sens. Environ.*, vol. 71, pp. 16–25, 2000.
- [66] Y. Wang, C. E. Woodcock, W. Buermann, P. Stenberg, P. Voipio, H. Smolander, T. Häme, Y. Tian, J. Hu, Y. Knyazikhin, and R. B. Myneni, "Evaluation of the MODIS LAI algorithm at a coniferous forest site in Finland," *Remote Sens. Environ.*, vol. 91, pp. 114–127, 2004.
- [67] J. S. Iames, A. N. Pilant, T. E. Lewis, and R. Congalton, "Leaf area index (LAI) change detection on loblolly pine forest stands with complete understory removal," presented at the 2004 Annu. Proc. Amer. Soc. Photogrammetry and Remote Sensing, Denver, CO, 2004.
- [68] T. Nilson. (2002) "Report on VALERI Estonian Campaign, 24–30 JUNE, 2002," Internal VALERI Report. [Online]. Available: http://www.avignon.inra.fr/valeri/fic_html/database/main.php
- [69] D. Guyon. "VALERI-2000 Campaign in Nezer Site (France) 17 July–10 August 2000," Internal VALERI Report. [Online]. Available: http://www.avignon.inra.fr/valeri/fic_html/database/main.php
- [70] S. G. Leblanc and J. M. Chen, "A practical scheme for correcting multiple scattering effects on optical LAI measurements," *Agricult. Forest Meteorol.*, vol. 110, pp. 125–139, 2001.
- [71] S. G. Leblanc, J. M. Chen, R. A. Fernandes, D. W. Deering, and A. Conley, "Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests," *Agricult. Forest Meteorol.*, vol. 129, no. 3–4, pp. 187–207, Apr. 2005.
- [72] CAN_EYE Software [Online]. Available: www.avignon.inra.fr/can_eye
- [73] W. G. Cochran, *Sampling Techniques*, 3rd ed. New York: Wiley.
- [74] F. Baret, M. Weiss, D. Allard, S. Garrigues, M. Leroy, H. Jeanjean, R. Fernandes, R. Myneni, J. Privette, J. Morisette, H. Bohbot, R. Bosseno, G. Dedieu, C. Di Bella, B. Duchemin, M. Espana, V. Gond 11, X. Fa Gu, D. Guyon, C. LeLong, P. Maisongrande, E. Mougín, T. Nilson, F. Veroustraelte, and R. Vintilla, "VALERI: A network of sites and a methodology for the validation of medium spatial resolution land satellite products," *Remote Sens. Environ.*, to be published.
- [75] W. B. Cohen, T. K. Maiersperger, S. T. Gower, and D. Turner, "An improved strategy for regression of biophysical variables and Landsat ETM+ data," *Remote Sens. Environ.*, vol. 84, pp. 561–571, 2003.
- [76] R. A. Fernandes and S. Leblanc, "Parametric (modified least squares) and non-parametric (Thiel–Sen) linear regressions for predicting biophysical parameters in the presence of measurement errors," *Remote Sens. Environ.*, vol. 95, no. 3, pp. 303–316, 2005.
- [77] D. Huang, W. Yang, B. Tan, M. Rautiainen, P. Zhang, N. Shabanov, S. Linder, Y. Knyazikhin, and R. Myneni, "The importance of measurement errors for deriving accurate reference leaf area index maps for validation Moderate Resolution satellite LAI products," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1866–1871, Jul. 2006.
- [78] E. F. Vermote, D. Tanre, J. L. Deuze, M. Herman, and J. J. Morcrette, "Second simulation of the satellite signal in the solar spectrum. 6S: An overview," *IEEE Trans. Geosci. Remote Sens.*, vol. 35, no. 3, pp. 675–686, May 1997.
- [79] B. N. Holben, T. F. Eck, I. Slutsker, D. Tanré, J. P. Buis, A. Setter, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, "AERONET—A federated instrument network and data archive for aerosol characterization," *Remote Sens. Environ.*, vol. 66, pp. 1–16, 1998.
