MODIS LAI/FPAR FINAL REPORT

Radiative Transfer Based Synergistic MODIS/MISR Algorithm for the Estimation of Global LAI & FPAR

(Contract: NAS5-96061)

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Summary of the algorithm. The objective of the contract is to develop a radiative transfer based synergistic algorithm for estimation of global leaf area index (LAI) and fraction of photosynthetically active radiation absorbed by vegetation (FPAR). The algorithm consists of a main procedure that exploits the spectral information content of MODIS measurements and the angular information content of MISR measurements to derive accurate estimation of LAI and FPAR. Should this main algorithm fail, a backup algorithm is triggered to estimate LAI and FPAR using vegetation indices. Both algorithms are capable of executing in MODIS-only or MISR-only mode, should cloud contamination, data frequency and spatial or temporal resolution requirements hinder a joint MODIS/MISR mode of operation. The MODIS-only mode of the algorithm requires a land cover classification that is compatible with the radiative transfer model used in the derivation. Such a classification is currently a part of MODIS landcover product and utilized in collection 4 MODIS LAI and FPAR algorithm. Therefore, our algorithm has interfaces with the MODIS/MISR surface reflectance product and the MODIS Land Cover Product. Validation of the LAI/FPAR product is an important part of algorithm development. We developed scaling-based validation strategy of the LAI and FPAR product and implementing it currently in our validation activity.

I. ACCOMPLISHMENTS OF THE MODIS LAI/FPAR PROJECT DURING THE DEFINITION AND EXECUTION PHASES (1996-2003)

The proposal *Radiative Transfer Based Synergistic MODIS/MISR Algorithm for the Estimation of Global LAI and FPAR* by the principal investigator, Myneni, was selected for *definition phase* investigation from September-27-1996 to June-27-1996. Subsequently, the investigation was modified to perform MODIS only retrievals in light of practical issues associated with transfer of large volumes of data across the wire between the separate MODIS and MISR data processing centers. The investigation was then carried into the *execution phase*, from June-01-1997 to December-14-2003. The objective was *to develop a radiative transfer based synergistic algorithm for the estimation of global LAI and FPAR from atmospherically corrected MODIS reflectance data with a minimum accuracy of 0.5 LAI and 0.1 FPAR.* The following is a summary of accomplishments from the definition and execution phases.

A. LAI & FPAR Algorithm

A.1. Accomplishment: An algorithm for operational production of LAI & FPAR products from MODIS data was developed.

Details: The operational algorithm ingests up to seven atmosphere-corrected surface spectral bi-directional reflectance factors (BRFs) and their uncertainties and outputs the most probable values for pixel LAI, FPAR and their respective uncertainties. A look-up-table (LUT) method is used to achieve inversion of the three-dimensional radiative transfer problem (the main algorithm). When this method fails to localize a solution, relations based on the normalized difference vegetation index (NDVI) and LAI & FPAR are used (the back-up algorithm). The theoretical basis of the algorithm is described in Knyazikhin et al. (1998a,b). Additional details regarding the physics of the algorithm are described in Shabanov et al. (2000), Knyazikhin and Marshak (2000), Panferov et al. (2001), Wang et al. (2001) and Tian et al. (2002a). Novel aspects of the algorithm include (a) Account of uncertainties in surface reflectance data, (b) Use of the law of energy conservation as a constraint in the inversion procedure, (c) Use of an invariance principle to decouple LUT size from the number of input reflectance wavebands (Red and NIR spectral bands are currently used), (d) spatial scale dependence of the algorithm and (f) Handling of reflectance saturation problems in dense canopies.

A.2. Accomplishment: The algorithm was successfully prototyped with surrogate data (AVHRR, SeaWiFS and LANDSAT) prior to Terra MODIS launch resulting in operational production from day one of MODIS science data collection (Tian et al., 2000 and Wang et al., 2001).

