Remote Sensing of Environment 119 (2012) 43–54

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Validation of MODIS and CYCLOPES LAI products using global field measurement data

Hongliang Fang [a,*], Shanshan Wei [a,b], Shunlin Liang [c,d]

[a] State Key Laboratory of Resources and Environmental Information System (LREIS), Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] Department of Geography, School of Urban and Environmental Sciences, Northeast Normal University, Changchun, Jilin Province 130024, China
[c] Department of Geography, University of Maryland, College Park, MD 20742, USA
[d] College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Article history:
Received 15 November 2010
Received in revised form 5 December 2011
Accepted 5 December 2011
Available online xxxx

Keywords:
Leaf Area Index (LAI)
MODIS
CYCLOPES
SPOT/VEGETATION
Validation
Uncertainty

ABSTRACT

The objective of this paper is to quantitatively validate the global MODIS and CYCLOPES leaf area index (LAI) products using a global LAI field measurement database created on the basis of a literature review and major validation campaigns. The MODIS LAI product suite, containing the Terra Collection 4 (C4), Terra Collection 5 (C5) and Terra + Aqua combined C5, was analyzed, with considerable attention paid to the quality control (QC) information. The CYCLOPES V3.1 LAI product was similarly analyzed with regard to the status map (SM) layer. In general, the MODIS LAI has improved consistently over all releases. MODIS C5 data retrieved with the main algorithm (QC<64) and CYCLOPES data showed a similar range of uncertainties (1.0–1.2). Uncertainties for the best MODIS C5 (QC = 0) and CYCLOPES (SM = 0) estimates were around 0.9–1.1. The overall mean differences between the best MODIS C5 and CYCLOPES were within ±0.10. The highest correspondence was obtained for woody biomes from the best MCD15 C5 data (RMSE = 0.80). Results indicate that the uncertainties in current LAI products (around ±1.0) are still unable to meet the accuracy requirement of GCOS (±0.5). Although there are limitations, we recommend MODIS C5 retrieved with the main algorithm (QC<64) and CYCLOPES for the user community. This study demonstrates the necessity of exploring uncertainties related to the true and effective LAIs separately, and reveals the importance of referring to the quality assessment information. More field measurements are required for further studies, which should focus on under-sampled biome types and areas.

1. Introduction

Global leaf area index (LAI) products have been provided using satellite observations on a routine basis, such as the MODIS LAI derived from sensors on the Terra and Aqua satellites (Myneni et al., 2002) and the CYCLOPES LAI derived from the VEGETATION sensors on the SPOT satellite (Baret et al., 2007). To effectively use remote sensing LAI in various disciplines, it is critical to understand the accuracy of these products (Morisette et al., 2006). The meteorological and environmental science communities have stressed the need for global, long-term, and validated estimates of LAI, with a typical target accuracy of around ±0.5 according to the Global Climate Observation System (GCOS) requirement (GCOS, 2006). In response, a hierarchical four-stage validation approach has been adopted by the Committee on Earth Observation Satellites (CEOS), following the consensus of the Land Product Validation (LPV) community (WWW1, Morisette et al., 2006). The MODIS/Terra C5 LAI product is considered to be validated to Stage 2 (WWW2, Nightingale et al., 2008). The same validation level has also been achieved for the CYCLOPES LAI product derived from SPOT/VEGETATION (Garrigues et al., 2008a; Weiss et al., 2007). Validation of these satellite products is therefore an ongoing process, with regular improvements of both the products and the independent validation schemes.

To improve the understanding of satellite LAI for users and developers, further validation studies are necessary. Firstly, validation results from Stages 1 and 2 lack sufficient generality for global interpretation of the product quality. Hence, conclusions may only be valid for a particular region. There have been few Stage 3 validation attempts, but it is worthy of more investigation to obtain globally meaningful results. Secondly, assessment of each product's uncertainty must be made, by referring to its associated quality information. However, quality information for satellite products is still poorly documented. There is no standard quality indicator for different products provided by different agencies, which confuses users and restricts the automation and transferability of validation studies. Thirdly, present validation efforts primarily focus on comparing the true LAI, whereas field optical measurement methods obtain effective estimates of LAI, and satellite products give an approximation of the true LAI (Baret et al., 2007). Converting the effective estimate to the true LAI is complex and prone to errors when applied globally.

---

* Corresponding author. Tel.: +86 10 64888005.
E-mail address: fanghl@lreis.ac.cn (H. Fang).

0034-4257/$ – see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2011.12.006

It is imperative to compare the true and effective LAIs separately, especially for the CYCLOPES product, which does not explicitly account for canopy clumping. Finally, there have not been many cross-validation studies other than those carried out by the respective science teams. With the advent of the latest MODIS Terra + Aqua (MCD15 C5) LAI, it became evident that the new collection needs to be examined with a reference to earlier releases (Gonsamo, 2010).

There are several validation schemes that develop uncertainty information about moderate resolution LAI products, such as the direct comparison method, the bridging method that makes comparison with upscaled high resolution products, and the cross-validation method (WWW2, Justice et al., 2002; Morisette et al., 2006). The direct comparison method has been found useful for validation of LAI products derived from MODIS (Sea et al., 2011) and AVHRR (Buermann et al., 2002; Nikolov & Zeller, 2006). The direct comparison method is promising when a sufficient number of ground points are used and when the field is homogeneous over a large area. It is used when high resolution data are difficult to obtain for the bridging validation method, or the method of estimating the high resolution LAI is determined to be problematic.

In this context, the primary objectives of this paper are twofold: (1) to initiate the Stage 3 validation of both MODIS and CYCLOPES LAI products, with a direct comparison of field LAI compiled from published literature and major validation campaigns, and (2) to investigate whether the current global LAI products could meet the observational requirements proposed by GCOS. We investigate the MODIS LAI product suite, containing the Terra Collection 4 (MOD15 C4), the Terra Collection 5 (MOD15 C5) and the Terra + Aqua combined Collection 5 (MCD15 C5) products. The MODIS products are further compared with the CYCLOPES V3.1 LAI to provide additional insights into the quality of global remote sensing LAI products. In these comparisons, the MODIS quality control (QC) layer and the CYCLOPES status map (SM) are carefully assessed.

2. Data and methods

2.1. MODIS LAI products

The 1 km 8-day MODIS LAI products are available through NASA's Warehouse Inventory Search Tool (WIST) interface (WWW3). The main retrieval algorithm is based on look-up tables (LUTs) simulated from three-dimensional (3D) radiative transfer models (Knyazikhin et al., 1998a, 1998b). Vegetation clumping has been accounted at the shoot and canopy scales for each biome type (Knyazikhin et al., 1998b). The recent C5 LUTs optimize the algorithm on the basis of the stochastic radiative transfer model (Huang et al., 2008; Shabanov et al., 2000, 2005). The LUT includes the red and near-infrared reflectances, and the corresponding illumination-view geometry. When the main algorithm fails, a back-up algorithm based on the LAI–NDVI relationships derived from the simulations of the 3D radiative transfer model (Myneni et al., 1997) is used to estimate the LAI for each biome.

The MODIS LAI product suite, containing the Terra C4 (MOD15 C4), Terra C5 (MOD15 C5) and Terra + Aqua C5 (MCD15 C5), was investigated. Based on the quality control (QC) layer, we categorized the data into the main ($QC<64$) and backup ($64 \leq QC < 128$) algorithms. To further investigate pixels with the best quality, the $QC = 0$ mask was applied to remove the influence of dead detectors and cloud contamination. The operational MODIS LAI algorithm uses biome types as *a priori* information to constrain the structural and optical parameter space of the vegetation. Six major biomes are used in the C4 algorithm: grasses and cereal crops (biome 1), shrubs (biome 2), broadleaf crops (biome 3), savanna (biome 4), broadleaf forest (biome 5), and needleleaf forest (biome 6). The C5 LAI product uses eight biome types, *i.e.*, the broadleaf and needleleaf forests are divided into deciduous and evergreen subclasses (Yang et al., 2006a). Nevertheless, for the purpose of consistency, only six biome types were used in our comparison of C4 and C5 products. It is important to note that, at the time of completion of this paper, the C4 data have been staged offline in WIST.

2.2. CYCLOPES LAI products

The CYCLOPES LAI is generated from the SPOT/VEGETATION sensor at a resolution of 1/112° (about 1 km at the Equator) every 10 days for the period 1999–2007 (Baret et al., 2007). The products (V3.1) can be downloaded from the Land Surface Thematic Centre POSTEL (WWW4). The LAI is estimated by a neural network trained using the one-dimensional SAIL radiative transfer model (Verhoef, 1984) simulations. The SAIL model assumes the canopy is a turbid medium in which leaves are randomly distributed in space. The input data for the neural network estimation include the atmospherically corrected reflectances in red, near-infrared, and shortwave-infrared bands, and solar zenith angles. Clumping at the plant and canopy scale is not specifically represented in the algorithm, whereas landscape clumping is taken into account by considering mixed pixels to be composed of both pure vegetation and pure bare soil. The CYCLOPES SM (status map) indicates the pixel's observational status. A value of $SM = 0$ indicates the best retrieval, while $SM > 0$ means the retrieval is not optimal due to potentially aerosol, cloud, or snow contamination.

