International Journal of Remote Sensing
Vol. 30, Nos. 1–2, January 2009, 169–187

Taylor & Francis
Taylor & Francis Group

Assessment and extension of the MODIS F_{PAR} products in temperate forests of the eastern United States

D. C. STEINBERG† and S. GOETZ*‡
†Yale School of Forestry and Environmental Studies, New Haven, CT 06511, USA
‡The Woods Hole Research Center, Falmouth, MA 02540, USA

(*Received 1 December 2006; in final form 2 October 2007*)

Spatial and temporal variability in the quality of the collection 4 and 5 MODIS F_{PAR} products were examined over a 1.1 million km^2 region dominated by temperate forests. The MODIS F_{PAR} products were parsed into different quality levels based on the retrieval method of the F_{PAR} estimates, and the spatial coverage of the different quality MODIS subsets was examined through time and by land cover. The spatial extent of good quality F_{PAR} estimates, derived from the main radiative transfer algorithm without saturation, was found to be quite limited, particularly during the growing season. The majority of the MODIS C4 F_{PAR} retrievals were derived from the back-up, empirically based algorithm. The C5 products available to date showed greater data quality but still had limitations in forested areas. As an alternative to using the lower-quality MODIS F_{PAR} data, we explored the utility of estimating F_{PAR} from the more spatially extensive (and higher resolution) MODIS NDVI product using a simple, regionally based linear regression. A strong linear relationship between high quality MODIS NDVI and F_{PAR} products within our study site was found, indicating its utility for estimating F_{PAR} at regional scales where good quality retrievals from the MODIS algorithm are not available and where higher resolution F_{PAR} maps are desired. We discuss these results and their significance for down-stream MODIS users.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS), a sensor onboard NASA's Terra and Aqua satellites, is a passive remote sensing instrument designed for studying the Earth's atmospheric, marine, and terrestrial environments (Barnes *et al.* 1998). The MODIS land science team, responsible for processing and disseminating data collected by the MODIS Aqua and Terra instruments, has developed a comprehensive suite of land data products that characterize the Earth's land surface and vegetation (Justice *et al.* 2002). The suite of 16 MODIS land products have been used for a wide variety of applications including mapping global terrestrial productivity (Running *et al.* 2004), energy balance (Bisht *et al.* 2005) and vector borne disease epidemiology (Tatem *et al.* 2004), among others. The widespread use of the MODIS land products demonstrates the utility of globally extensive vegetation and land surface data with high temporal periodicity. The ultimate utility of the MODIS products depends, however, on the quality and accuracy of the data sets. Beginning with the initial release of the MODIS land products, there has been an ongoing effort

*Corresponding author. Email: daniel.steinberg@yale.edu

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160802244276

by both the MODIS land science team and the 'down-stream' MODIS users to evaluate and document the quality of the products (Morisette *et al.* 2002, 2006). Product validation and assessment is necessary to establish confidence in the data sets, and to provide a basis for improving the MODIS algorithms. The evaluations are, however, an ongoing process as regular improvements to the algorithms and input data continually influence the quality of the resulting products.

One of the most widely used products from the MODIS land suite is the leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (F_{PAR}) product (Myneni *et al.* 2002). LAI and F_{PAR} are key biophysical variables fundamental to a range of ecosystem processes such as primary productivity, evapotranspiration, and net energy exchange (Sellers *et al.*1997, Goetz *et al.* 1999, Running *et al.* 2004). It is useful to have global measurements of LAI and F_{PAR} with a high periodicity in order to support regional to global scale modelling and monitoring efforts (Nemani *et al.* 2003). The MODIS LAI/F_{PAR} products provide global 1-km resolution estimates at 8-day intervals.

There have been a number of efforts to assess the quality and accuracy of the MODIS LAI/F_{PAR} products as they have progressed through time (collections 3, 4, 5), with the majority focusing on the assessment of LAI (Privette *et al.* 2002, Tian *et al.* 2004, Cohen *et al.* 2003, 2006, Fensholt *et al.* 2004, Wang *et al.* 2004, Hill *et al.* 2006, Morisette *et al.* 2006, Yang *et al.* 2006b). Relatively fewer studies have assessed the MODIS F_{PAR} products (Fensholt *et al.* 2004, Huemmrich *et al.* 2005, Steinberg *et al.* 2006, Yang *et al.* 2006a) despite the simplicity of F_{PAR} measurements relative to LAI, which is derived from similar measurements (Hyer and Goetz 2004).

The MODIS land products are released as collections with each subsequent collection including algorithm and input data improvements to the previous collection. The collection 3 (C3) MODIS LAI/F_{PAR} product was the first significant public release of the dataset, and was therefore the first version available for both application and validation. The C3 product was found to significantly overestimate LAI and F_{PAR} values across several land cover classes, and the spatial extent of 'good' quality flagged LAI and F_{PAR} estimates was limited (Cohen *et. al,* 2003, Yang *et al.* 2006b). Collection 4 (C4) LAI/F_{PAR} products incorporated several improvements to the input data sets (reflectance products), the algorithms, the associated look-up tables (LUTs), and the temporal compositing scheme from which the 8-day products are calculated. Improvements to the atmospheric correction algorithm used in the derivation of the reflectance products increased the spatial extent of high quality data derivatives, which, in turn, resulted in increased extent and quality of the LAI/F_{PAR} products. In addition, the MODIS land cover map used in C4 processing (Friedl *et al.* 2002) improved upon the AVHRR land cover used for the C3 product.

Although the C4 products were shown to be improved over the C3 version, assessment and validation studies indicated that the algorithms continued to overestimate LAI and F_{PAR} in various cover types (Huemmrich *et al.* 2005, Shabanov *et al.* 2005, Yang *et al.* 2006a). Specifically, the algorithm failed more frequently in the broadleaf and needleleaf forest classes, which resulted in fewer high quality LAI and F_{PAR} estimates, as well as limited spatial coverage in regions dominated by these cover types (Fang and Liang 2005, Shabanov *et al.* 2003, 2005).

The MODIS C5 F_{PAR} product addresses some documented data quality issues in earlier products by implementing a stochastic radiative transfer model, as well as newly parameterized look-up tables, which parse forested areas into deciduous and needleleaf components. Initial assessment of the prototype C5 data demonstrated that algorithm refinements led to an overall increase in main algorithm retrievals, but resulted in an increase in the number of retrievals with saturation (QC2 cases) (Shabanov *et al.* 2005).

Our primary objective was to examine the quality and spatial extent of the MODIS F_{PAR} products over a 1.1 million km^2 study region dominated by forest land cover classes. We focused on this topic and geographic region for carbon management applications that could potentially benefit from MODIS products, including those that require higher resolution products than currently exist (for example 250–500m F_{PAR} products). We also assessed the quality of the F_{PAR} products through time, and derived simplified F_{PAR} estimates based on the MODIS NDVI and high quality F_{PAR} products.

2. Data sets

This study employed three of the MODIS Terra Land products: LAI/F_{PAR}, Normalized Difference Vegetation Index (NDVI), and Land Cover type classification. Each dataset provides global coverage and is projected onto the World Sinusoidal 10° grid, where the globe is divided into individual $1200\,km \times 1200\,km$ tiles for processing and distribution purposes (36 tiles along the east–west axis, and 18 tiles along the north–south). In addition to the data layers, each MODIS tile contains at least one quality assessment (QA) layer, which provides data quality information on a pixel-by-pixel basis. The quality layer is made up of a number of bit fields, which include values indicating general quality of the product, cloud contamination, algorithm use, aerosol density, snow cover, sensor issues, as well as other quality descriptors.