A.3. Accomplishment: The physics of the algorithm has been verified with field measurements.

Details: The main algorithm involves matching MODIS reflectances to model reflectances evaluated from Look-Up-Table (LUT) entries. The algorithm ingests any number of spectral surface reflectances and evaluates the matching model values on-the-fly with the same LUT entries by exploiting the so-called spectral invariance principle (Knyazikhin et al., 1998a,b; Panferov et al., 2001; Shabanov et al., 2003) through the use of certain scale-dependent parameters which can be measured in the field (Fig. 1).

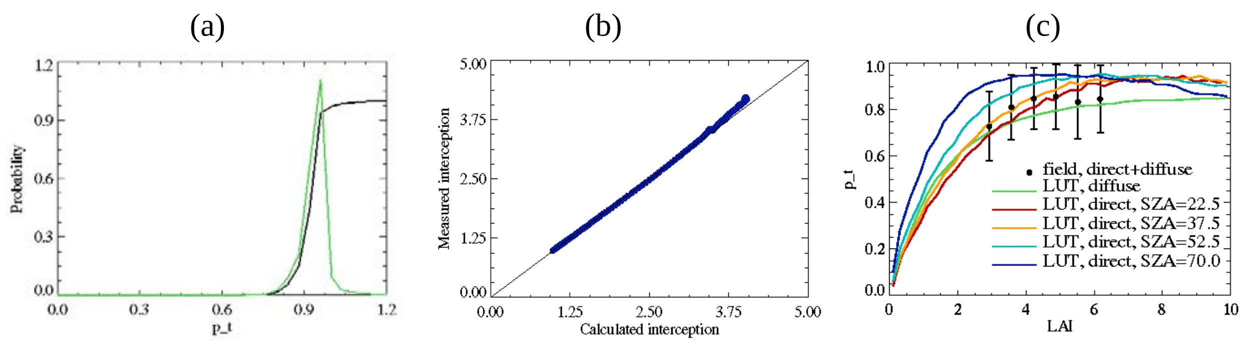

Figure 1. The canopy spectral invariance indicates that some simple algebraic combinations of leaf and canopy spectral tramsmittances eliminate their dependences on wavelength through the specification of two scale dependent parameters. (a) Specification of a scale-dependent parameter from field measured canopy and leaf spectral transmittances (Panferov et al., 2001); (b) Given the scale dependent parameter and canopy absorption at a reference wavelength, canopy spectral absorptance and transmittance can be evaluated at any wavelength of solar spectrum; (c) Comparison of scale dependent parameter measured in broadleaf forests (Shabanov et al., 2003) with values stored in LUTs of the LAI and FPAR algorithm. The LUTs include four curves for vegetation illuminated by direct sunlight from different angles and an additional curve for diffuse radiation.

B. LAI & FPAR Products

B.1. Accomplishment: LAI & FPAR products have been produced from day one of MODIS science data collection and were made available to the public from the EDC DAAC five months after MODIS first acquired Earth view (Myneni et al., 2002).

Details: MODIS LAI & FPAR products are produced at 1 km spatial resolution daily (MOD15A1) and composited over an 8-day period based on the maximum FPAR value. The 8-day product (MOD15A2) is distributed to the public from the EDC DAAC. Example product images are shown in Fig. 2. MODIS product versions are technically called Collections. Collection 1 runs from Feb 2000 to Feb 2001. Collection 3 runs from Nov 2000 to Dec 2002. Collection 4 runs from Feb 2000 to present time. There was no Collection 2. Extensive documentation describing the availability and usage of the products can be found at the PI, MODIS, EDC DAAC and MODIS LAND web sites.