2.3. Compilation of field LAI

A number of validation studies (Morisette et al., 2006) have involved taking detailed *in situ* measurements of LAI using destructive harvesting, allometry, or radiometric methods (Bréda, 2003; Jonckheere et al., 2004; Weiss et al., 2004). In this study, LAI data for 28 sites were obtained from existing research networks including FluxNet (WWW5), BigFoot (WWW6; Cohen & Justice, 1999), and VALERI (WWW7). FluxNet (WWW5), including AmeriFlux, has been vital to ongoing validation studies, but usage of the FluxNet sites is limited because these networks are not particularly designed for land product validation. In reality, many sites lack the representation and data services required for satellite product verification. More importantly, the field LAI measurements have not been conducted consistently, with some publicized LAI values based on field experts' best estimations. Only five of the nine BigFoot sites, and 20 of the 33 VALERI sites, were used, because of data availability and site size considerations. Most of the field data (62 sites) were collected from a wide literature survey concurrent with the MODIS and CYCLOPES time frames. The data were based on field measurements from documented experimental plots for a range of biome types. The data varied from single date and point measurements to time series of physical measurements. The two main direct measurement methods are the destructive sampling method and the specific leaf area (SLA) method (Bréda, 2003; Jonckheere et al., 2004; Weiss et al., 2004). LAI-2000 and digital hemispherical photography (DHP) are the two most popular indirect optical methods. All of the VALERI LAI values were obtained with either the LAI-2000 or the DHP method (WWW7).

2.4. Quality control of field LAI

In the field database, all measurement methods, periods, and ground cover types were recorded. Suspicious points, such as extremely high values, were removed based on field experience and literature reports. The data were rigorously scrutinized to minimize the influence of different measurement methods, clumping effects, temporal periods, biome types and the scaling effect. It is necessary to distinguish the true and effective LAI, corresponding to the MODIS and CYCLOPES LAI products. In general, LAI obtained from the direct measurement methods are considered the most accurate “true LAI” and were used directly in the validation, followed by those from the allometric methods. LAI obtained from the indirect optical methods correspond to the effective LAI, because of the violated leaf randomness assumptions on canopy architecture (Baret et al., 2007). To derive the true LAI of a vegetation canopy, the effective LAI has to be corrected for the contribution of woody canopy elements to light interception, and for foliage clumping (Chen, 1996). Although it is theoretically possible to estimate the true LAI from the effective LAI, in reality this is a complicated process, and was therefore not attempted in this study. Instead, the corrections have been completed by the respective investigators who made the field LAI available. We compared the effective and true LAI separately to avoid uncertainties caused by the empirical clumping correction (Chen, 1996; Fournier et al., 2003; Schlerf et al., 2005).

Where several optical methods were available, the mean LAI values were used. Long term field measurements are valuable for direct validation, and so when monthly, seasonal, or yearly LAI values were available, the averaged values of the satellite LAI for the same period were compared. The quality mask of the satellite product was applied (majority rule) in the averaging. The field LAI obtained from the litter traps method was compared with the seasonal mean LAI. The database was pruned to remove discrepancies between the field vegetation and the MODIS biome types. All pruned data were synthesized to one of the six MODIS biome types in the subsequent direct comparison.

In any intercomparison or validation, geolocation uncertainties due to different projection systems, target shift, and different point spread functions, could be an issue (Weiss et al., 2007). The mean or median LAI values of surrounding pixels (*e.g.*, a 3×3 array of pixels) have been recommended for validation studies (Pisek et al., 2010; Verger et al., 2008; Weiss et al., 2007). However, the number of sites representing a literally homogeneous 3 km × 3 km area is rather limited. An initial test shows that using the 3×3 pixels would introduce more uncertainties at a global scale. A single pixel would provide a better match, and was thus extracted for each field observation, concurrent with the satellite product.

Field measurements are usually collected for relatively small areas. The difference in scale between the field measurements and the remote sensing products will bring some errors and biases into the comparison. Efforts were made to acquire field measurements over relatively large (>1 km^2) and homogeneous areas. Many agricultural LAI measurements, usually carried out at small experimental fields, were excluded. It is acceptable to have more forest points, because they are less affected by human activity than agricultural fields. On pooling the network and literature data together, it was found that the database contained a total of 217 field observations over 90 sites from 1999–2006 (WWW8).

In this study, we defined the remote sensing LAI accuracy as the root-mean-squared error (RMSE) between ground LAI and satellite estimation. We compared both MODIS and CYCLOPES products with field data using the direct comparison approach. In the comparison, the impact of the MODIS QC and CYCLOPES SM layers was taken into account. Finally, the best quality MODIS ($QC=0$) and CYCLOPES ($SM=0$) were compared at common field measurement locations.

3. Results

3.1. Characteristics of field measured LAI

The compiled LAI values are distributed globally across a wide range of geographical locations. However, the site distribution indicates more samples are available in North America and Europe than other regions (Fig. 1). Biomes whose LAI values are well represented in the database include forests, shrubs, grasses, and cereal croplands, with the exception of broadleaf crops ($n=4$) (Table 1). The true LAI values in the database range from 0.50 ± 0.58 for shrubs to 3.65 ± 1.88 for needleleaf forest (Table 1). Biomes with the highest LAI values are in the order needleleaf forest > broadleaf forest > broadleaf crops, whereas those with the lowest LAI values are in the order shrubs < savanna < grasses and cereal crops. For shrubs and savanna, the effective LAI was overestimated (>100%) due to leaf clumping and the impact of woody elements. For broadleaf forest, the effective LAI estimates are comparable with the true LAI (bias < 10%). This suggests that the underestimation of LAI due to clumping effects is somehow compensated by the overestimation of LAI through woody structures (Fournier et al., 2003; Schlerf et al., 2005). Conversely, the relative difference between true and effective LAI is 48.8% for needleleaf forest. This agrees with Chen and Cihlar (1995) and Stenberg et al. (1996) who suggested that not accounting for clumping can produce errors of 30–70%.

In comparison to the statistics reported by Asner et al. (2003), the overall LAI values (mean (SD)) decreased from 4.5 (2.5) to 1.98 (1.61) after 2000. This decrease is partly due to the large number of temperate forest ($LAI>5.0$) and plantation systems ($LAI=8.7$) prior to 2000, which usually have very high LAI values (Asner et al., 2003). LAI data located in plantations were seldom used in our study due to their typically smaller size (the largest one recorded is 100 ha). The mean and standard deviation of LAI values for temperate forest calculated by Asner et al. (2003) are very high, which may be partly due to the relatively small sites (0.2 ha on average) (Scurlock et al., 2001).

3.2. Overall evaluation of MODIS and CYCLOPES LAI

3.2.1. All valid MODIS LAI retrievals ($QC<128$)

All valid MODIS retrievals from both the main and background algorithms ($QC<128$) were evaluated to explore the overall quality.

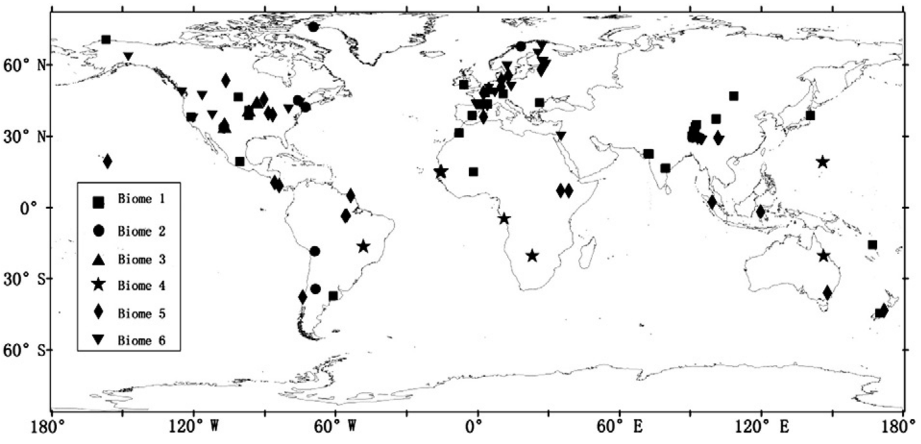

Fig. 1. Distribution of global field LAI measurement sites.

Table 1
Statistical distribution of field measured LAI values by biome types. Blank cells indicate no point/data available.

Biome type	True		Effective		Overall	
	n	Mean (SD)	*n*	Mean (SD)	*n*	Mean (SD)
1. Grasses and cereal crops	39	1.63 (1.09)			39	1.63 (1.09)
2. Shrubs	17	0.50 (0.58)	8	1.08 (0.79)	25	0.68 (0.70)
3. Broadleaf crops	4	2.36 (1.11)			4	2.36 (1.11)
4. Savanna	39	0.83 (0.84)	3	3.08 (2.53)	42	0.99 (1.14)
5. Broadleaf forest	31	3.31 (1.61)	20	3.64 (1.74)	51	3.44 (1.65)
6. Needleleaf forest	10	3.65 (1.88)	46	1.87 (1.10)	56	2.19 (1.43)
Overall	140	1.81 (1.61)	77	2.30 (1.57)	217	1.98 (1.61)

SD: standard deviation

MODIS agreed reasonably well with ground true LAI (RMSE ≤ 1.53, Fig. 2). A comparison of MOD15 C4 with field measurements indicates that this product overestimates LAI (RMSE = 1.42) when all biomes are taken into account (Fig. 2a). The discrepancies are greater at LAI > 3, especially for woody vegetation (savanna, broadleaf and needleleaf forests). Among the 134 pairs of data, only 63.4% are within the ±1.0 range (Fig. 2a). Similar findings have been reported by other studies (Fang & Liang, 2005; Yang et al., 2006b). The poor performance of the C4 product for woody vegetation is attributed to the limited variability of MODIS surface reflectance data in the LUTs, which has been addressed in the C5 products (Shabanov et al., 2005).

The improvement in the C5 products was verified using field measurements. The new collection shows a much better agreement with the field measurements, revealing results that are closer to the 1:1 line (Fig. 2b and c). The disparities for woody vegetation at LAI > 3 have improved marginally in the Terra-only C5 (RMSE = 1.53). In contrast, there is a large improvement in the correspondence of the combined Terra + Aqua C5 products. In total, 67.9% and 75.9% of the pixels for the MOD15 C5 and the MCD15 C5 products, respectively, are within the ±1.0 range, although there are some overestimations for broadleaf forest. The superiority of the Terra + Aqua combined product (RMSE = 1.09) is to be expected, given the improved retrieval algorithm and additional satellite observations (Shabanov et al., 2005). The underestimation of the MODIS LAI in a few needleleaf forest sites is due to large scale deviations between the MODIS and ground measurements. It may also be partly due to the ground measurements that do not include the understory.