The MODIS LAI/F_{PAR} product (MOD15A2) is produced at 1-km spatial resolution and is composited over an eight-day period based on the maximum LAI/F_{PAR} value. The main LAI/F_{PAR} retrieval algorithm uses a look-up table (LUT) approach to calculate the most probable values of LAI and F_{PAR} for each pixel. The algorithm uses the MODIS Land Cover product, up to seven bi-directional Reflectance Distribution Function (BRDF) adjusted reflectances, and associated sun-view geometries as inputs. The approach compares observed MODIS reflectance product values (MOD09) with modelled reflectances based on a range of canopy and ground cover conditions typical of a given land cover type. For all cases where the uncertainty between observed and modelled reflectances is less than the uncertainty of the observed reflectances, canopy structural variables (i.e. LAI and F_{PAR}) used as inputs to the model are taken as possible solutions. The retrieved LAI/F_{PAR} values are calculated as the mean of all possible solutions. In cases where no solution is found (i.e. uncertainty between observed and modelled reflectances is greater than uncertainty in observed reflectances), a back-up algorithm is used to estimate F_{PAR}. Alternative solutions may be required due to saturation in the red or NIR bands, geometrical inaccuracies, or other sensor issues. The back-up algorithm is based on biome-specific, nonlinear relationships between NDVI and F_{PAR} values derived from MODIS data (Knyazikhin *et al.* 1999). The relationships are defined using highest quality main algorithm retrievals from the MODIS C3 F_{PAR} and NDVI products (R. Myneni, personal communication). When the main algorithm fails, NDVI is calculated from the reflectance data, and is subsequently transformed into F_{PAR} using biome specific relationships, selected using the land cover map.

Some collection 5 (C5) MODIS F_{PAR} products have recently been released and 'forward processing' of the data has been completed for the period beginning 1 January

2007. Back-processing of data from February 2002 and onward has been initiated but, as of this writing, processing has only been completed for the time period February 2000 to March 2002. Using this limited amount of data, we assess here the relative quality of the C5 products and observed differences with the C4 products.

The MODIS 1-km Vegetation Index (VI) products (MOD13) are produced at 250-m, 500-m, and 1-km spatial resolutions and are composited over a 16-day period based on the maximum VI value throughout the compositing period. The MODIS VI products contain values for both the NDVI and the Enhanced Vegetation Index (EVI), as well as a layer of quality information. The MODIS Land Cover product is produced at 0.05° and 1-km spatial resolutions.

The 8-day MOD15A2 F_{PAR}, the 16-day MOD13A2 Vegetation Index, and the MOD12Q1 Land Cover products were acquired for six tiles across our study area (figures 1(*a*), (*b*) and (*c*)) from the NASA Earth Observing System (EOS) Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). We conducted most of the analyses described in this paper using the 2004 C4 data product, and then supplemented that analysis when sufficient C5 F_{PAR} data became available for a full year of data (2001).

3. Methods

Using the quality assessment layers (tables 1(*a*) and (*b*)), both the F_{PAR} and NDVI products were screened on a per pixel basis using four different quality control schemes (referred to as QC1–QC4). F_{PAR} images were screened based on the retrieval method by which individual pixels were produced. F_{PAR} QC1 level images retained pixels produced using only the main retrieval algorithm without saturation (i.e. 'best quality' pixels). F_{PAR} QC2 images retained pixels produced using the main algorithm with saturation, and F_{PAR} QC3 images retained pixels produced using the back-up (empirical) algorithm irrespective of saturation. F_{PAR} QC4 images retained all pixels produced under cloud-free conditions regardless of their quality (figure 2). Pixels produced under cloudy conditions were omitted under every quality control scheme.

The MODIS NDVI product was screened using the 'Usefulness Index' found in the vegetation index product quality assessment layer (QA bits 2–5, table 1(*b*)). The four quality levels for the NDVI product corresponded to the 'good', 'acceptable', 'fair' and 'intermediate quality' designations in the VI usefulness index (table 1(*b*)), where NDVI QC1 images retained pixels with quality designation 'good,' NDVI QC2 images retained pixels with designation 'acceptable,' NDVI QC3 images retained pixels with designation 'fair,' and NDVI QC4 images retained pixels with designation 'intermediate.' As with the F_{PAR} product, any pixel contaminated with clouds was omitted regardless of the quality control level.

Following quality screening, individual MODIS tiles were mosaicked with coincident tiles, mapped into an Albers equal area projection, and subset to our study area in order to create a time series of maps of 8-day F_{PAR} (QC1-QC4) and 16-day NDVI (QC1-QC4) for the north-east and mid-Atlantic United States. 16-day F_{PAR} composites were subsequently calculated from the 8-day F_{PAR} images for each quality control level, resulting in a product that could be readily compared to the 16-day NDVI images. 16-day F_{PAR} composites were calculated by averaging the two corresponding 8-day images. If, for a single pixel in the composite image, there were values present from only one of the two 8-day images, then that single value was used for the composite image. If no values were present in either of the two images, then the composite pixel was coded as 'no data.'

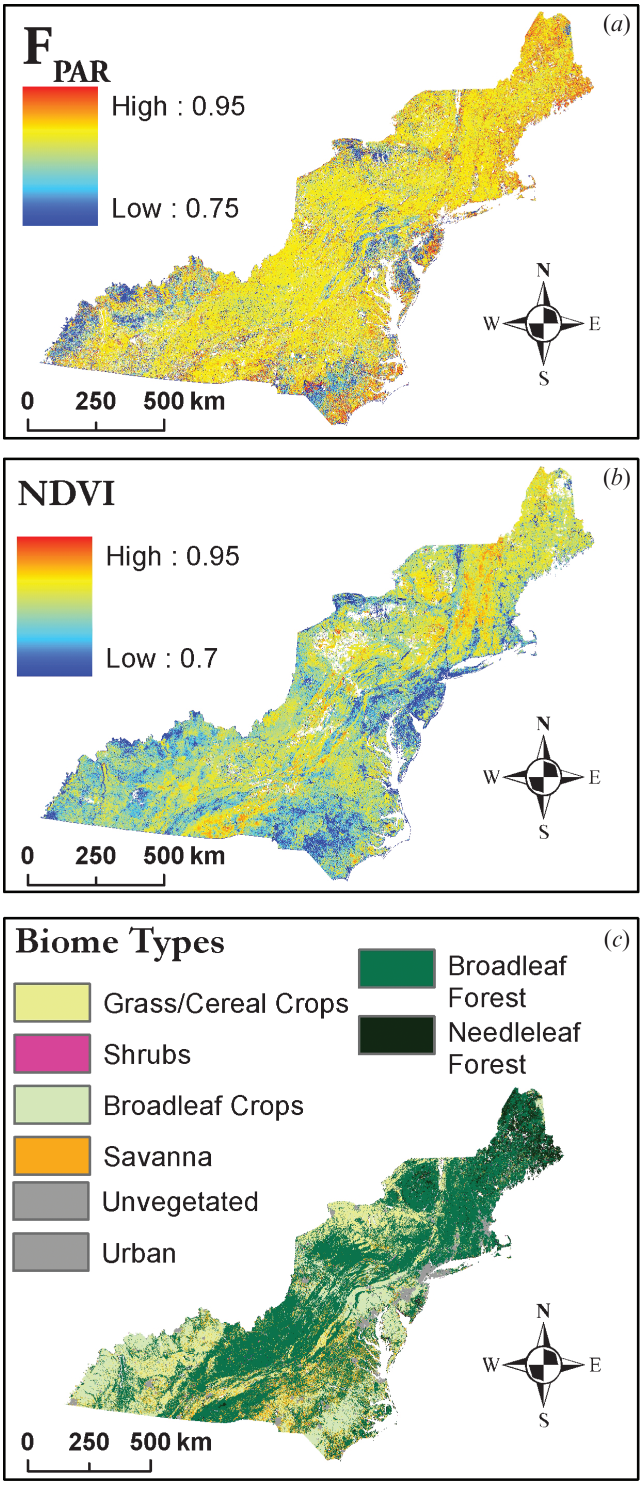


Figure 1. Examples of the MODIS data products utilized in this study. Each image depicts a mosaic of the six MODIS tiles encompassing our study area from (*a*) F_{PAR}, (*b*) NDVI, and (*c*) Land Cover products.