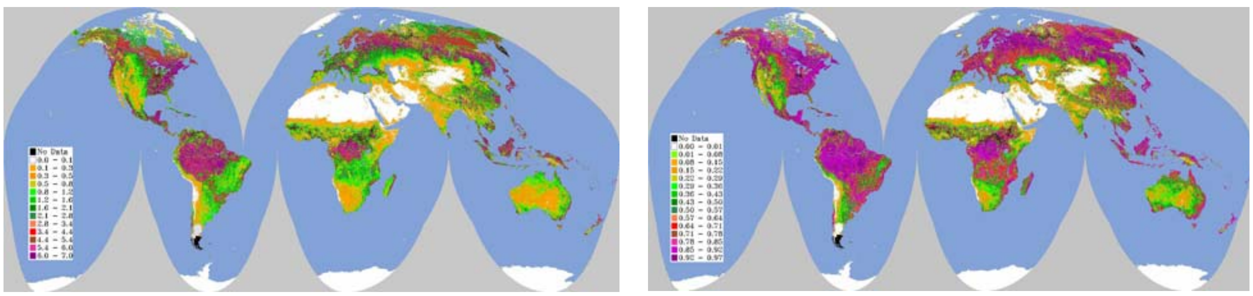

Figure 2. Example LAI (left panel) and FPAR (right panel) images generated from the standard MODIS LAI & FPAR products (day 201-208 composite in year 2001, Collection 4).

B.2. Accomplishment: The LAI & FPAR product spatial coverage index (SCI) has been improved from 55% in Collection 1 to 70% in Collection 3 to 77% in Collection 4.

Details: The SCI (fraction of pixels with valid reflectance data for which the main radiative transfer algorithm produces a retrieval) has improved from 55% in Collection 1 to 70% in Collection 3 (Fig. 3a) and to 77% in Collection 4. The LAI profiles are shown in Fig. 3b for different biomes. Grasses/cereal crops and shrubs have values less than 1, broadleaf crops and savannas have values between 1.5 and 2.5, and broadleaf forests have higher LAI values, of about 4. The winter time LAI in needle forests is about 2, some what low, and the rather strong seasonality, with peak values of about 4, requires further investigation. The LAI & FPAR retrievals from most of the vegetated pixels identified as having snow are from the back-up NDVI-based algorithm (Fig. 3c) because the main radiative transfer algorithm fails as expected.

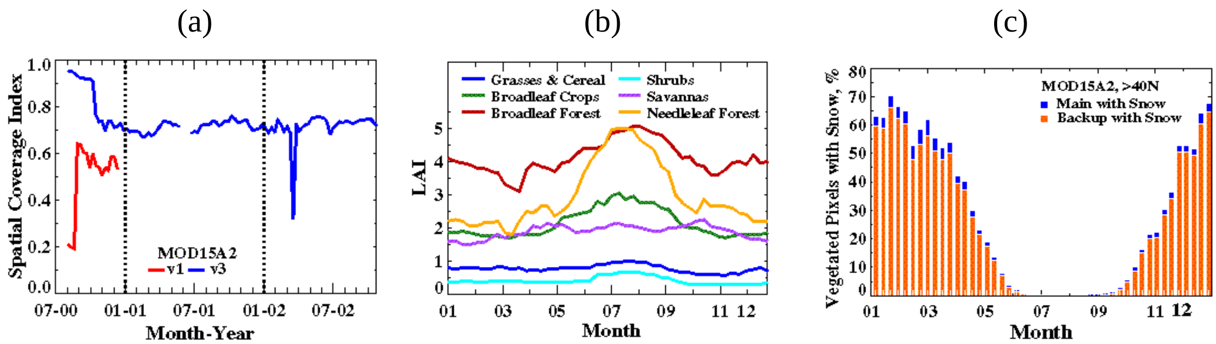

Figure 3. Analysis of Collection 3 (Nov 200 to Dec 2002) LAI & FPAR products (Yang et a., 2003). (a) Product spatial coverage index for Collections 1 and 3. (b) Biome LAI profiles and (c) Fraction of vegetated pixels with retrievals from the main radiative transfer algorithm and the NDVI-based back-up algorithm.