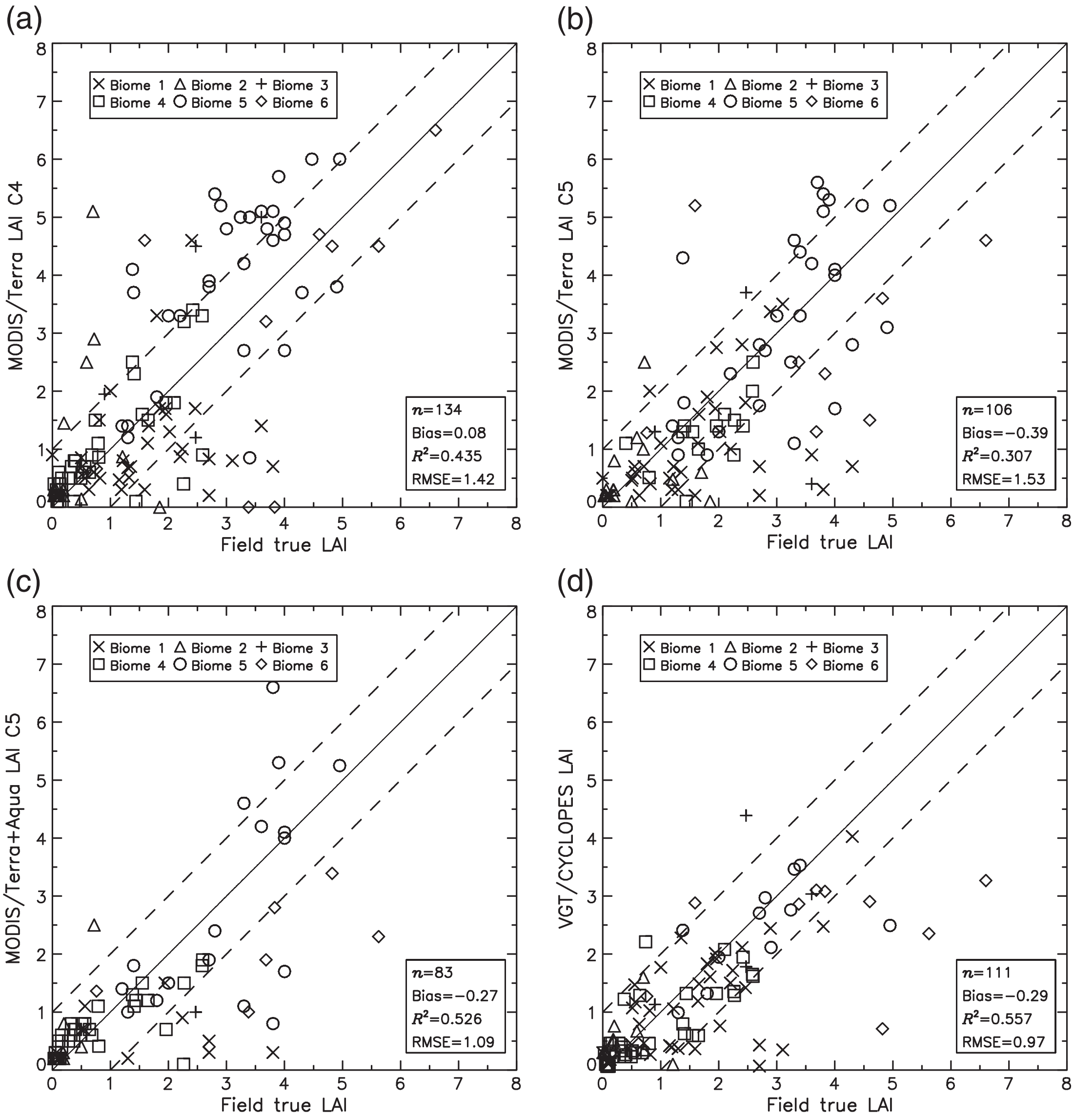

Fig. 2. Comparison of all valid MODIS (QC < 128) and CYCLOPES retrievals with field true LAI. The four panels show (a) MODIS/Terra C4, (b) MODIS/Terra C5, (c) MODIS/Terra + Aqua C5, and (d) SPOT/VEGETATION CYCLOPES. The intercepts for the dashed lines are ±1.0, respectively.

3.2.2. All valid CYCLOPES retrievals ($LAI \leq 6.0$)

The CYCLOPES LAI has a valid range of 0–6.0 (CYCLOPES, 2006). CYCLOPES corresponds best with the field true LAI (RMSE = 0.97, Fig. 2d), although its margin of superiority over the MCD15 C5 is small. The superiority of CYCLOPES over MODIS should be interpreted under the consideration that no quality flag has yet been applied for both products. CYCLOPES is seen to outperform the C4 MODIS LAI, a finding also reported by Weiss et al. (2007) and Garrigues et al. (2008a). CYCLOPES products are also found to be considerably better than the Terra-only C5 product. More than 83.8% of CYCLOPES LAI is within a ±1.0 offset of the field measurement (Fig. 2d). Among the 111 observations, almost all CYCLOPES retrievals are <4.0, with only two outlier points. Some underestimations are observed for broadleaf and needleleaf forests, especially for $LAI > 4.0$. These may have been caused by the canopy clumping effect and the spatial mismatch between ground measurements and pixel (Weiss et al., 2007).

3.2.3. Comparison with field effective LAI

When considering the effective LAI, it is not unexpected that the deviations ($RMSE > 1.60$) for MODIS estimates are much larger than when considering the true LAI (Fig. 3). The MODIS LAI improves slightly over different releases, as shown by the decreasing RMSE values. CYCLOPES products are comparable with the effective LAI (RMSE = 1.34, Fig. 3d). This figure also illustrates that MODIS is closer to the true LAI, since MODIS includes some clumping in the biome characterization, whereas CYCLOPES is closer to the effective LAI. This evaluation suggests that comparison with the effective LAI warrants further investigation with more field data. In the subsequent analysis, we focus on comparing the satellite LAI with the field true LAI, with a reference to the effective LAI, particularly for CYCLOPES.

3.3. Comparison of all good MODIS LAI retrievals ($QC < 64$)

3.3.1. Good MODIS retrievals from the main algorithm ($QC < 64$)

The MODIS data were split into products retrieved using the main and the backup algorithms (Table 2). The advantage of the radiative-transfer-based retrievals is obvious. The total number of good quality retrievals ($QC < 64$) increases from 85.8% for C4 to 92.5% and 97.6% for the MOD15 C5 and MCD15 C5 products, respectively. In the C4 product, about 94.5% and 79.7% of the herbaceous and the woody pixels, respectively, have good data quality. In C5, more than 96% of

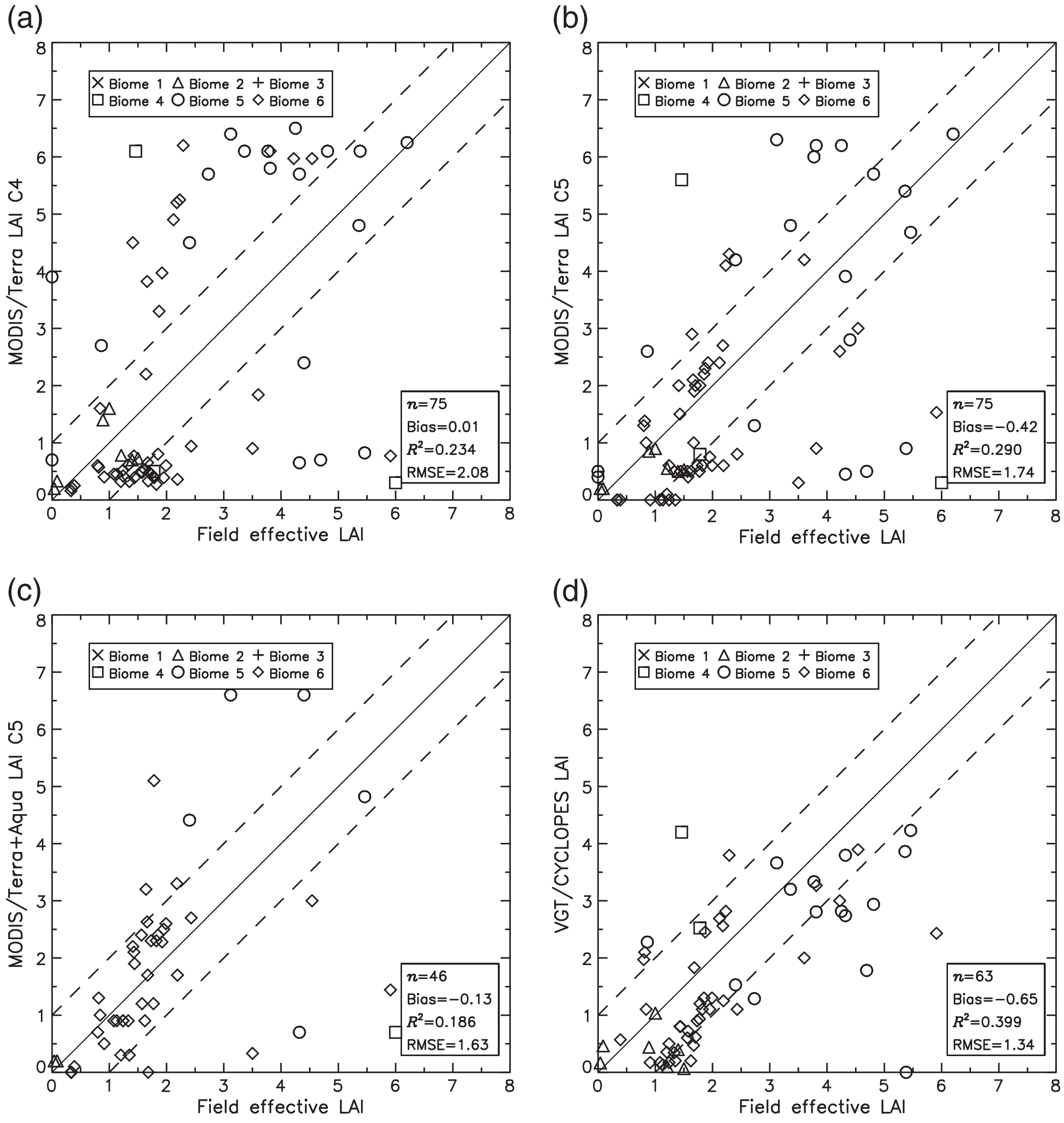

Fig. 3. Comparison of all valid MODIS ($QC < 128$) and CYCLOPES retrievals with field effective LAI. The four panels show (a) MODIS/Terra C4, (b) MODIS/Terra C5, (c) MODIS/Terra + Aqua C5, and (d) SPOT/VEGETATION CYCLOPES. The intercepts for the dashed lines are ±1.0, respectively.