Table 1. MODIS quality assessment definitions: (*a*) F_{PAR}/LAI; (*b*) Vegetation Index (VI).

(*a*)

Bitfield	Description of Bitfield(s)
MODLAND Bits 0–1	00=Best possible 01=OK, but not the best 10=Not produced, due to cloud 11=Not produced, due to other reasons
DEAD-DETECTOR Bit 2	00=Detectors OK for up to 50% of channels 1,2 01=Dead detectors forced >50% adjacent retrievals
CLOUDSTATE Bits 3–4	00=Significant clouds NOT present 01=Significant clouds WERE present 10=Mixed cloud present on pixel 11=Cloud state not defined, assumed clear
SCF_QC Bits 5–7	000=Main (RT) method used with the best possible results 001=Main (RT) method used with saturation 010=Main (RT) method failed due to geometry problems, empirical method used 011=Main (RT) method failed due to problems other than geometry, empirical method used 100=Couldn't retrieve pixel

(*b*)

Bitfield	Description of Bitfield(s)
MODLAND Bits 0–1	00=VI produced with good quality 01=VI produced with unrealiable quality and thus examination of other QA bits recommended 10=VI produced, but contaminated with clouds 11=VI not produced due to bad quality
VI Usefulness Index Bits 2–5	0000=Perfect quality 0001=High quality 0010=Good quality 0011=Acceptable quality 0100=Fair quality 0101=Intermediate quality 0110=Below intermediate quality 0100=Average quality 1000=Below average quality 1001=Questionable quality 1010=Above marginal quality 1011=Marginal quality 1100=Low quality 1101=No atmospheric correction performed 1110=Quality too low to be useful 1111=Not useful for other reasons

3.1 *Temporal trends in quality*

In order to assess how the quality of the C4 and C5 F_{PAR} products varied through time, we created quality level maps for each 8-day F_{PAR} period, where the pixel value indicated the quality level of each individual pixel: 1–3 for QC1–QC3, and 4 for pixels produced under cloudy conditions or not produced due to heavy cloud cover or other problems. 16-day quality level composites were subsequently created by combining

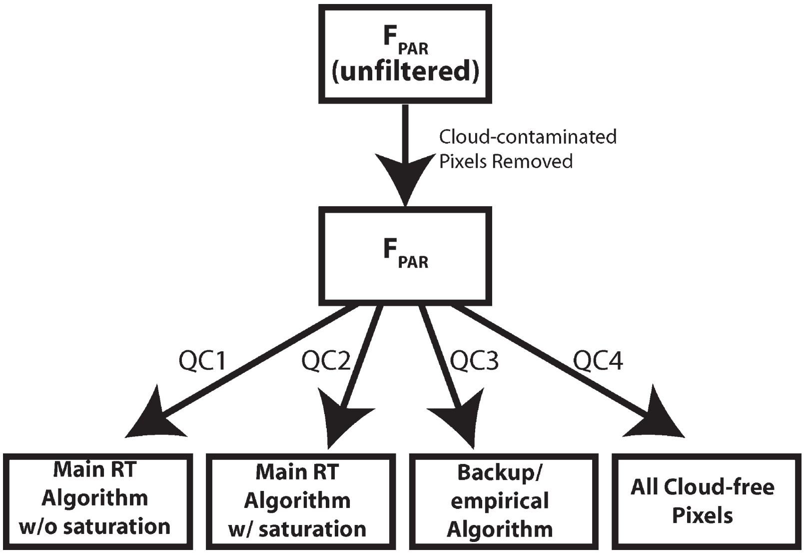


Figure 2. Flowchart depicting the steps of quality control processing of the MODIS F_{PAR} product.

two sequential 8-day quality level images. For each pixel in the 16-day composite, the minimum quality level (i.e. best quality designation) of the two corresponding pixels in the 8-day images was selected as the value for the composite image. The total number of pixels from each quality designation was calculated for each 8-day quality image and plotted through time to elucidate any temporal trends in F_{PAR} quality.

3.2 *Land cover influences on data quality*

The MODIS Land Cover product is used to parameterize the vegetation structural components of the MODIS LAI/F_{PAR} algorithm. As a result, biome misclassification in the land cover product can introduce error in the LAI/F_{PAR} product. We examined the F_{PAR} product in relation to MODIS land cover over our study area in order to assess how F_{PAR} retrievals vary by land cover type. The per cent coverage of each biome type over the study region was calculated from the MODIS Land Cover product. In addition we examined how quality of the F_{PAR} product varied through time when parsed by land cover type. The number of pixels from each quality level within each land cover type was calculated for every 8-day quality level composite and the results were plotted through time.

Temporal trends in quality of the C5 product were also examined in relation to land cover. C5 QC images were parsed by land cover type, and, as with the C4 products, the number of pixels from each quality level within each land cover type was calculated for every 8-day QC composite and the results plotted through time.

3.3 *Derivation of an NDVI-based F_{PAR} product*

Examination of MODIS F_{PAR} quality demonstrated that the spatial coverage of best quality data, i.e. main algorithm retrievals without saturation (QC1), was greatly limited throughout the year. Rather than rely on lower quality back-up algorithm retrievals, we examined the utility of a regionally based F_{PAR} product derived empirically from the best quality MODIS NDVI data. Linear relationships between NDVI and F_{PAR} were defined by comparing 16-day F_{PAR} composites to the 16-day MODIS NDVI products on a per pixel basis for three different time periods throughout 2004 (early season: days 129–144; mid-season: days 193–208; and late-season: days 257–272). For each time period, NDVI products of all quality levels (QC1–QC4) were related to F_{PAR} QC1 images and regressions were fit to the data. In addition, the data from all three time periods were combined and a simple linear regression was fit in order to examine the general relationship between NDVI and QC1 F_{PAR} irrespective of seasonality. Relationships between MODIS NDVI and QC1 F_{PAR} over individual land cover types were examined by comparing all values falling within each individual land cover class.

Using the regression results from the multi-period NDVI–F_{PAR} comparison, we transformed the 250 m and 1 km NDVI data to F_{PAR}, creating 16-day 250 m and 1 km F_{PAR} images. In order to test how our NDVI-derived F_{PAR} data compared to the MODIS back-up algorithm data, F_{PAR} values from each dataset were parsed by land cover and the mean F_{PAR} value for each biome type was calculated for the three time-periods described above. In addition, the difference between our F_{PAR} product and the MODIS F_{PAR} product was calculated for each time-period and the mean difference over individual land cover type was examined.

4. Results

4.1 *Seasonality and land cover influences on data quality*

Visual examination of the 8 and 16-day F_{PAR} quality level images (figure 3) clearly demonstrated a temporal trend in F_{PAR} quality, which tended to poorest in mid-growing season. QC3 solutions from the back-up algorithm dominate throughout the growing season (figure 4). QC1 pixels, produced under cloud-free conditions using the main RT algorithm without saturation, make up a significant portion of those produced only between days 89–121 and days 257–273. Throughout the entire study period, little more then half of the pixels within the study area contained F_{PAR} estimates of any quality level. The remaining values were either produced under significant cloud cover, and were therefore excluded from analysis, or were not produced at all due to other sensor or algorithm issues.

All eight classes of the MODIS land cover product were represented in the 1.1 million km^2 study area. The broadleaf forest class was the most common, comprising over 51% of the total area (table 2). Other large land cover classes included broadleaf crops, grasses/cereal crops, and savanna (17%, 13% and 9%, respectively). Temporal changes in quality of the C4 F_{PAR} product over individual land cover types showed similar patterns in quality among most land cover types (figure 5). QC3 level F_{PAR} retrievals were common over all land cover types throughout most of the growing season. With exception to the needleleaf forest class, QC1 retrievals peaked during the winter months and were consistently sparse during the growing season. In contrast, the needleleaf forest class exhibited a bimodal pattern in quality where QC1 level retrievals peaked in both the winter and late spring/summer months and reached local minima in the mid summer and late winter months.