B.3. Accomplishment: The product accuracy index (PAI) is 80% for Collection 3 LAI & FPAR products (Huang et al., 2003).

Details: The product accuracy index is defined as 1 minus the threshold uncertainties in surface reflectance product below which uncertainties in the LAI & FPAR products exceed uncertainties in input MODIS surface reflectances because of deficiencies in algorithm physics (Fig. 4).

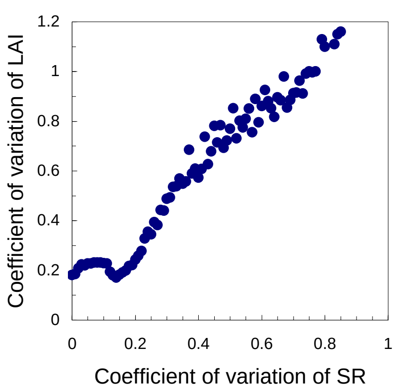

Figure 4. Uncertainties in LAI retrievals as a function of uncertainties in MODIS surface reflectance at the red spectral band (Huang et al., 2003). Using nine consecutively dated Collection 3 products, mean, standard deviation and coefficient of variation (std/mean) of LAI and surface reflectance were calculated for every biome 1 (grasses and cereal crops) pixel. Uncertainties in LAI exceed uncertainties in surface reflectance below a threshold value of 20% indicating that the upper limit of Collection 3 LAI & FPAR product accuracy is 80%. Above this threshold value, LAI & FPAR uncertainties are linearly related to surface reflectance uncertainties suggesting that reductions in LAI & FPAR accuracy below 80% are driven by inaccuracies or uncertainties in the surface reflectance product.

B.4. Accomplishment: The LAI & FPAR product quality index (PQI; ratio of unsaturated main algorithm retrievals to total retrievals) has been improved from 49% in Collection 3 to 71% in Collection 4.

B.5. Accomplishment: The Collection 4 Quality Assessment scheme allows for identification of saturation conditions not traceable in previous Collections.

Details: The products have separate data layers called Quality Control (QC) that specify product quality for every pixel. These flags indicate quality of the input to the algorithm and the output from the algorithm. Ambiguities in the Collection 3 QA were resolved to result in simpler and more meaningful interpretation of the flags in Collection 4.

B.6. Accomplishment: The AVHRR-based at-launch six-biome map in Collections 1 and 3 has been replaced in Collection 4 with a six biome map derived from the MODIS IGBP land cover product (MOD12Q1).

B.7. Accomplishment: A new compositing scheme based on utilizing only the best quality retrievals has been implemented in Collection 4 replacing compositing over all retrievals in Collections 1 and 3 which is one reason why the product quality index improved from 49% in Collection 3 to 71% in Collection 4 (Figure 5).

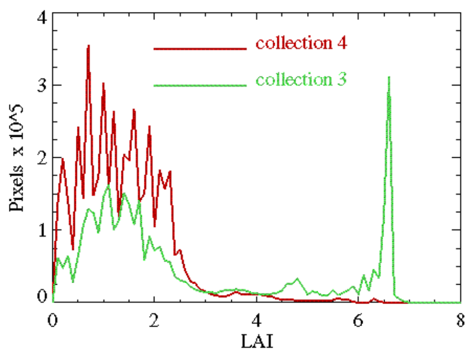

Figure 5. Distribution of global LAI values for broadleaf crops (biome 3) derived from collection 3 (shown in green) and collection 4 (shown in red) data. Collection 3 LAI was significantly overestimated over some areas. A non-physical peak at LAI=6.5 in collection 3 data is due to saturation of LAI. This peak has been removed in collection 4 by improving physics of the algorithm and compositing scheme. The PQI increased from 49% to71%.