Table 2
Comparison of all valid MODIS and CYCLOPES with field LAI. MODIS retrievals from the main (QC<64) and the backup (64≤QC<128) algorithms were compared with field true LAI, respectively. CYCLOPES (SM≥0) was compared with the true and effective LAI, respectively. The numbers in parenthesis indicate the percentage of points.

	Herbaceous			Woody			All biomes		
	Points	R^2	RMSE	Points	R^2	RMSE	Points	R^2	RMSE
MODIS/Terra C4	55	0.137	1.29	79	0.481	1.50	134	0.436	1.42
QC<64	52 (94.5%)	0.061	1.25	63 (79.7%)	0.718	1.13	115 (85.8%)	0.559	1.19
64≤QC<128	3 (5.5%)	0.682	1.78	16 (20.2%)	0.155	2.46	19 (14.2%)	0.146	2.37
MODIS/Terra C5	54	0.171	1.18	52	0.140	1.82	106	0.307	1.53
QC<64	52 (96.3%)	0.221	1.09	46 (88.5%)	0.382	1.27	98 (92.5%)	0.465	1.17
64≤QC<128	2 (3.7%)	1.000	2.58	6 (11.5%)	0.178	4.04	8 (7.5%)	0.010	3.73
MODIS/Terra+Aqua C5	24	0.042	1.16	59	0.593	1.06	83	0.526	1.09
QC<64	24	0.042	1.16	57 (96.6%)	0.599	1.05	81 (97.6%)	0.528	1.09
64≤QC<128				2 (3.4%)	1.000	1.30	2 (2.4%)	1.000	1.30
VGT/CYCLOPES (true)	53	0.449	0.87	58	0.629	1.05	111	0.557	0.97
VGT/CYCLOPES (effective)	7	0.005	0.82	56	0.348	1.39	63	0.399	1.34

the herbaceous biomes and 88–97% of the woody vegetation are retrieved with the main algorithm, which is consistent with findings from the prototype study (Yang et al., 2006a). The best result is achieved for MCD15 C5 using the main retrieval algorithm (RMSE = 1.09). The combined C5 increases the number of good quality retrievals by 9% for woody vegetation, and retrieves all the herbaceous pixels with the main algorithm. Similarly good results were obtained for MOD15 C5 (RMSE = 1.17). Retrievals from the backup algorithm turn out to be poor and unacceptable.

Comparison of the MODIS (QC<64) and field LAIs was conducted for individual biome types (Table 3). The uncertainties for both grasses and needleleaf forests are slightly high for MCD15 C5 (RMSE = 1.49). This poor performance is attributed to the small number of corresponding points. For shrubs and savanna, the MODIS LAI has improved consistently over all releases. The two biomes usually have a small LAI, and the uncertainties are also small (<0.60) for the combined C5 product, close to the GCOS accuracy requirement. For broadleaf forest, the data quality appears to have improved consistently over all releases, with the smallest RMSE value being <1.0. Crop pixels usually suffer from cloud conditions during field experiments. Obviously, more crop points are necessary in order to achieve a conclusive result.

3.3.2. Best MODIS retrievals (QC = 0)

Application of the best quality mask shows an improved correspondence for MODIS (by about 10% or 0.1 LAI unit, Table 4). The overall RMSE has decreased consistently, from 1.10 for the C4 product to 1.00 and 0.90 for the MOD15 C5 and MCD15 C5 products, respectively. For MCD15 C5, the smallest error (RMSE = 0.80) is observed for the woody biome types. Retrievals for the herbaceous biome are generally better than for the woody biome types, except for MCD15 C5. This might have been caused by the small number of field points and high uncertainties in grasses and cereal crops. For individual biome types, the uncertainties for the grasses and cereal crops and forest types are generally higher than those of the other types. In shrubs and savanna, the uncertainties for the combined C5 product are below the GCOS threshold (<0.5). Caution should be exercised when interpreting the results for individual biomes, due to the relatively few corresponding observations.

Different collections of the MODIS LAI were compared with their best quality data (QC = 0) at common field points (Fig. 4). All of the biases are positive, reflecting an overestimation in the earlier collections. The difference is most pronounced between the C4 and the MOD15 C5 products (Fig. 4a), especially for LAI > 3.0, indicating the large improvement of C5 over C4. The difference is minute (0.10) between the two C5 products, with 95.7% of points within the ±1.0 range (Fig. 4c), indicating the extent of stability in the best MODIS C5 products.

3.4. Comparison of CYCLOPES retrievals

3.4.1. All valid CYCLOPES retrievals (LAI ≤ 6.0)

CYCLOPES is found to outperform MODIS using the main algorithm (Table 2), especially for the herbaceous biomes (RMSE = 0.87). For woody biomes, the performance of CYCLOPES appears to be in line with the MCD15 C5 main retrieval products (RMSE = 1.05). For all biome types except forests (Table 3), the RMSE values are close to or less than 1.0. The uncertainty for grasses and cereal crops (RMSE = 0.95) is smaller than MODIS, and in shrubs and savanna, the small uncertainties (<0.60) are comparable with those of the MODIS C5 products. The CYCLOPES appears to be more consistent with the field true LAI for broadleaf forest (RMSE = 0.87), and with the field effective LAI for needleleaf forest (RMSE = 1.06).

3.4.2. Best CYCLOPES LAI (SM = 0)

We attempted to utilize the status map by comparing the best CYCLOPES (SM = 0) with field data (Table 4). With the small number of points, the application of the SM does not give significantly better results, even though suspicious pixels were removed. This might indicate that the valid CYCLOPES LAI could be recommended for the user community if the application of quality information proves difficult. Overall, CYCLOPES performs similarly to the MOD15 C5, but is

Table 3
Comparison of MODIS from the main algorithm (QC<64) and CYCLOPES with field LAI for six individual biome types. MODIS was compared with field true LAI only. CYCLOPES (SM≥0) was compared with the true and effective LAI, respectively.

	Grasses and cereal crops			Shrubs			Broadleaf crops			Savanna			Broadleaf forest			Needleleaf forest		
	n	R^2	RMSE	n	R^2	RMSE	n	R^2	RMSE	n	R^2	RMSE	n	R^2	RMSE	n	R^2	RMSE
MODIS/Terra C4	36	0.109	1.16	14	0.297	1.46	2	1.000	1.17	31	0.572	0.61	9	0.623	1.72	23	0.394	1.37
MODIS/Terra C5	35	0.165	1.24	15	0.131	0.64	2	1.000	0.92	13	0.366	0.73	11	0.407	1.28	22	0.170	1.49
MODIS/Terra+Aqua C5	12	0.004	1.49	11	0.684	0.58	1			35	0.600	0.52	7	0.739	0.96	15	0.126	1.77
VGT/CYCLOPES (true)	36	0.367	0.95	13	0.033	0.49	4	0.340	1.06	38	0.608	0.55	11	0.358	0.87	9	0.054	2.23
VGT/CYCLOPES (effective)				7	0.005	0.82				2	1.000	2.01	15	0.033	1.93	39	0.428	1.06

Table 4
Comparison of the best quality MODIS (QC = 0) and CYCLOPES (SM = 0) with field LAI for all biome types. MODIS was compared with field true LAI only. CYCLOPES was compared with the true and effective LAI, respectively.

	Individual biome type				Herbaceous/ Woody			All biomes		
	Biomes	n	R^2	RMSE	n	R^2	RMSE	n	R^2	RMSE
MODIS/ Terra C4	1	15	0.046	0.96	23	0.087	0.91	48	0.534	1.10
	2	8	0.754	0.82						
	4	9	0.862	0.57	25	0.513	1.25			
	5	5	0.180	1.44						
	6	11	0.217	1.53						
MODIS/ Terra C5	1	30	0.195	1.12	46	0.270	0.99	78	0.478	1.00
	2	14	0.144	0.65						
	3	2	1	0.92						
	4	11	0.582	0.55	32	0.509	1.01			
	5	6	0.0001	1.35						
	6	15	0.648	1.11						
MODIS/ Terra + Aqua C5	1	6	0.005	1.46	12	0.083	1.05	33	0.542	0.90
	2	6	0.592	0.28						
	4	15	0.878	0.31	21	0.674	0.80			
	5	2	1	0.63						
	6	4	0.103	1.67						
VGT/ CYCLOPES (true)	1	26	0.435	0.89	39	0.508	0.84	76	0.557	0.99
	2	9	0.040	0.53						
	3	4	0.340	1.06						
	4	28	0.786	0.44	37	0.655	1.12			
	5	4	0.050	1.41						
	6	5	0.003	2.56						
VGT/ CYCLOPES (effective)	5	11	0.010	1.94	19	0.004	1.774	20	0.043	1.74
	6	8	0.002	1.52						

marginally inferior to the MCD15 C5 (Table 4). Good results were obtained for herbaceous biomes (RMSE = 0.84). This performance is better than the MODIS counterparts, which has only 12 observations (Table 4). CYCLOPES does not fully account for the clumping effect and is conceptually closer to the field effective LAI. The good correspondence indicates that the CYCLOPES LAI is very close to the true LAI for herbaceous biomes (RMSE = 0.84). The clumping effect for crops may be compensated by not accounting for the non-green elements in satellite estimates (Baret et al., 2010). It is clear that CYCLOPES is more comparable with the field true LAI than the effective LAI (RMSE = 1.41 *vs.* 1.94) for broadleaf forest, and more comparable with the field effective LAI than the true LAI (RMSE = 1.52 *vs.* 2.56) for needleleaf forest. The mixed results for forests are explained by the clumping effect. The relative difference between the true and effective LAIs is small for broadleaf forest (<10%), while it is larger for needleleaf forest (Section 3.1). Obviously, more data points are necessary for the forest biomes in order to achieve a more robust result.