The C5 F_{PAR} data displayed a larger percentage of primary algorithm retrievals than the C4 product (figures 5(*a*) and (*b*)), and QC1 and QC2 solutions covered a larger proportion of the study area, indicating the C5 products are improved over C4. As with the C4 product, fewer QC1 solutions occurred during the growing season, but unlike the C4 product the majority of the solutions were acquired with the main

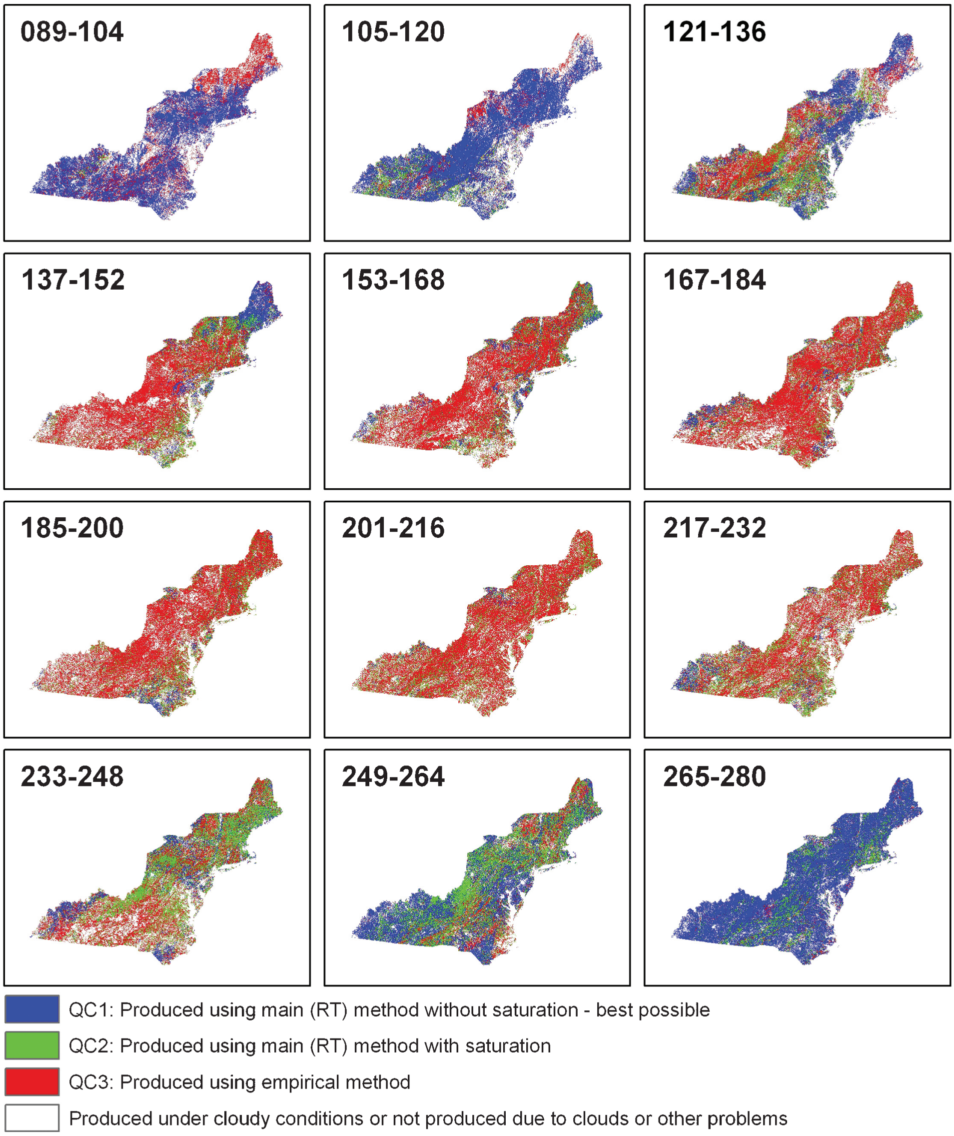


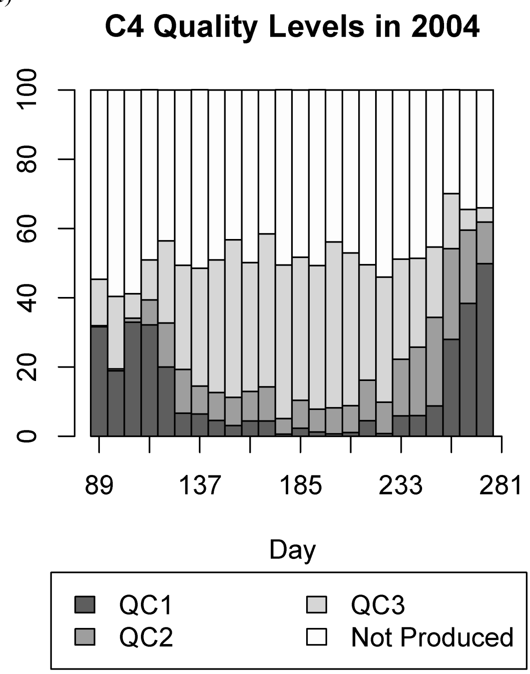
Figure 3. Images of the quality control (QC) level of MODIS collection 4 F_{PAR} data throughout the extended growing season of 2004. Images shown are 16-day composites derived from the 8-day QC images. The composite period (given in day numbers) is indicated in the upper left-hand corner of the image.

algorithm—either with or without saturation. The C5 product had higher data quality across all land cover types, although the broadleaf and needleleaf forest cover types still showed much reduced high quality data in the growing season (figure 5).

4.2 *F_{PAR} products derived from higher quality and resolution NDVI*

Comparisons between F_{PAR} and NDVI demonstrated that relationships between the two MODIS products were relatively consistent throughout the year, but differed based on the quality level of the data considered (figure 6.). Relationships between

(*a*)



(*b*)

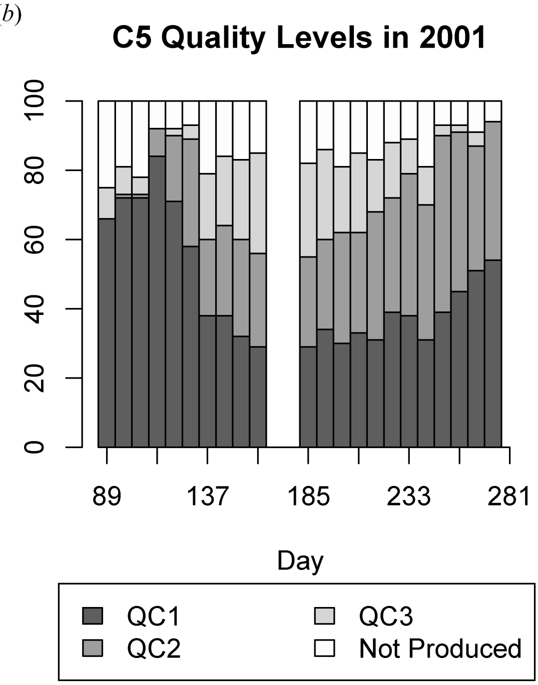


Figure 4. F_{PAR} quality levels through time, with % coverage of the study area by pixels from each quality designation (QC1–QC3) throughout the extended growing season. (*a*) Collection 4, (*b*) Collection 5.

Table 2. Per cent coverage of each biome type over the study area in eastern USA.