- [80] C. Butson and R. A. Fernandes, "A consistency analysis of surface reflectance and leaf area index retrieval from overlapping clear-sky Landsat ETM+ imagery," *Remote Sens. Environ.*, vol. 89, pp. 369–380, 2004.
- [81] H. Rahman and G. Dedieu, "SMAC: A simplified method for the atmospheric correction of satellite measurements in the solar spectrum," *Int. J. Remote Sens.*, vol. 15, pp. 123–143, 1994.
- [82] ETM+ [Online]. Available: <http://edc.usgs.gov/products/satellite/landsat7.html>
- [83] TM [Online]. Available: <http://edc.usgs.gov/products/satellite/tm.html>
- [84] SPOT [Online]. Available: <http://smc.cnes.fr/SPOT/>
- [85] Y. Yamaguchi, A. B. Kahle, H. Tsu, T. Kawakami, and M. Pniel, "Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)," *IEEE Trans. Geosci. Remote Sens.*, vol. 46, no. 4, pp. 1062–1071, Jul. 1998.
- [86] ASTER [Online]. Available: <http://edc.usgs.gov/products/satellite/aster.html>
- [87] F. Baret, J. Morisette, R. A. Fernandes, J. L. Champeaux, R. Myneni, J. Chen, S. Plummer, M. Weiss, C. Bacour, and G. Derive, "Evaluation of the representativeness of networks of sites for the global validation and intercomparison of land biophysical products: Proposition of the CEOS-BELMANIP," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 7, pp. 1794–1803, Jul. 2006.
- [88] G. P. Asner, J. M. O. Scurlock, and J. A. Hicke, "Global synthesis of leaf area index observations: Implications for ecological and remote sensing studies," *Global Ecol. Biogeog.*, vol. 12, pp. 191–205.
- [89] N. V. Shabanov, S. Kotchenova, D. Huang, W. Yang, B. Tan, Y. Knyazikhin, R. B. Myneni, D. E. Ah, S. T. Gower, A. Huete, L. E. Aragao, and Y. E. Shimabukuro, "Analysis and optimization of the MODIS leaf area index algorithm retrievals over broadleaf forests," *IEEE Trans. Geosci. Remote Sens.*, no. 8, pp. 1855–1865, Aug. 2005.
- [90] V. Masson, J. L. Champeaux, F. Chauvin, C. Mériquet, and R. Lacaze, "A global database of land surface parameters at 1 km resolution for use in meteorological and climate models," *J. Clim.*, vol. 16, pp. 1261–1282, 2003.
- [91] A. S. P. Pfaff, S. Kerr, R. F. Hughes, S. Liu, G. A. Sanchez-Azofeifa, D. Schimel, J. Tosi, and V. Watson, "The Kyoto protocol and payments for tropical forests: An interdisciplinary method for estimating carbon-offset supply and increasing the feasibility of a carbon market under the CDM," *Ecol. Econ.*, vol. 35, pp. 203–221, 2000.
- [92] ORNL DAAC [Online]. Available: <http://www.daac.ornl.gov/>
- [93] The Mercury Search Tool [Online]. Available: <http://mercury.ornl.gov/orlnodaac/>
- [94] W. B. Cohen, T. K. Maiersperger, and D. Pflugmacher. (2004) Big-Foot Leaf Area Index Surfaces for North and South American Sites, 2000–2003. [Online]. Available: <http://www.daac.ornl.gov>
- [95] B. Tan, J. Hu, P. Zhang, D. Huang, N. V. Shabanov, M. Weiss, Y. Knyazikhin, and R. B. Myneni, "Validation of the Moderate Resolution Imaging Spectroradiometer leaf area index product in croplands of Alpiilles, France," *J. Geophys. Res.*, vol. 110, no. D01107, 2005. DOI: 10.1029/2004JD004860.
- [96] M. Meroni, R. Colombo, and C. Panigada, "Inversion of a radiative transfer model with hyperspectral observations for LAI mapping in poplar plantations," *Remote Sens. Environ.*, vol. 92, no. 2, pp. 195–206, 2004.