3.5. Intercomparison of MODIS and CYCLOPES LAI

3.5.1. Common MODIS, CYCLOPES and field points

The consistency of MODIS (QC<64) and CYCLOPES products is checked for 80 concurrent observations, and compared with field true LAI (Fig. 5). Compared to the field LAI, the remote sensing products underestimate the LAI of grasses by about 0.38–0.81. Shrubs have a low value (field LAI = 0.32), and this shows a good correspondence between remote sensing and field LAI. For savanna, the MCD C5 and CYCLOPES products give lower LAIs than the field values, by 1.01 and 0.63, respectively. For broadleaf forest, both MODIS C5 products show a better correspondence with the field LAI than the C4 product. MODIS C5 and CYCLOPES are comparable for forests, and the mean field value is within the range of MODIS variations. The LAI values of

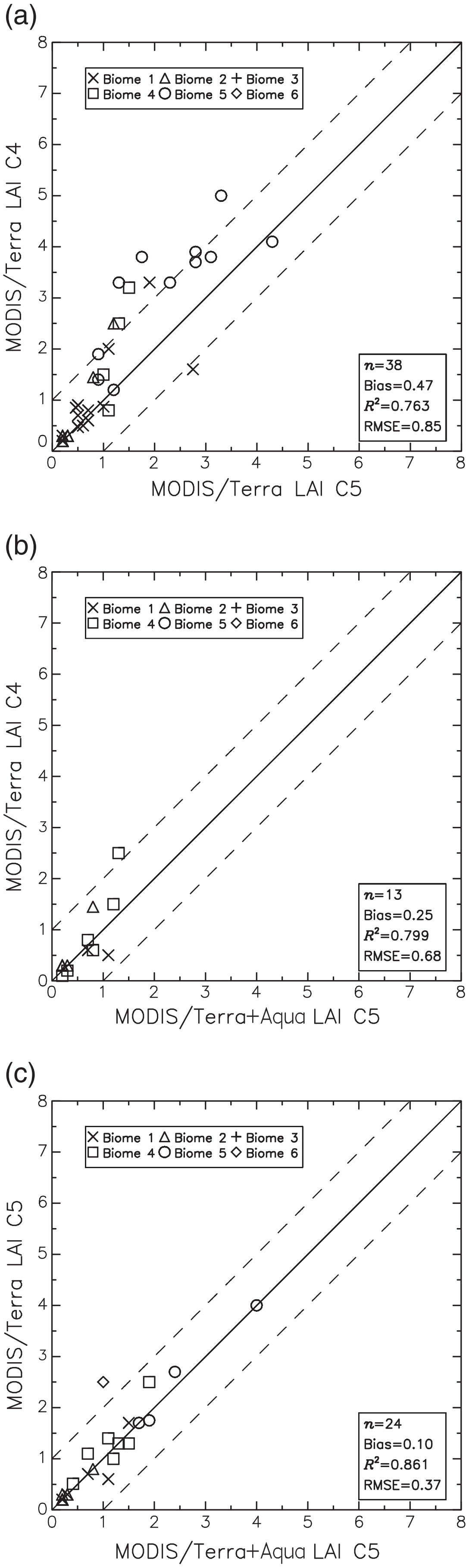

Fig. 4. Intercomparison of the best MODIS LAI (QC = 0) from different collections at the common true LAI points.

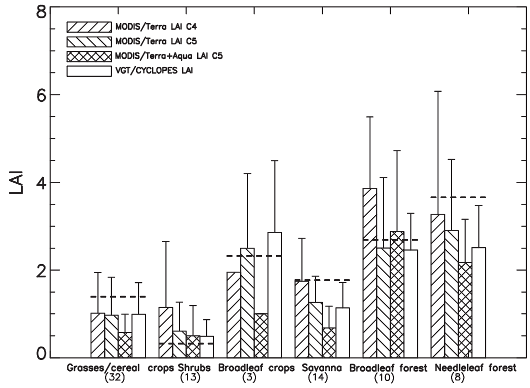

Fig. 5. Intercomparison of mean (+1 SD) MODIS main algorithm (QC<64) and CYCLOPES LAI values at common field true LAI points for each biome type. The dashed horizontal line indicates the mean field true LAI. The common number of observations for each biome is shown in the parenthesis.

broadleaf forests from MODIS C5 and CYCLOPES corresponds well to the field measurements (bias<0.25). For needleleaf forest, however, there are some underestimations, ranging from 0.64 for MCD15 C5 to 1.14 for CYCLOPES. The underestimation of CYCLOPES is partly due to the lack of clumping treatment. For broadleaf crops, the differences between products are quite obvious due to the small number of common observations.

3.5.2. Best MODIS (QC = 0) and CYCLOPES (SM = 0)

The correspondence between the best MODIS (QC = 0) and CYCLOPES (SM = 0) data is illustrated in Fig. 6. There is a small overestimation (0.32) for the offline MOD15 C4 (Fig. 6a), especially for LAI > 3.0. This may reflect the clump processing and the true LAI for the MODIS product. The deviations are very low (≤0.06) for both MODIS C5 products (Fig. 6b and c), indicating the consistency between the best MODIS and CYCLOPES products. MCD15 C5 and CYCLOPES agree very well, with 90% of points falling within the ±1.0 range (Fig. 6c). Considering the small number of points (n = 20) and the limited range of LAI values (<3.0), more observations are necessary for a full MODIS and CYCLOPES intercomparison.

3.5.3. Seasonal characteristics

We evaluated the seasonal trajectory of the two MODIS C5 (QC<64) and CYCLOPES products across six selected sites for the period 2000–2005 (Fig. 7). The MODIS C4 was not examined, as the product was offline during the later stages of this study and exhibits high temporal variability (Cohen et al., 2006). The satellite products agree reasonably well with field measurements. Fig. 7 shows a generally consistent seasonal variation, with smoother variability for the CYCLOPES LAI. The two MODIS C5 collections agree very well, overlapping for much of the time. MODIS C5 shows some temporal discontinuity, and an unrealistically strong variability in summer, especially for forest biomes. This is partly due to the impact of cloud cover.

MODIS and CYCLOPES capture the proper seasonal trajectory of the grasslands (Fig. 7a). However, CYCLOPES experiences greater ranges over the summer than MODIS C5, especially in 2004 (by about 0.70), possibly due to the persistent aerosol status as indicated by the quality mask (SM = 8 or 12). The remote sensing LAI values for shrubs (Fig. 7b) are mostly lower than 0.5, while the field measurement LAIs are all less than 0.2. Remote sensing derived similar peak LAI estimates in summer, with smoother seasonal variability for CYCLOPES (Fig. 7b). The cropland site (Fig. 7c) is a mixture of cereal

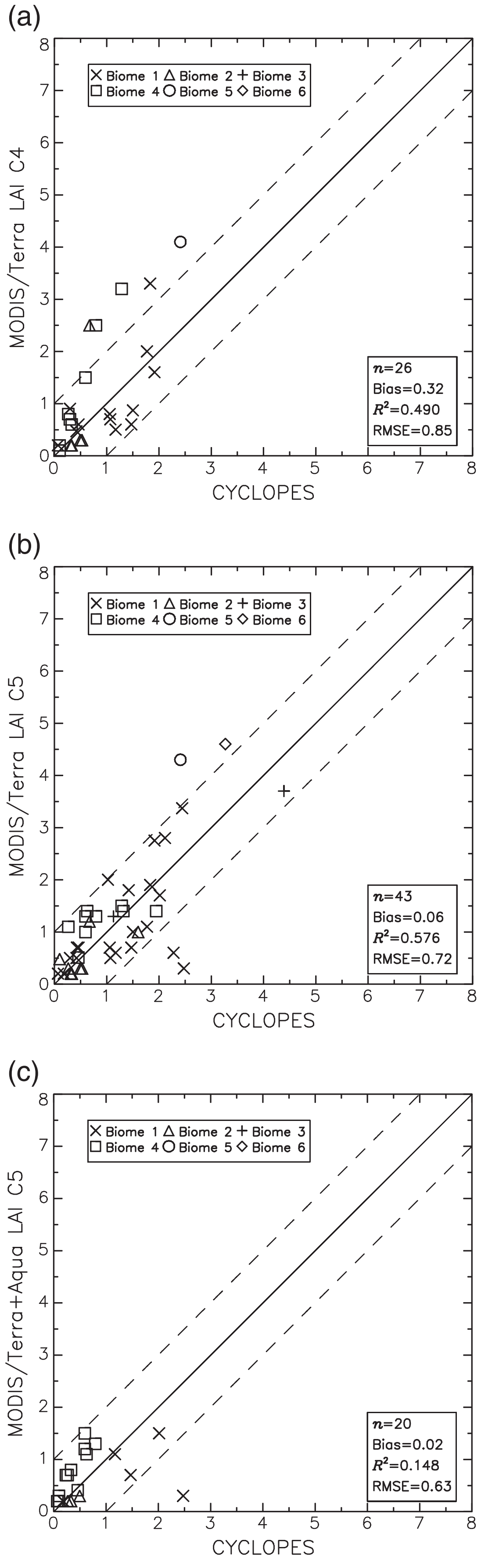

Fig. 6. Comparison of the best quality MODIS (QC = 0) and CYCLOPES (SM = 0) at common field true LAI points. The panels compare CYCLOPES with (a) MODIS/Terra C4, (b) MODIS/Terra C5, and (c) MODIS/Terra + Aqua C5, respectively.

and broadleaf crops. Due to cloud contamination, there are higher deviations in early spring (*e.g.*, 2002) and summer (*e.g.*, 2004). The level of variability in CYCLOPES, ranging on average from 0.1 to 2.5, remains higher than the MODIS products (0.1–1.6).