Land cover type	Pixels	Per cent of total area
Broadleaf forest	578706	51.3
Broadleaf crops	189491	16.8
Grasses/cereal crops	149166	13.2
Savanna	104542	9.3
Needleleaf forest	61541	5.5
Urban	38858	3.4
Shrubs	4676	0.4
Unvegetated	1270	0.1

F_{PAR} QC1 data and NDVI QC1-4 data were linear ($0.69<R<0.91$), and followed a nearly one-to-one relationship (slopes ranged from 0.86 to 1.14). There was little temporal variation in the regressions throughout the study periods. For example, the slopes of the QC1 F_{PAR}–QC1 NDVI regressions from the three different time periods differed by less than 0.05, and the intercepts by less then 0.04 (figure 6). The relationships between lower quality F_{PAR} (QC2 and QC3) and NDVI were not well defined. We found no relationship between F_{PAR} QC2 data and NDVI ($R^2=0.0$), and variable relationships between F_{PAR} QC3 and NDVI (R^2 values ranging from 0.15 to 0.64).

The regression comparing all F_{PAR} QC1 data from every sampling period to NDVI QC1-4 for each land cover class is shown in figure 7. Variability was observed in the F_{PAR}/NDVI relationship by class. For reference the regression fit derived from the entire dataset (slope=0.86, intercept=0.2, $R^2=0.52$) is included in each plot. Although the overall trends between land cover types were similar, we found greater variability in the NDVI/F_{PAR} data over the broadleaf and needleleaf forest classes.

An example of our 250-m NDVI-derived F_{PAR} results is shown in figure 8. Spatial coverage of the product was found to be greater than that of the high quality MODIS F_{PAR} QC1 product and similar to that of the MODIS F_{PAR} product when all quality levels were considered (QC1–QC3) (figure 9). Comparisons between the MODIS back-up retrievals and the NDVI-derived estimates demonstrated that our F_{PAR} estimates were systematically higher than the MODIS back-up algorithm estimates, but by only 1–5%. Differences were most apparent over the broadleaf forest land cover class (table 3). Although the differences were highly statistically significant ($p<0.0001$), due to the large sample size, they are relatively small in magnitude and this should be considered in the context of uncertainties in the F_{PAR} estimates.

5. Discussion

Our analysis of temporal trends in quality of the MODIS C4 F_{PAR} product revealed that the majority of the F_{PAR} retrievals within the study region were derived from the back-up, empirical algorithm (QC3) (figure 3(*a*)). Only a small percentage of pixels were produced using the main algorithm without saturation (i.e. best quality). The percentage of retrievals derived using the main algorithm without saturation decreased in the growing season months, reaching a minimum in mid-summer near the peak of the growing season. Our assessment of the C5 F_{PAR} data demonstrated that the C5 product provides greater spatial coverage of high quality (QC1) data when compared to C4 data, although the broadleaf and needleleaf forest classes, which comprise the majority of our study region, were dominated by lower quality

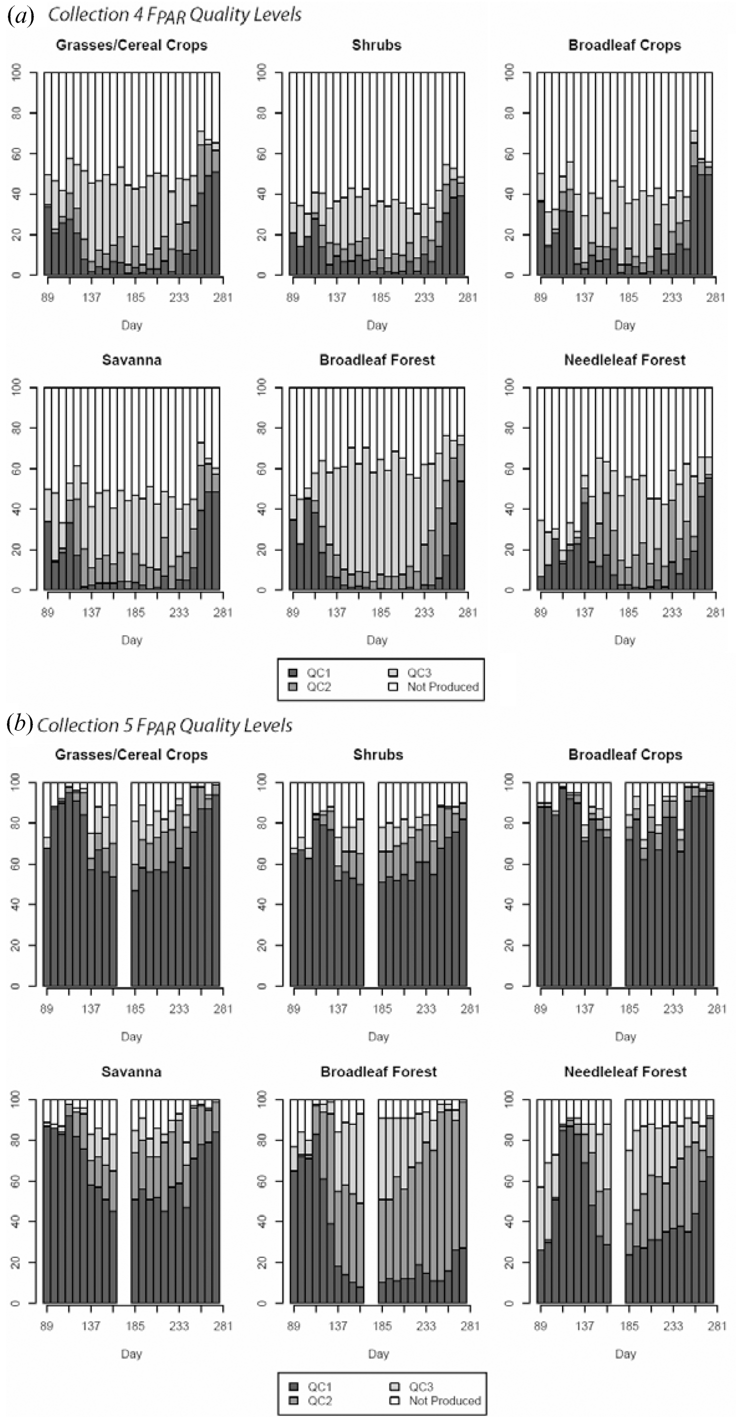


Figure 5. F_{PAR} quality levels through time by land cover class, with % coverage of each land cover type by pixels from each quality designation throughout the year. (*a*) Collection 4, (*b*) Collection 5.

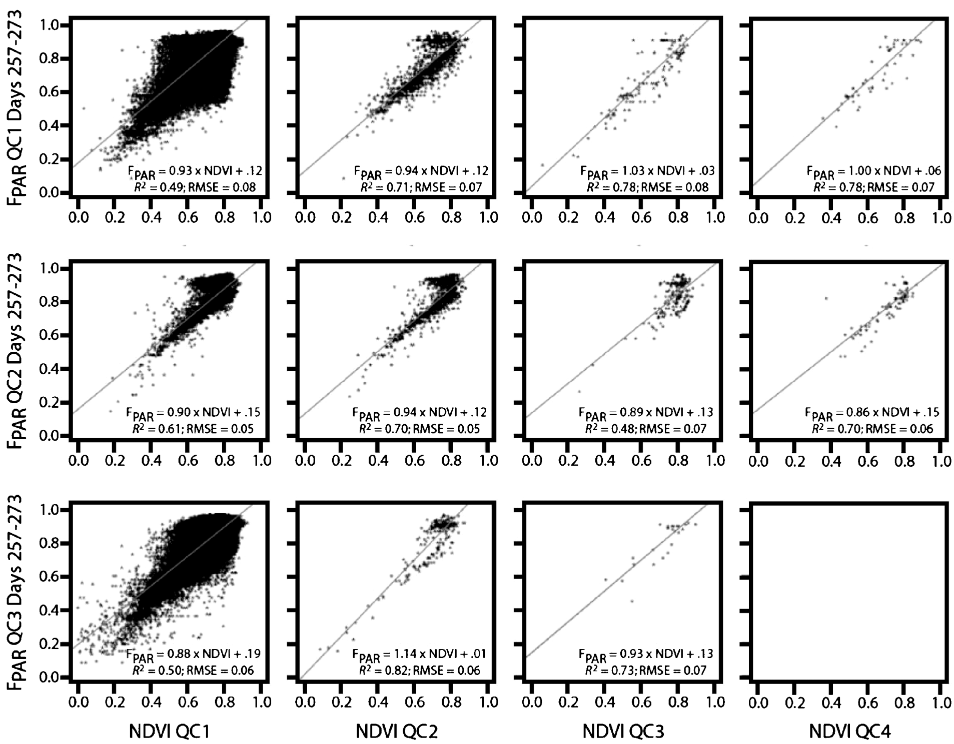


Figure 6. A scatterplot matrix depicting relationships between MODIS F_{PAR} and MODIS NDVI at all quality levels. Regression statistics and rms errors (RMSE) are indicated within each plot.