Jeffrey T. Morisette received the Ph.D. degree from North Carolina State University, Raleigh, in 1997.

He is currently with the NASA Goddard Space Flight Center, Greenbelt, MD, where a portion of his research is directed toward the coordination of global land product validation effort.



Frédéric Baret received the Ph.D. degree in 1986 on the application of remote sensing to agriculture.

Since 1986, he has been with the National Institute of Agronomical Research (INRA), Avignon, France, focusing on radiative transfer modeling in the solar domain, estimates of canopy and soil characteristics from radiometric observations, and assimilating these data into canopy functioning models. He was also coordinating large experiments such as Alpiilles-ReSeDA, ADAM, and is currently in charge of the VALERI and CYCLOPES projects for the development and validation of medium-resolution satellite products.



Jeffrey L. Privette (M'95) received the B.A. degree from The College of Wooster, Wooster, OH, the B.S. degree from the University of Michigan, Ann Arbor, and the M.S. and Ph.D. degrees in aerospace engineering sciences from the University of Colorado, Boulder.

After postdoctoral work with the University of Maryland, he joined the Biospheric Sciences Branch, NASA Goddard Space Flight Center (GSFC), Greenbelt, MD, in 1996. His research focuses on the retrieval of land biophysical parameters

from spaceborne sensors. He is Deputy Project Scientist and a science team member for the NPOESS Preparatory Project at GSFC.



Ranga B. Myneni received the Ph.D. degree in biology from the University of Antwerp, Antwerp, Belgium, in 1985.

He is currently a Professor and Faculty member in the Department of Geography, Boston University, Boston, MA, where his research interests are in radiative transfer, remote sensing of vegetation, and climate-vegetation dynamics.



Jaime E. Nickeson is currently a Staff Scientist with Science Systems and Applications, Incorporated, Lanham, MD. She has supported research activities in the Biospheric Sciences Branch at NASA's Goddard Space Flight Center since 1984. She has extensive experience in earth science remote sensing, data management and coordination, and with multiple large field experiments.



Sébastien Garrigues received the Ph.D. degree in remote sensing and geostatistics from Ecole Nationale Supérieure Agronomique de Rennes, Rennes, France, in 2004.

His main research interests include geostatistical modeling of spatial heterogeneity from remote sensing data and the validation of land products.



Nikolay V. Shabanov received the Ph.D. degree in remote sensing from Boston University, Boston, MA, in 2002.

He is currently a Research Assistant Professor in the Geography Department, Boston University, where his research includes parameterizing the effect of vegetation spatial heterogeneity with stochastic radiative transfer theory and development of algorithms for retrieving biophysical parameters from satellite data.



Richard A. Fernandes received the Ph.D. degree in hydrology from the University of Toronto, Toronto, ON, Canada, in 1999.

He is currently a Research Scientist with the Canada Centre for Remote Sensing, Ottawa, ON. His current research interests include radiative transfer and regional hydrological modeling in northern vegetation landscapes and vegetation phenology.



Sylvain G. Leblanc received the B.Sc. degree in physics from the University of Montreal, Montreal, QC, Canada, and the M.Sc. degree in atmospheric and oceanic sciences from McGill University, Montreal, in 1992 and 1994, respectively. He is currently pursuing the Ph.D. degree at the University of Sherbrooke, Sherbrooke, QC, conducting research on the use of portable LiDARs to improve *in situ* forest structure measurements.

He is currently an advisor on the use of remote sensing data for climate change within the Earth Observation Applications and Advisory Section of CCRS, Canadian Space Agency, Saint-Hubert, QC, and is part of the NRCan Earth Science Sector programs on Climate Change and Ground Water. His research interest is focused on *in situ* and remote sensing vegetation structure retrieval.



Margaret Kalacska received the Ph.D. degree from the University of Alberta, Edmonton, AB, Canada, in 2006, where her research is the application of remotely sensed data to neotropical dry forest ecology.

Her other research interests include Bayesian networks, tropical dry forest ecology, and environmental and forensic applications of multi/hyperspectral remote sensing.



G. Arturo Sánchez-Azofeifa received the Ph.D. degree in earth sciences from the University of New Hampshire, Durham.

He is currently an Associate Professor at the University of Alberta, Edmonton, AB, Canada. His research is related to the study of impacts of land use/cover change on biodiversity loss and habitat fragmentation in tropical dry forest environments.



Michael Chubey received the M.Sc. degree from the University of Calgary, Calgary, AB, Canada, in 2004. He is currently pursuing the Ph.D. degree at the University of Alberta, Edmonton, AB.

He is currently a Senior Remote Sensing Analyst with Silvatech Consulting, Salmon Arm, BC, Canada. He is involved primarily with applied research in the areas of precision forestry, total land base inventory, and vegetation biometrics.

Marie Weiss, photograph and biography not available at the time of publication.



Benoit Rivard received the Ph.D. degree in earth and planetary sciences from Washington University, St. Louis, MO, in 1990.

He is currently a Professor in the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada. His research interests include the visible, near-, and thermal-IR scattering properties of ore and broken/cut rock surfaces.



Timothy E. Lewis received the Ph.D. degree in environmental science from Rutgers University, Piscataway, NJ.