MODIS, CYCLOPES, and ground measurements agree well across grass savanna sites (Fig. 7d), even though CYCLOPES gives a consistently lower (by about 0.12) LAI than MODIS. Over the broadleaf forest site (Harvard forest, USA, Fig. 7e), the remote sensing LAI

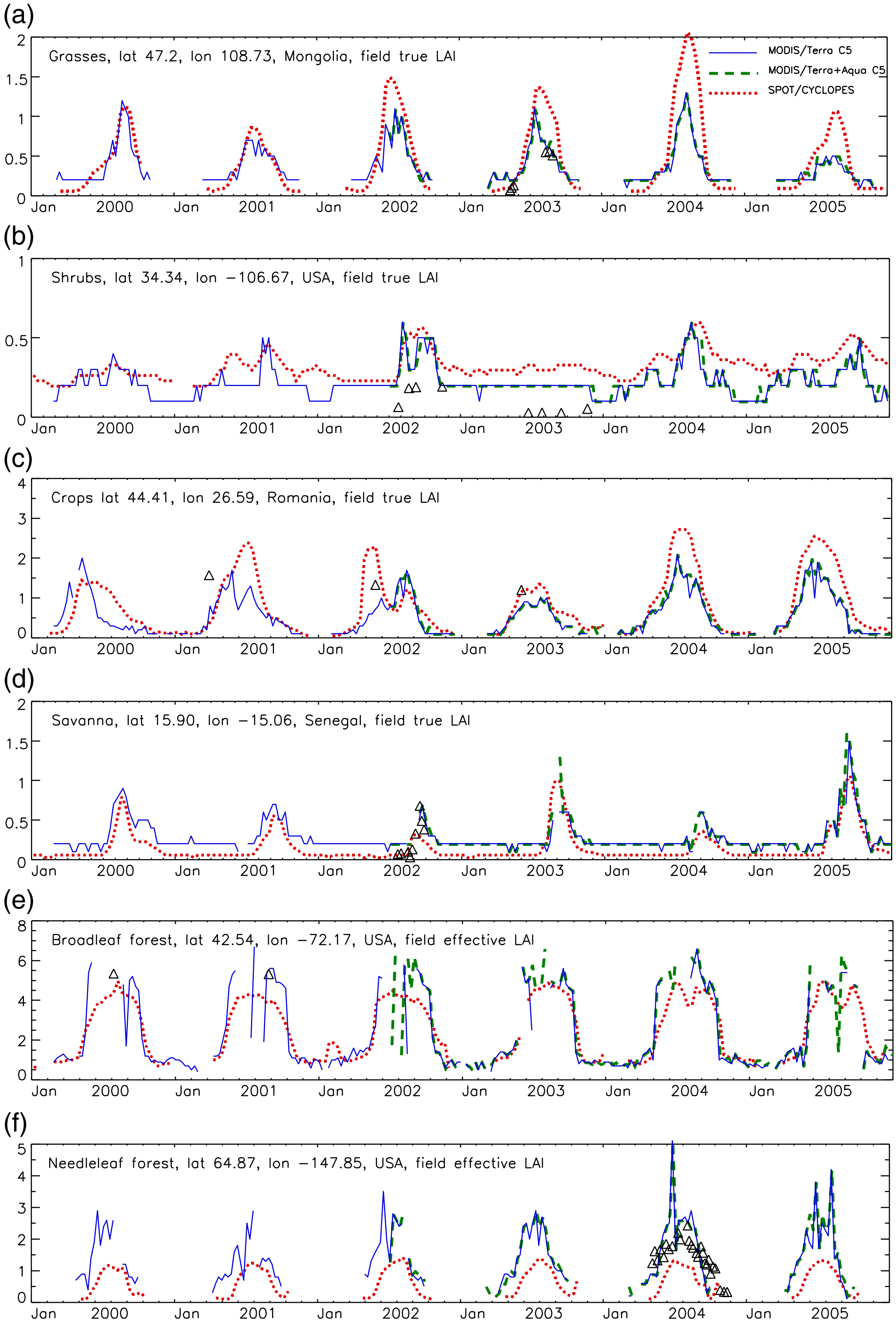

Fig. 7. Interannual and seasonal variations of MODIS/Terra C5, MODIS/Terra + Aqua C5, and CYCLOPES LAI over some typical sites (2000–2005). Triangles represent the field effective LAI for forests and true LAI for other types. MODIS LAI are retrieved with the main algorithm (QC<64).

shows similar seasonal patterns, but a higher variability in summer because of mixed cloud present in the pixels. Over the needleleaf forest site (Fig. 7f), similar high variabilities are observed for MODIS C5 in summer. CYCLOPES shows a smooth seasonal pattern, but is systematically lower (by about 0.80) than the MODIS retrievals and ground measurements. This underestimation is caused by the fact that CYCLOPES does not explicitly account for clumping, which could produce a difference of about 50% between the true and effective estimates of LAI in coniferous forests (Chen & Cihlar, 1995; Stenberg, 1996). The MODIS LAI tends to increase earlier in spring (by up to one month in 2003 and 2004), which may be attributable to its sensitivity to the exposure of understory vegetation in spring (Kobayashi et al., 2010). CYCLOPES uses a generic radiative transfer algorithm (SAIL) which, unlike the MODIS algorithm, does not account for the structural heterogeneity for a specific biome (Baret et al., 2007).

4. Discussion

4.1. Comparison with other similar studies

Comparison with other similar studies for a variety of vegetation types and different validation schemes confirms the feasibility of the direct comparison method.

Overestimation of the MODIS C4 has been reported by many previous studies with the bridging method at a local or global level (Fang & Liang, 2005; Garrigues et al., 2008a; Hill et al., 2006; Pisek & Chen, 2007; Weiss et al., 2007). Our analysis suggests that MOD15 C5 shows an improved consistency with the *in situ* measurements and a more realistic temporal LAI dynamic. However, the results suggest that MOD15 C5 underestimates the upper range of *in situ* LAI measurements, which agrees with findings reported recently by De Kauwe et al. (2011) for coniferous forest using the bridging method. MOD15 C5 shows temporal gaps and unrealistically strong variability, especially for forest biomes during the growing season (Fig. 7), a drawback also indicated by Kobayashi et al. (2010) for a deciduous needleleaf forest in Siberia. This study is unique in that the latest Terra + Aqua C5 products were compared with *in situ* measurements and the CYCLOPES products. The combined retrieval algorithm is advantageous, as it enhances the temporal compositing periods and reduces the environmental impact (Horn & Schulz, 2010; Yang et al., 2006a). It was not unexpected to find that the CYCLOPES performed better than the MODIS C4 product (Garrigues et al., 2008a; Weiss et al., 2007). Validation studies with either the bridging and cross-validation methods have indicated that the RMSE values generally vary from 1.06–1.37 for MODIS, and from 0.50–1.24 for CYCLOPES (Garrigues et al., 2008a; Kobayashi et al., 2010; Verger et al., 2011; Weiss et al., 2007). This represents the status of current MODIS and CYCLOPES LAI validation efforts. Our results (Tables 2–4) are within the range of other similar studies. The RMSE values ($\text{RMSE}=1.19$, $n=115$) for MOD15 C4 (Table 2) are higher than those ($\text{RMSE}=0.66$, $n=29$) reported in earlier studies (Yang et al., 2006b, WWW2). The lower RMSE value in Yang et al. (2006b) might be attributed to the ideal field validation sites and the very good correspondence for herbaceous biome types.

4.2. Implications for CEOS LPV validation and GCOS accuracy requirement

The MODIS LAI product has achieved the Stage 2 validation (Nightingale et al., 2008). With this enhanced study and that of other researchers (Garrigues et al., 2008a; Weiss et al., 2007), we aim to achieve the Stage 3 validation. The Stage 3 validation involves assessing product accuracy via independent measurements representing global conditions (WWW2). In-depth Stage 3 validation should involve more comprehensive field data for under-represented biome types and areas. The most enhanced Stage 4 validation requires the provision of automatic quality information with the product, which is more difficult to realize within the existing schemes.

It is clear that the available MODIS C5 and CYCLOPES LAI products are currently unable to meet the threshold accuracy requirements, set by GCOS, of around ±0.5. We are convinced that they are able to meet a threshold accuracy of ±1.0. A few individual biome types, such as the shrubs and savanna, have been shown to have met the requirement (Table 4; Sea et al., 2011). Nevertheless, this positive performance should be attributed to the small average LAI values for these two biomes (Table 1). Some studies on improved products have reported meeting the accuracy requirements at a selected number of sites (Pisek et al., 2010). However, this is not the case at a global level.

4.3. Limitations of the study

The major issue facing our validation study is the mismatch of spatial scales for the point-to-pixel comparison between moderate resolution LAI products and reference LAI values (Chen et al., 2002; Myneni, et al., 2005; Reich et al., 1999). This is the reason why the bridging method is generally chosen for validation of satellite-derived products with 1 km or coarser resolution (Garrigues et al., 2008a; Huang et al., 2006; Morisette et al., 2006). In this study, the ground measurement sites are carefully chosen to be distributed in a large homogeneous landscape (> 3–5 km) that yields a representative LAI in order to minimize scale effects. With sufficient number of samples collected from large and homogeneous sites, the LAI distributions from field measurements and satellite data should approximate the true intrinsic distribution of the biome (Buermann et al., 2002).