F_{PAR} data (QC2 and QC3), particularly during the growing season. While the percentage of QC1 retrievals remained low, there was a clear increase in the number of QC2 retrievals and an associated decrease in the number of QC3 retrievals. This translated to a significantly greater number of main algorithm retrievals with saturation and a diminished reliance on the back-up algorithm. These results are consistent with an initial assessment of prototype C5 data (Shabanbov *et al.* 2005).

Low quality data during the growing season in forested areas presents a problem for users of the MODIS F_{PAR} products in this region, as the spatial extent of good quality data is limited, and the estimates are the poorest during the time of greatest photosynthetic rates, when F_{PAR} estimates are most essential. It has been previously shown that the MODIS LAI/F_{PAR} algorithm does not perform well over this land cover class, mainly due to saturation in the surface reflectance with respect to LAI and F_{PAR} values (Shabanov *et al.* 2005, Yang *et al.* 2006a). We note that examination of quality of C4 data over other land cover types yielded similar results in this region, i.e. high quality F_{PAR} retrievals were more limited during the growing season (figure 3(*b*)).

As an augmentation to the MODIS F_{PAR} products in areas with lower data quality, or in cases where use of higher resolution F_{PAR} data are desirable, we examined an approach for estimating F_{PAR} that relied solely on the high quality NDVI products, which have much greater spatial coverage than the high quality F_{PAR} products. In addition, the MODIS NDVI product is available at much higher spatial resolution (250 m) than the F_{PAR} product, allowing for the derivation of F_{PAR} at 16 times higher spatial resolution than the current (globally produced) 1-km

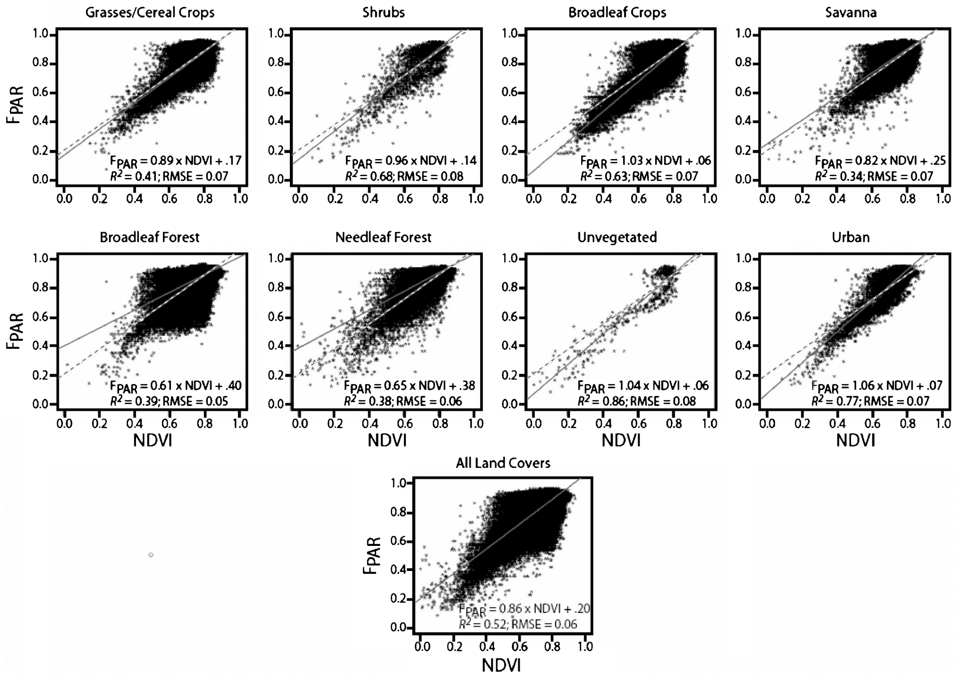


Figure 7. Relationships between best quality F_{PAR} (QC1) and best quality NDVI (QC1) over each land cover type, and over all biomes (bottom).

F_{PAR} products. This method of transforming NDVI to F_{PAR} is similar to that implemented in the MODIS back-up algorithm, however the relationship is derived for a specific region (in our case, eastern temperate forest), irrespective of biome type. In contrast, the MODIS back-up algorithm is based on globally derived biome specific relationships between NDVI and F_{PAR}. The MODIS LAI/F_{PAR} science team is limited in their approach to estimating LAI and F_{PAR} from NDVI, as they are required to produce results globally at high temporal scales. The best method, therefore, is to derive biome specific global relationships between F_{PAR} and NDVI and apply these relationships to reflectance data when the primary algorithm fails. Methods of transforming NDVI to F_{PAR} based on linear relationships have been used for many years (Sellers *et al.* 1985), however, they are best utilized at local to regional scales at high resolution, where relationships between NDVI and F_{PAR} are likely to remain relatively less variable over the spatial extent of the study area. Over larger areas, spanning a greater distribution of land cover and plant functional types, the NDVI/ F_{PAR} relationship is likely to be less generalized (Baret and Guyot 1991).

Our regional scale analysis indicates that much of the variation in F_{PAR} was captured at a resolution of 1 km^2, and that this simple approach has utility when adequate MODIS F_{PAR} product results are lacking. Comparisons between best quality F_{PAR} and NDVI demonstrated a moderately strong (R=0.72) linear relationship (slope=0.86) between the two 1 km^2 products, and the relationship was reasonably consistent across differing land cover types (figure 7). The relationships between lower quality F_{PAR} and NDVI QC1-4 were much less well defined. Based on the assumption that the 'best quality' F_{PAR} retrievals are indeed the closest to reality, specification of the transformation of NDVI to F_{PAR} was limited to these best-case retrievals (i.e. the weak relationships between lower quality F_{PAR} (QC2