C. Validation of LAI & FPAR Products

C.1. Accomplishment: The product validity index (PVI) for Collection 3 MODIS LAI & FPAR is *Stage-1 Validated.*

Details: Validation refers to assessing the uncertainty of satellite-derived products by analytical comparisons to reference data (e.g., in situ, aircraft and high-resolution satellite sensor data), which are presumed to represent the target values (Justice et al., 2000). Stage-1 Validation is defined by the MODIS as follows - product accuracy has been estimated using a small number of independent measurements from selected locations and time periods through ground-truth and validation efforts. The basis for declaring MODIS LAI & FPAR products as Stage-1 Validated are the following accomplishments (Huang et al., 2003; Privette et al., 2002; Shabanov et al., 2003; Tan et al., 2003; Tian et al., 2002b,c; Wang et al., 2003a,b).

C.2. Accomplishment: A sampling strategy for validation of moderate resolution products from point field measurements through the use fine resolution satellite data has been developed and tested.

Details: Our strategy for validation of MODIS (1 km) LAI & FPAR products is the following: considering the scale of in situ measurement (generally <10 m per sample) and the large amount of work associated with field measurements, it is unrealistic to expect sufficient data for a pixel-by-pixel comparison. An alternative is to employ both field measurements and high resolution satellite data (10-30 m) to produce validated fine resolution LAI & FPAR maps over a

sufficiently extended area, say a 10 x 10 km region, degrade these to 1 km resolution, and use as benchmarks to validate the MODIS products. The fine resolution maps can be produced using statistical methods, neural networks, or the MODIS LAI & FPAR algorithm but with look-up-tables tuned to the fine resolution (10-30 m) (Cohen et al., 2003; Combal et al., 2002; Huang et al., 2003; Tan et al., 2003; Tian et al., 2002b,c; Wang et al., 2003a,b; Weiss et al., 2000). A pixel-by-pixel comparison is not feasible even with this method for the following reason.
Three random variables impact the LAI & FPAR retrievals (a) uncertainties in surface reflectance product (e.g., due to correction for atmosphere and other environmental effects), (b) uncertainties in land cover identification (e.g., due to biome mixture within 1 km pixel) and (c) uncertainties in geo-registration. The predicted pixel LAI value should therefore be treated as an observation of *a random variable*. The availability of validated fine resolution LAI & FPAR maps degraded to the 1 km resolution is therefore not sufficient for a pixel-by-pixel comparison (Tian et al., 2002b,c; Wang et al., 2003a,b). It is essential to identify multi-pixel patches in the image data to validate the product. Figures 6 and 7 demonstrate a patch-level based approach to validation of the 1 km MODIS LAI & FPAR products.