Sampling across long transects (Sea et al., 2011) and validation at the patch (multi-pixel) scale (Myneni et al., 2005) have been recommended for ground-based validation of MODIS LAI. Our results showed that, with a sufficient number of field data across the globe, a direct comparison of the mean value for multiple scattered and similar pixels is also a legitimate method for LAI product validation.

A second source of uncertainty is the consistency of ground-based LAI definitions and values, as a result of the diversity of measurement methods (*e.g.*, inclusion/exclusion of understory LAI). Direct measurement methods usually suffer from artifacts related to an observer's experiences. In optical measurement methods, foliage is assumed to be distributed randomly throughout the canopy. The assumption of random foliage distribution is typically invalid in forests (Chen et al., 1997; Gower & Norman, 1991; Kucharik et al., 1998), and this assumption can produce errors of up to 100% (Fassnacht et al., 1997). The clumping effect accounts for another source of error when we consider that field investigators have made corrections for this effect using different methods (*e.g.*, Chen, 1996; Chen et al., 1997; Sonnentag et al., 2007). Clumping correction may not be necessary for broadleaf forests because the underestimation of LAI due to clumping effects could be compensated by the overestimation of LAI due to woody structures (Fournier et al., 2003; Schlerf et al., 2005). Several studies have indicated that the measurement biases as a result of different measurement techniques are usually low (Asner et al., 2003; Chen et al., 2006; Coops et al., 2004; Garrigues et al., 2008). The amplitude of uncertainties attached to the ground measurements is reasonably expected to be on par with the uncertainties of the ground reference LAI map used in the bridging method (20% or 1.0 LAI unit, Fernandes et al., 2003; Garrigues et al., 2008a).

4.4. Prospects for future studies

Our results serve as a reference for further validation work and algorithm refinement. Due to the absence of more detailed field information, we could not further investigate the uncertainties brought about by the various measurement methods. Future validation efforts are particularly necessary for biome types and regions that have not been adequately represented, *e.g.*, for crops and in the southern hemisphere. This work should also be updated based on the eight biome types in MODIS C5. For CYCLOPES, consideration of the SM value is essential, as this choice can have significant effects on the resulting LAI quality. There is certainly a need for more guidance about proper usage of the SM information. Sufficient amounts of *in situ* measurements would certainly help to address the scaling issues and possible pixel-shift errors in projection. In addition to the generic quality assessments, as illustrated in this and other studies, the user community also requires spatially continuous uncertainty information for the entire globe to drive the process models. The cross-validation method should be able to address issues that could not be solved by either the direct comparison or the bridging method. Comparison of the results with other validation schemes, particularly the cross-validation method, will be conducted in a future paper.

5. Conclusions

This study validated the global MOD15 C4, MOD15 C5, MCD15 C5 and CYCLOPES LAI products by a direct comparison method based on measurements from field campaigns and a literature survey. In general, the MODIS estimates have improved consistently over all releases, with an RMSE decreasing by about 0.10 for each new release. While the offline MOD15 C4 has its drawbacks, uncertainties of the MOD15 C5 and MCD15 C5 products retrieved with the main algorithm ($QC<64$) are similar to those of the CYCLOPES product. For all products with the best quality flags ($QC=0$ for MODIS, $SM=0$ for CYCLOPES), the highest correspondence with field LAI is obtained for woody biomes from the MCD15 C5 product ($RMSE=0.80$). It should be noted that the overall mean differences between the best MODIS C5 and CYCLOPES estimates are very small (around 0.10). Applying the quality flags significantly reduces the number of usable pixels. Therefore, we recommend the use of MODIS C5 data retrieved with the main algorithm ($QC<64$) and the valid CYCLOPES V3.1. Nevertheless, the uncertainties of current satellite products (within ±1.0) are still unable to meet the threshold accuracy requirements stipulated by GCOS (±0.5). Further studies should focus on spatial uncertainties and consider the scale difference between field measurements and moderate resolution pixels while utilizing more comprehensive observations.

Acknowledgments

Part of the data were collected when H. Fang was a Research Assistant Professor at the Department of Geography, University of Maryland, College Park, USA. We are indebted to many investigators and the FluxNet (WWW5), BigFoot (WWW6), and VALERI (WWW7) projects for providing the field measurement data. The global field LAI database is available at WWW8. The WIST (WWW3) and POSTEL (WWW4) teams facilitated the distribution of the MODIS and CYCLOPES products. We thank the four anonymous reviewers who provided helpful comments of the manuscript. H. Fang is currently supported by the Hundred Talent Program of the Chinese Academy of Sciences, China.

References

Asner, G. P., Scurlock, J. M. O., & Hicke, J. A. (2003). Global synthesis of leaf area index observations: Implications for ecological and remote sensing studies. *Global Ecology and Biogeography*, *12*, 191–205.

Baret, F., de Solan, B., Lopez-Lozano, R., Ma, K., & Weiss, M. (2010). GAI estimates of row crops from downward looking digital photos taken perpendicular to rows at 57.5° zenith angle: Theoretical considerations based on 3D architecture models and application to wheat crops. *Agricultural and Forest Meteorology*, *150*, 1393–1401.

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., et al. (2007). LAI, fPAR, and fCover CYCLOPES global products derived from VEGETATION Part 1: Principles of the algorithm. *Remote Sensing of Environment*, *110*, 275–286.

Bréda, N. J. J. (2003). Ground-based measurements of leaf area index: A review of methods, instruments and current controversies. *Journal of Experimental Botany*, *54*, 2403–2417.

Buermann, W., Wang, Y. J., Dong, J. R., Zhou, L. M., Zeng, X. B., Dickinson, R. E., et al. (2002). Analysis of a multiyear global vegetation leaf area index data set. *Journal of Geophysical Research — Atmosphere*, *107*, doi:10.1029/2001JD000975.

Chen, J. M. (1996). Optically-based methods for measuring seasonal variation of leaf area index in boreal conifer stands. *Agricultural and Forest Meteorology*, *80*, 135–163.

Chen, J. M., Blanken, P. D., Black, T. A., Guilbeault, M., & Chen, S. (1997). Radiation regime and canopy architecture in a boreal aspen forest. *Agricultural and Forest Meteorology*, *86*, 107–125.

Chen, J. M., & Cihlar, J. (1995). Plant canopy gap-size analysis theory for improving optical measurements of leaf-area index. *Applied Optics*, *34*, 6211–6222.

Chen, J. M., Govind, A., Sonnentag, O., Zhang, Y., Barr, A., & Amiro, B. (2006). Leaf area index measurements at Fluxnet-Canada forest sites. *Agricultural and Forest Meteorology*, *140*, 257–268.

Chen, J. M., Pavlic, G., Brown, L., Cihlar, J., Leblanc, S. G., White, H. P., et al. (2002). Derivation and validation of Canada-wide leaf area index maps using ground measurements and high and moderate resolution satellite imagery. *Remote Sensing of Environment*, *80*, 165–184.

Cohen, W. B., & Justice, C. O. (1999). Validation MODIS terrestrial ecology products: Linking *in situ* and satellite measurements. *Remote Sensing of Environment*, *70*, 1–3.

Cohen, W. B., Maiersperger, T. K., Turner, D. P., Ritts, W. D., Pflugmacher, D., Kennedy, R. E., et al. (2006). MODIS land cover and LAI collection 4 product quality across nine sites in the Western Hemisphere. *IEEE Transactions on Geoscience and Remote Sensing*, *44*, 1843–1857.

Coops, N. C., Smith, M. L., Jacobsen, K. L., Martin, M., & Ollinger, S. (2004). Estimation of plant and leaf area index using three techniques in a mature native eucalypt canopy. *Austral Ecology*, *29*, 332–341.

CYCLOPES (2006). *CYCLOPES products read me, V3.1. MEDIAS-France.* 11 pp.

De Kauwe, M. G., Disney, M. I., Quaife, T., Lewis, P., & Williams, M. (2011). An assessment of the MODIS collection 5 leaf area index product for a region of mixed coniferous forest. *Remote Sensing of Environment*, *115*, 767–780.

Fang, H., & Liang, S. (2005). A hybrid inversion method for mapping leaf area index from MODIS data: Experiments and application to broadleaf and needleleaf canopies. *Remote Sensing of Environment*, *94*, 405–424.

Fassnacht, K. S., Nordheim, E. V., Liliesand, T. M., Gower, S. T., & MacKenzie, M. D. (1997). Estimating the leaf area index of North Central Wisconsin forests using the landsat thematic mapper. *Remote Sensing of Environment*, *61*, 229–245.

Fernandes, R. A., Butson, C., Leblanc, S. G., & Latifovic, R. (2003). Landsat-5 and Landsat-7 ETM+ based accuracy assessment of leaf area index products for Canada derived from SPOT-4 VEGETATION data. *Canadian Journal of Remote Sensing*, *29*, 241–258.

Fournier, R. A., Mailly, D., Walter, J. -M. N., & Soudani, K. (2003). Indirect measurements of forest canopy structure from in situ optical sensors. In M. A. Wulder, & S. E. Franklin (Eds.), *Remote sensing of forest environments—Concepts and case studies* (pp. 77–114). Boston: Kluwer Academic Publishers.

Garrigues, S., Lacaze, R., Baret, F., Morisette, J. T., Weiss, M., Nickeson, J. E., et al. (2008). Validation and intercomparison of global Leaf Area Index products derived from remote sensing data. *Journal of Geophysical Research*, *113*, doi:10.1029/2007JG000635.