He is currently a Senior Ecologist with the U.S. Environmental Protection Agency's National Center for Environmental Assessment, Research Triangle Park, NC, where he is responsible for assessing the effects of air pollutants and land use change on both aquatic and terrestrial ecosystems.

Pauline Stenberg received the Ph.D. degree in forestry from the University of Helsinki, Helsinki, Finland, in 1987.

She is currently a Senior Scientist in the Department of Forest Ecology of the University of Helsinki. Her research has focused on the mathematical modeling of the shortwave radiation field of coniferous canopies with applications in forest production ecology and optical remote sensing.



John S. James received the Ph.D. degree in natural resources and environmental science from the University of New Hampshire, Durham.

He is currently a Research Biologist within the Landscape Characterization Branch at the U.S. Environmental Protection Agency, Research Triangle Park, NC. He is the Principal Investigator for EPA MODIS LAI validation research examining the needle-leaf biome in the southeastern U.S.

Miina Rautiainen received the Ph.D. degree in forestry from the University of Helsinki, Helsinki, Finland, in 2006.

She is currently with the Department of Forest Ecology, University of Helsinki.



Roberto Colombo is currently a Researcher at the Remote Sensing Laboratory, University of Milan-Bicocca. His present research interests focus on the quantitative retrieval of key land surface variables by optical remote sensing and their assimilation in ecosystem process models.

Pekka Voipio is currently a Senior Research Assistant with the Finnish Forest Research Institute, Helsinki, Finland.

He has been involved in LAI and canopy measurements at the Suonenjoki Research Station since 1992.



Terhikki Manninen received the Ph.D. degree in physics from the Helsinki University of Technology, Espoo, Finland, in 1996.

She is currently a Senior Research Scientist with the Finnish Meteorological Institute, Helsinki. Her current research interests are related to the surface description of the Earth, such as broadband surface albedo and leaf area index.



Michele Meroni received the Ph.D. degree in forest ecology from the University of Tuscia, Viterbo, Italy.

He is currently with the Remote Sensing Laboratory, University of Milan-Bicocca, Milan, Italy, continuing studies of satellite spectral analysis and vegetation physiological functioning.



Andrew N. Pilant received the Ph.D. degree in geology from Michigan Technological University, Houghton, in 1996.

He is currently a Research Scientist with the U.S. Environmental Protection Agency, Research Triangle Park, NC. His research involves applying remote sensing and geospatial science to understanding natural and anthropogenic environments and processes.



Lorenzo Busetto is currently pursuing the Ph.D. degree in environmental sciences at the University of Milano-Bicocca, Milan, Italy.

As a Research Fellow at the Institute on Atmospheric Pollution of the National Research Council, he studies the extraction of vegetation biophysical parameters and estimation of primary production in forest ecosystems from MODIS data.



Warren B. Cohen received the Ph.D. degree from Colorado State University, Fort Collins, in 1989.

He is currently a Research Forester at the U.S. Department of Agriculture's Forest Service, Pacific Northwest Research Station, Corvallis, OR. His interests include the analysis and modeling of vegetation across multiple biomes and spatially explicit modeling of ecological processes, with significant attention to scaling issues.



G. W. Petersen received the Ph.D. degree in soil genesis and morphology from the University of Wisconsin, Madison, in 1965.

He is currently a Professor of Soil and Land Resources at The Pennsylvania State University, State College, PA. His research interests are pedology, landscape and watershed processes, land use, remote sensing, and GIS.



David P. Turner received the Ph.D. degree in botany from Washington State University, Pullman, in 1984.

He is currently an Associate Professor in the Forest Science Department, Oregon State University, Corvallis. His research interests are in the area of remote sensing and ecological modeling.



Guenther Seufert is currently Project Leader within the Climate Change Unit of the Joint Research Center Institute for Environmental Sustainability. His interests focus to define, implement, manage, and follow-up the research activities dealing with emissions and sinks of long-lived greenhouse gases, the implementation of the Kyoto Protocol, and its future developments.



Robert Cook received the Ph.D. degree in geochemistry from Columbia University, New York.

He is currently a Research Scientist at the Oakridge National Laboratory, Oakridge, TN. His research interests include biogeochemistry, global change, transport and fate of contaminants in aquatic ecosystems, and water resources management.

Eric D. Warner is currently a Research Associate within the Penn State Institutes of the Environment at The Pennsylvania State University, University Park, PA.