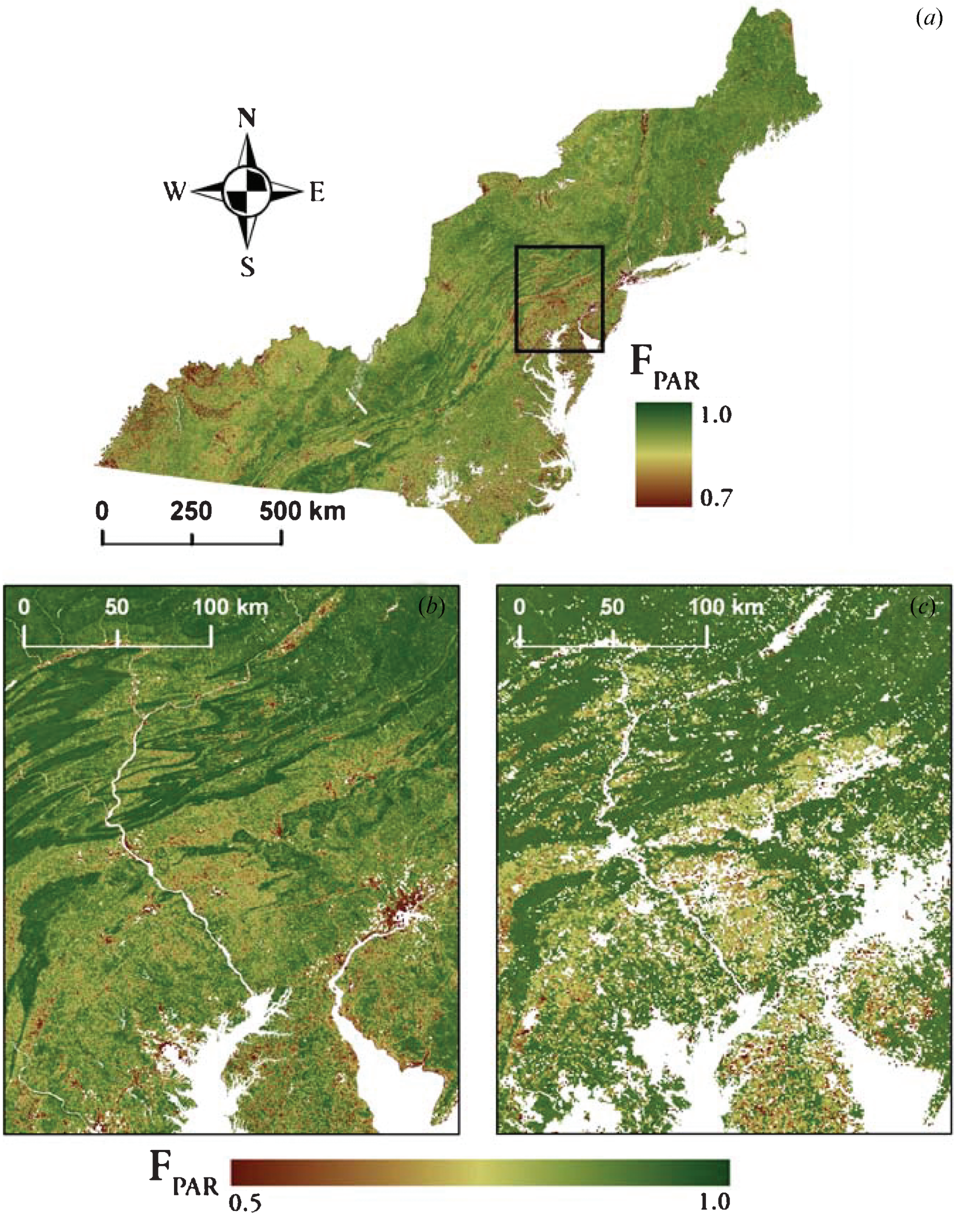


Figure 8. Maps showing the spatial coverage of the 250-m NDVI-derived Fpar product (*a* and *b*) and the 1-km MODIS F_{PAR} combined QC1-QC3 product (*c*) for the period covering days 257–273 (14–30 September).

and QC3) and NDVI were not considered in the calculation of the general transformation). Thus, rather than using the MODIS back-up algorithm solutions, which are based on collection 3 data and globally defined nonlinear relationships between NDVI and F_{PAR}, we used a regionally defined, linear NDVI transform based on the existing best-quality (QC1) F_{PAR} solutions.

The resulting NDVI-derived F_{PAR} maps had better spatial coverage with fewer gaps relative to the high quality MODIS F_{PAR} product (figure 9). In addition, we

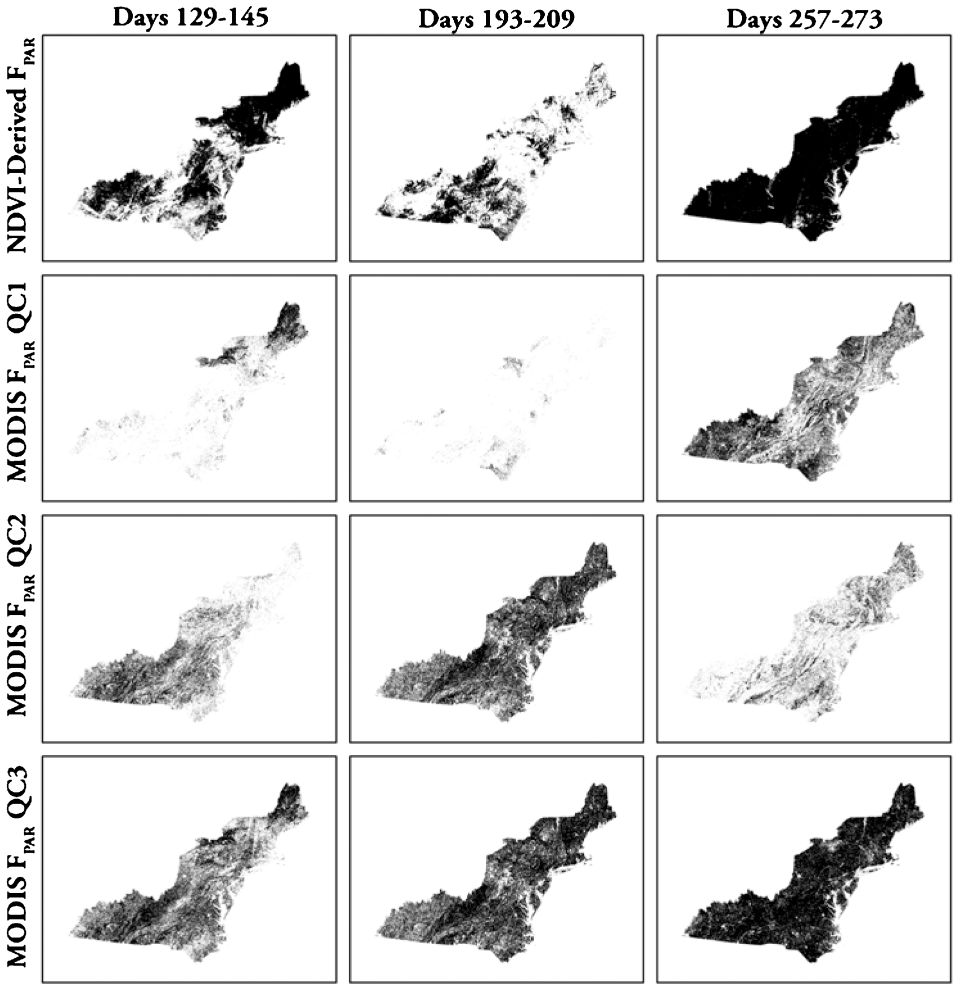


Figure 9. Maps depicting the total spatial coverage of the NDVI-derived F_{PAR} (top), the MODIS F_{PAR} QC1 (2nd row), the MODIS F_{PAR} QC3 (3rd row), and the MODIS F_{PAR} combined QC1-QC3 (bottom) products for the composite periods of days 129–145, 193–209, and 257–273 (across). Areas covered are shown in black, and data gaps are shown in white.

were able to produce F_{PAR} maps at 250-m resolution, which allowed for finer scale applications of the dataset (figure 8). This transformation is specific to this study region, but similar methods could be replicated in other regions and for other time periods where needed. Additional validation of this approach, and the C5 F_{PAR} products as they become available, would be useful, particularly at sites where field measurements exist and can be spatially scaled (e.g. Huemmrich *et al.* 2005, Steinberg *et al.* 2006).

6. Conclusion

MODIS collection 4 F_{PAR} products derived from the MODIS LAI/F_{PAR} algorithm were found to be of limited utility for the study area considered, primarily due to little spatial coverage of good quality data during the growing season. The majority of the MODIS F_{PAR} product estimates were derived from the back-up algorithm,

Table 3. Comparison of F_{PAR} values derived from the MODIS backup algorithm and the NDVI-derived estimates over the four dominant biome types. The first two columns report the mean F_{PAR} value over each biome type. The third column displays the average of all differences (MODIS F_{PAR} QC3 – NDVI Derived F_{PAR}) over each biome type. All differences reported are highly significant ($p<0.0001$).