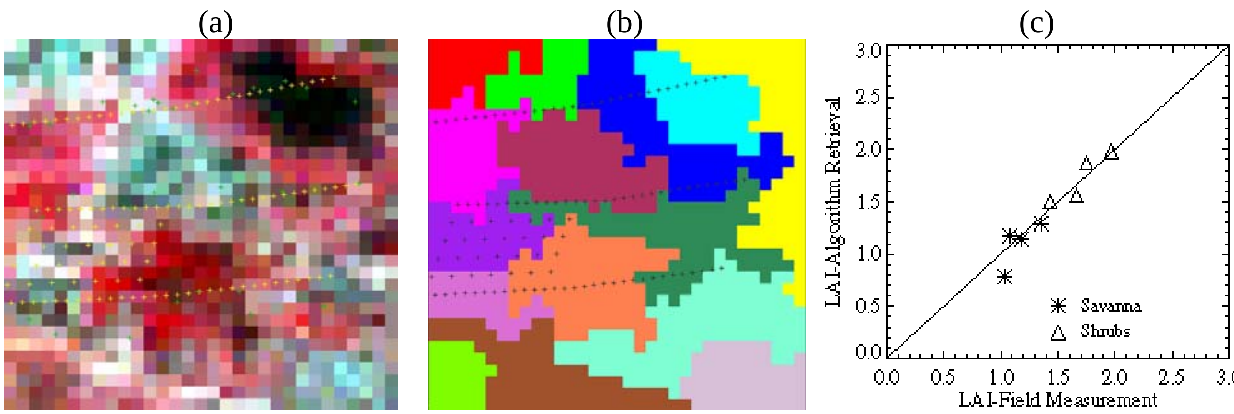

Figure 6. SAFARI 2000 Wet Season Field campaign: Maun, Botswana, Mar 3-18, 2000 (Tian et al., 2002b,c). (a) Color RGB image from ETM+ Bands 4, 3, and 2 of a 1 by 1 km region of the Maun site. The symbol "+" represents sampling points. (b) Map of the same region using a segmentation procedure which groups pixels into patches based on spectral similarity and adjacency. Patches 3, 5 6, 10, 11, and 14 are shrubs. Patches 1, 2, 4, 7, 8, 9, 12, 13 and 15 are savannas. (c) A fine resolution LAI map was produced with the MODIS LAI & FPAR algorithm and ETM+ data with appropriately tuned LUTs. The mean LAI of patches derived from field measurements and ETM+ data are shown in this plot.

C.3. Accomplishment: The products have been validated with data from 8 different field campaigns conducted during the past 3 years (2000-2002) with 1 more planned in 2003.

Details: We conducted 8 field campaigns (Table 1). Ground measurements of LAI, FPAR, leaf and canopy hemispherical reflectance and transmittance, and directional canopy reflectance were made using the LAI-2000 plant canopy analyzer, AccuPAR ceptometer, LI-1800 portable spectroradiometer and ASD handheld spectroradiometer. Data needed for validation of algorithm physics and LAI & FPAR products were collected during these campaigns. Example results are shown in Fig. 8 (also see Figs. 6 and 7).