Garrigues, S., Shabanov, N., Swanson, K., Morisette, J. T., Baret, F., & Myneni, R. (2008). Intercomparison and sensitivity analysis of leaf area index retrievals from LAI-2000, AccuPAR, and digital hemispherical photography over croplands. *Agricultural and Forest Meteorology*, *148*, 1193–1209.

GCOS (2006). *Systematic observation requirements for satellite-based products for climate, supplemental details to the satellite-based component of the implementation plan for the Global Observing System for Climate in support of the UNFCCC, GCOS-107 (WMO/TD No. 1338).* 90 pp.

Gonsamo, A. (2010). Leaf area index retrieval using gap fractions obtained from high resolution satellite data: Comparisons of approaches, scales and atmospheric effects. *International Journal of Applied Earth Observation and Geoinformation*, *12*, 233–248.

Gower, S. T., & Norman, J. M. (1991). Rapid estimation of leaf area index in conifer and broad-leaf plantations. *Ecology*, *72*, 1896–1900.

Hill, M. J., Senarath, U., Lee, A., Zeppel, M., Nightingale, J. M., Williams, R. D. J., et al. (2006). Assessment of the MODIS LAI product for Australian ecosystems. *Remote Sensing of Environment*, *101*, 495–518.

Horn, J., & Schulz, K. (2010). Post-processing analysis of MODIS leaf area index subsets. *Journal of Applied Remote Sensing*, *4*, 043557.

Huang, D., Knyazikhin, Y., Wang, W., Deering, D. W., Stenberg, P., Shabanov, N., et al. (2008). Stochastic transport theory for investigating the three-dimensional canopy structure from space measurements. *Remote Sensing of Environment*, *112*, 35–50.

Huang, D., Yang, W., Tan, B., Rautiainen, M., Zhang, P., Hu, J., et al. (2006). The importance of measurement errors for deriving accurate reference leaf area index maps for validation of moderate-resolution satellite LAI products. *IEEE Transactions on Geoscience and Remote Sensing*, *44*, 1866–1871.

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M., et al. (2004). Review of methods for in situ leaf area index determination Part I. Theories, sensors and hemispherical photography. *Agricultural and Forest Meteorology*, *121*, 19–35.

Justice, C. O., Townshend, J. R. G., Vermote, E. F., Masuoka, E., Wolfe, R. E., Saleous, N., et al. (2002). An overview of MODIS Land data processing and product status. *Remote Sensing of Environment*, *83*, 3–15.

Knyazikhin, Y., Martonchik, J. V., Diner, D. J., Myneni, R. B., Verstraete, M., Pinty, B., et al. (1998). Estimation of vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MISR data. *Journal of Geophysical Research*, *103*, 32,239–232,256.

Knyazikhin, Y., Martonchik, J. V., Myneni, R. B., Dine, D. J., & Running, S. W. (1998). Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data. *Journal of Geophysical Research*, *103*, 32,257–232,276.

Kobayashi, H., Delbart, N., Suzuki, R., & Kushida, K. (2010). A satellite-based method for monitoring seasonality in the overstory leaf area index of Siberian larch forest. *Journal of Geophysical Research*, *115*, doi:10.1029/2009jg000939.

Kucharik, C. J., Norman, J. M., & Gower, S. T. (1998). Measurements of leaf orientation, light distribution and sunlit leaf area in a boreal aspen forest. *Agricultural and Forest Meteorology*, *91*, 127–148.

Morisette, J. T., Baret, F., Privette, J. L., Myneni, R. B., Nickeson, J. E., Garrigues, S., et al. (2006). Validation of global moderate-resolution LAI products: A framework proposed within the CEOS land product validation subgroup. *IEEE Transactions on Geoscience and Remote Sensing*, *44*, 1804–1817.

Myneni, R., Yang, W., B, T., Shabanov, N., & Knyazikhin, Y. (2005). Global products of vegetation leaf area and fraction absorbed PAR from MODIS sensors onboard NASA Terra and Aqua satellites. In S. Liang, J. Liu, X. Li, R. Liu, & M. Schaepman (Eds.), *The 9th International Symposium on Physical Measurements and Signatures in Remote Sensing. Beijing, China* (pp. 200–202).

Myneni, R. B., Hoffman, S., Knyazikhin, Y., Privette, J. L., Glassy, J., Tian, Y., et al. (2002). Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment*, *83*, 214–231.

Myneni, R. B., Ramakrishna, R., Nemani, R., & Running, S. W. (1997). Estimation of global leaf area index and absorbed par using radiative transfer models. *IEEE Transactions on Geosciences and Remote Sensing*, *35*, 1380–1393.

Nightingale, J., Nickeson, J. E., Justice, C. O., Baret, F., Garrigues, S., Wolfe, R., et al. (2008). Global validation of EOS land products, lessons learned and future challenges: A MODIS case study. pp. 4. Available from. *Proceedings of 33rd International Symposium on Remote Sensing of Environment: Sustaining the Millennium Development Goals, Stresa, Italy*. http://landval.gsfc.nasa.gov/pdf/ISRSE_Nightingale.pdf

Nikolov, N., & Zeller, K. (2006). Efficient retrieval of vegetation leaf area index and canopy clumping factor from satellite data to support pollutant deposition assessments. *Environmental Pollution*, *141*, 539–549.

Pisek, J., & Chen, J. M. (2007). Comparison and validation of MODIS and VEGETATION global LAI products over four BigFoot sites in North America. *Remote Sensing of Environment*, *109*, 81–94.

Pisek, J., Chen, J. M., Alikas, K., & Deng, F. (2010). Impacts of including forest understory brightness and foliage clumping information from multiangular measurements on leaf area index mapping over North America. *Journal of Geophysical Research*, *115*, doi:10.1029/2009jg001138.

Reich, P. B., Turner, D. P., & Bolstad, P. (1999). An approach to spatially distributed modeling of net primary production (NPP) at the landscape scale and its application in validation of EOS NPP products. *Remote Sensing of Environment*, *70*, 69–81.

Schlerf, M., Atzberger, C., & Hill, J. (2005). Remote sensing of forest biophysical variables using HyMap imaging spectrometer data. *Remote Sensing of Environment*, *95*, 177–194.

Scurlock, J. M. O., Asner, G. P., & Gower, S. T. (2001). Worldwide historical estimates of leaf area index, 1932–2000. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Sea, W. B., Choler, P., Beringer, J., Weinmann, R. A., Hutley, L. B., & Leuning, R. (2011). Documenting improvement in leaf area index estimates from MODIS using hemispherical photos for Australian savannas. *Agricultural and Forest Meteorology*, *151*, 1453–1461.

Shabanov, N. V., Knyazikhin, Y., Baret, F., & Myneni, R. B. (2000). Stochastic modeling of radiation regime in discontinuous vegetation canopies. *Remote Sensing of Environment*, *74*, 125–144.

Shabanov, N. V., Kotchenova, S., Huang, D., Yang, W., Tan, B., Knyazikhin, Y., et al. (2005). Analysis and optimization of the MODIS leaf area index algorithm retrievals over broadleaf forests. *IEEE Transactions on Geoscience and Remote Sensing*, *43*, 1855–1865.

Sonnentag, O., Talbot, J., Chen, J. M., & Roulet, N. T. (2007). Using direct and indirect measurements of leaf area index to characterize the shrub canopy in an ombrotrophic peatland. *Agricultural and Forest Meteorology*, *144*, 200–212.

Stenberg, P. (1996). Correcting LAI-2000 estimates for the clumping of needles in shoots of conifers. *Agricultural and Forest Meteorology*, *79*, 1–8.

Verger, A., Baret, F., & Weiss, M. (2008). Performances of neural networks for deriving LAI estimates from existing CYCLOPES and MODIS products. *Remote Sensing of Environment*, *112*, 2789–2803.

Verger, A., Baret, F., & Weiss, M. (2011). A multisensor fusion approach to improve LAI time series. *Remote Sensing of Environment*, *115*, 2423–2750.

Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sensing of Environment*, *16*, 125–141.

Weiss, M., Baret, F., Garrigues, S., & Lacaze, R. (2007). LAI and fPAR CYCLOPES global products derived from VEGETATION. Part 2: Validation and comparison with MODIS collection 4 products. *Remote Sensing of Environment*, *110*, 317–331.

Weiss, M., Baret, F., Smith, G. J., Jonckheere, I., & Coppin, P. (2004). Review of methods for in situ leaf area index (LAI) determination Part II: Estimation of LAI, errors and sampling. *Agricultural and Forest Meteorology*, *121*, 37–53.

Yang, W., Shabanov, N. V., Huang, D., Wang, W., Dickinson, R. E., Nemani, R. R., et al. (2006). Analysis of leaf area index products from combination of MODIS Terra and Aqua data. *Remote Sensing of Environment*, *104*, 297–312.

Yang, W., Tan, B., Huang, D., Rautiainen, M., Shabanov, N. V., Wang, Y., et al. (2006). MODIS leaf area index products: From validation to algorithm improvement. *IEEE Transactions on Geoscience and Remote Sensing*, *44*, 1885–1898.

WWW Sites

WWW1: Committee on Earth Observation Satellites (CEOS) Land Product Validation (LPV) Subgroup. http://lpvs.gsfc.nasa.gov/

WWW2: The MODIS Land Validation http://landval.gsfc.nasa.gov/

WWW3: Warehouse Inventory Search Tool (WIST). http://wist.echo.nasa.gov/

WWW4: PÔle d'Observation des Surfaces continentales par TELédétection. http://postel.mediasfrance.org/

WWW5: FLUXNET Integrating Worldwide CO2 Flux Measurements. http://www.fluxnet.ornl.gov/

WWW6: BigFoot Project. http://www.fsl.orst.edu/larse/bigfoot/

WWW7: Validation of Land European Remote sensing Instruments. http://w3.avignon.inra.fr/valeri/

WWW8: Global validation sites from major field campaigns and the literature. http://www.lreis.ac.cn/upload/dataset/Global_Field_LAI.pdf