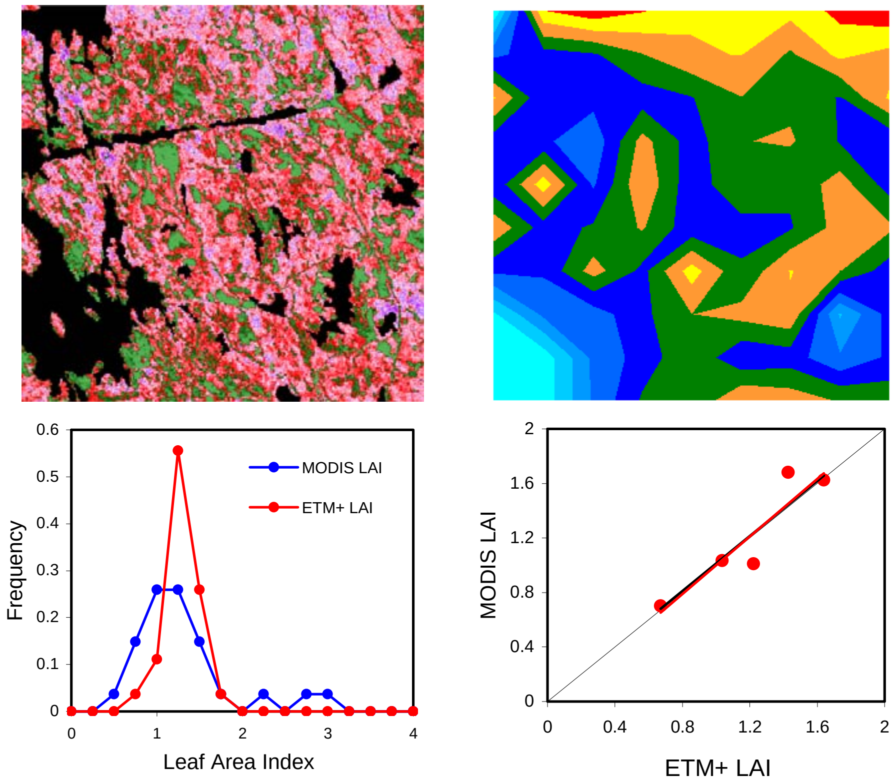

Figure 7. Field campaign at Ruokolahti, Finland June 14-June 21, 2000 (Wang et al., 2003b). Top-Left: 30 m resolution LAI map of a 10x10 km region derived from the ETM + data image using the reduced simple ratio. Top-Right: Contour plot of 1 km resolution LAI map aggregated from the fine resolution ETM+ LAI map. Bottom-Left: Histograms of LAI values for the 10x10 km area obtained from aggregated ETM+ LAI and the MODIS LAI fields. A t-test (p=0.83) shows that the mean values of these histograms are not significantly different. Bottom-Right: Patch level correlation between the MODIS and aggregated LAI values.

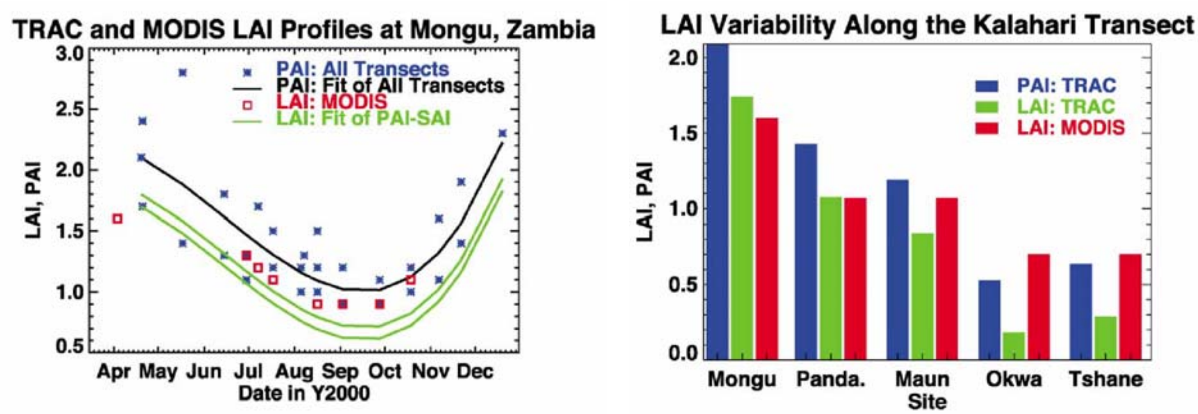

Figure 8. Results from the SAFARI 2000 field campaign suggest that the MODIS LAI & FPAR algorithm correctly accommodates structural and phenological variability in semi-arid woodlands and savannas, and is accurate to within the uncertainty of the validation approach used. Left panel: Comparison of TRAC (Tracing Radiation and Architecture in Canopies instrument) derived green LAI range and MODIS green LAI values. Right panel: Mean TRAC

PAI (Plant Area Index), TRAC-derived LAI, and MODIS LAI product values for five structurally different sites along the Kalahari Transect in March 2000 (Privette et al., 2002).

Table 1. Field campaigns in support of MODIS LAI & FPAR product validation

Field Campaign	Date	Publications
SAFARI-2000 Wet and Dry seasons field Campaigns	March 3 to 18, 2000 August 20 to 29, 2000	Privette et al., 2002; Tian et al., 2002b,c
2001 and 2002 Harvard Forest Field Campaigns	July 21 to 15, 2000 August 1 to 8, 2001	Shabanov et al., 2003.
2000 Ruokolahti Field Campaign, Finland	June 14 to 21, 2000	Wang et al., 2003a,b.
2000 Kejimkujik, Canada.	August 10 to 18, 2000	Under investigation
2001 VALERI/MODLAND Field Campaign, France	June 11 to 15, 2001	Tan et al., 2003.
2002 Flakaliden Field Campaign, Sweden	June 25 to July 4, 2002	Under investigation

II.C.4. Accomplishment: Protocols for the validation of moderate resolution satellite products have been developed and fostered under the aegis of CEOS-LPV and NASA sponsorship.

Details: Global validation requires field data from a range of sites representing a logical subset of Earth's major land covers. Field campaigns are expensive and often the data can be used for a number of similar investigations. Therefore, a working sub-group focused on the validation of moderate resolution satellite sensor products under the aegis CEOS was formed with the goal of fostering close collaboration and data exchange between investigators working on validation. Details about CEOS-LPV can be found in Morisette et al. (2002).

D. Outreach and Service

II.D.1. Accomplishment: Monthly 1 and 4 km products in binary format were developed from the standard products (MOD15A2) by spatial and temporal averaging (Yang et al., 2003). The monthly products, QC, documentation and software tools have been distributed to the community since May 2002 via a ftp data pool from the PI web site (over 500 downloads) and a subset of the data distributed on CD-ROMs at various scientific meetings (over 300 CD-ROMs).

II.D.2. Accomplishment: A user community workshop was organized in July 2002 in Missoula, Montana, to inform and train the participants about the products. Over 150 participants from about 35 states and 15 countries attended this three-day workshop.

II.D.3. Accomplishment: Since product release in August 2000, there has been a steady increase in the number of users contacting the PI for various reasons: questions about the algorithm, products, interpretation, collaborative research plans, etc. Presently these queries average about 100 a month. We have actively participated in these interactions.

E. Publications and Student Training

E.1. Accomplishment: The work performed under this contract since the definition phase (Sep 1996) is described in 29 peer-refereed journal articles (21 published, 3 in press and 5 submitted). Those quoted as part of this proposal are marked with an asterisk in the Bibliography.

E.2. Accomplishment: A significant part of the research was performed by graduate students. A total of 16 graduate students were involved (4 PhDs and 7 MAs graduated; 5 PhDs currently active).

II. LESSONS LERNED

A. Model and Input uncertainties

The model uncertainty characterizes the accuracy of vegetation - radiation interaction model to approximate the observed variability in surface reflectances. Uncertainties in the land surface reflectance are due atmospheric effects, calibration uncertainties etc. Accurate specification of model and input uncertainties in the algorithm determine the quality of the retrieved LAI/FPAR fields.

When the amount of spectral information input to the retrieval technique is increased, not only does this increase the overall information content but also decreases the summary accuracy in the data. The former enhances quality of retrievals, while the latter suppress it.

B. Physically based vs. empirically based LAI/FPAR algorithm

Physically based theory was developed to explain scale dependence of the main RT algorithm. Scale issues arise due to mixture of different land cover types at coarse resolution of satellite measurements. Adjustment of the structural parameters of the LUTs of the main algorithm accounts for scaling issues.

Physically based algorithm is sensitive to BRDF effects. Information on BRDF dependence on geometry is lost when LAI/FPAR retrievals are based on vegetation indexes instead.

Physically based algorithm fails if uncertainties of input are high (cloud contamination etc.) However, quality of input data can not be discriminated by empirically based algorithm. This explains the fact that main algorithm generally produces reliable LAI retrievals, consistent with field measurements, while retrievals by back-up algorithm contains high frequency noise due to atmospheric effects.

C. Validation

Due to natural heterogeneity of vegetation, point field measurements of LAI are not directly comparable to coarse resolution LAI derived from MODIS sensor. Therefore, a sampling strategy for validation of moderate resolution products from point field measurements through the use of fine resolution satellite data has been developed and implemented at our field validation excursuses.

Field measurements along with analysis of MODIS surface reflectances helped to adjust LUTs of the algorithm for best quality retrievals and consistency with ground observations

Publications during the Definition and Execution Phases

(* indicates publications describing research funded under the definition and execution phases of the MODIS LAI & FPAR contract)

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