	Land cover type	MODIS back-up	NDVI-derived	Mean difference
Day 129	Broadleaf forest	0.87	0.87	−0.043
	Broadleaf crop	0.82	0.77	−0.005
	Grasses/cereal crops	0.85	0.84	−0.013
	Needleleaf forest	0.78	0.79	−0.043
Day 193	Broadleaf forest	0.88	0.92	−0.043
	Broadleaf crop	0.85	0.87	−0.016
	Grasses/cereal crops	0.86	0.88	−0.023
	Needleleaf forest	0.89	0.89	−0.027
Day 257	Broadleaf forest	0.88	0.92	−0.050
	Broadleaf crop	0.83	0.84	−0.029
	Grasses/cereal crops	0.86	0.87	−0.027
	Needleleaf forest	0.89	0.87	−0.025

and only a small portion were calculated using the main radiative transfer based algorithm without saturation. Assessment of the currently available C5 F_{PAR} data demonstrated greater spatial coverage of high quality retrievals than that of C4 product, but broadleaf and needleleaf forest classes remained dominated by lower quality retrievals, particularly during the growing season. This lack of widespread coverage of quality F_{PAR} data presents a difficulty for down-stream uses of the F_{PAR} products. Rather than use lower quality results, where and when high quality data were not available (as gauged by the MODIS data quality flags), and in order to take advantage of the higher resolution NDVI data, we explored the utility of estimating F_{PAR} directly from the MODIS NDVI products.

Good quality NDVI data exhibited much greater spatial coverage than comparable quality F_{PAR} data, allowing for increased spatial coverage in an NDVI-derived F_{PAR} product. A robust linear relationship was found between the two products across land cover types, indicating its utility for estimating F_{PAR} throughout the growing season at regional scales and thereby extending the utility of MODIS observations for mapping and monitoring applications. We suggest that an NDVI-based linear approach to modelling F_{PAR}, similar to that outlined above, will remain useful with the next generation MODIS F_{PAR} products, particularly in areas dominated by broadleaf and needleleaf forests. Additional studies exploring the utility of the approach are encouraged, particularly in forested areas where a wide range of research applications would benefit from finer resolution and more complete F_{PAR} coverage.

References

Baret, F. and Guyot, G., 1991, Potential and limitations of vegetation indices for LAI and APAR assessment. *Remote Sensing of Environment*, **35**, pp. 161–173.

Barnes, W.L., Pagano, T.S. and Salomonson, V.V., 1998, Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1. *IEEE Transactions on Geoscience and Remote Sensing*, **36**, pp. 1088–1100.

Bisht, G., Venturini, V., Islam, S. and Jiang, L., 2005, Estimation of the net radiation using MODIS (Moderate Resolution Imaging Spectroradiometer) data for clear sky days. *Remote Sensing of Environment*, **97**, pp. 52–67.

Cohen, W.B., Maiersperger, T.K., Yang, Z., Gower, S.T., Turner, D.P., Ritts, W.D., Berterretche, M. and Running, S.W., 2003, Comparisons of land cover and LAI estimates derived from ETM+ and MODIS for four sites in North America: a quality assessment of 2000/2001 provisional MODIS products. *Remote Sensing of Environment*, **88**, pp. 233–255.

Cohen, W.B., Maiersperger, T.K., Turner, D.P., Ritts, W.D., Pflugmacher, D., Kennedy, R.E., Kirschbaum, A., Running, S.W., Costa, M. and Gower, S.T., 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**, pp. 1843–1857.

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

Fensholt, R., Sandholt, I. and Rasmussen, M.S., 2004, Evaluation of MODIS LAI, fAPAR and the relation between fAPAR and NDVI in a semi-arid environment using in situ measurements. *Remote Sensing of Environment*, **91**, pp. 490–507.

Friedl, M.A., McIver, D.K., Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schneider, A., Cooper, A., Baccini, A., Gao, F. and Schaaf, C., 2002, Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, **83**, pp. 287–302.

Goetz, S.J., Prince, S.D., Thawley, M.M., Small, J. and Johnston, A., 1999, Mapping net primary production and related biophysical variables with remote sensing: application to the BOREAS region. *Journal of Geophysical Research*, **104**, pp. 27719–27733.

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

Huemmrich, K.F., Privette, J.L., Mukelabai, M., Myneni, R.B. and Knyazikhin, Y., 2005, Time-series validation of MODIS land biophysical products in a Kalahari woodland, Africa. *International Journal of Remote Sensing*, **26**, pp. 4381–4398.

Hyer, E. and Goetz, S.J., 2004, Comparison and sensitivity analysis of instruments and radiometric methods for LAI estimation: assessments from a boreal forest site. *Agricultural and Forest Meteorology*, **122**, pp. 157–174.

Justice, C.O., Townshend, J.R.G., Vermote, E.F., Masuoka, E., Wolfe, R.E., Saleous, N., Roy, D.P. and Morisette, J.T., 2002, An overview of MODIS land data processing and product status. *Remote Sensing of Environment*, **83**, pp. 3–15.

Knyazikhin, Y., Glassy, J., Privette, J.L., Tian, Y., Lotsch, A., Zhang, Y., Wang, Y., Morisette, J.T., Votava, P., Myneni, R.B., Nemani, R.R. and Running, S.W., 1999, MODIS Leaf Area Index (LAI) and fraction of photosynthetically active radiation absorbed by vegetation (FPAR) product (MOD15) algorithm theoretical basis document. Available online at: http://eospso.gsfc.nasa.gov/atbd/modistables.html (accessed March 2007).

Morisette, J.T., Privette, J.L. and Justice, C.O., 2002, A framework for the validation of MODIS Land products. *Remote Sensing of Environment*, **83**, pp. 77–96.

Morisette, J.T., Baret, F. and Liang, S.L., 2006, Special issue on global land product validation. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 1695–1697.

Myneni, R.B., Hoffman, S., Knyazikhin, Y., Privette, J.L., Glassy, J., Tian, Y., Wang, Y., Song, X., Zhang, Y. and Smith, G.R., 2002, Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment*, **83**, pp. 214–231.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B. and Running, S.W., 2003, Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, **5625**, pp. 1560–1562.

PRIVETTE, J.L., MYNENI, R.B., KNYAZIKHIN, Y., MUKELABAI, M., ROBERTS, G., TIAN, Y., WANG, Y. and LEBLANC, S.G., 2002, Early spatial and temporal validation of MODIS LAI product in the Southern Africa Kalahari. *Remote Sensing of Environment*, **83**, pp. 232–243.

RUNNING, S.W., NEMANI, R.R., HEINSCH, F.A., ZHAO, M., REEVES, M. and HASHIMOTO, H., 2004, A continuous satellite-derived measure of global terrestrial primary production. *BioScience*, **54**, pp. 547–560.

SELLERS, P.J., 1985, Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing*, **6**, pp. 1335–1372.

SELLERS, P.J., DICKINSON, R.E., RANDALL, D.A., BETTS, A.K., HALL, F.G., BERRY, J.A., COLLATZ, G.J., DENNING, A.S., MOONEY, H.A., NOBRE, C.A., SATO, N., FIELD, C.B. and HENDERSON, A., 1997, Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. *Science*, **275**, pp. 502–509.

SHABANOV, N.V., WANG, Y., BUERMANN, W., DONG, J., HOFFMAN, S., SMITH, G.R., TIAN, Y., KNYAZIKHIN, Y. and MYNENI, R.B., 2003, Effect of foliage spatial heterogeneity in the MODIS LAI and FPAR algorithm over broadleaf forests. *Remote Sensing of Environment*, **85**, pp. 410–423.

SHABANOV, N.V., HUANG, D., YANG, W.Z., TAN, B., KNYAZIKHIN, Y., MYNENI, R.B., AHL, D.E., GOWER, S.T., HUETE, A.R., ARAGAO, L. and SHIMABUKURO, Y.E., 2005, Analysis and optimization of the MODIS leaf area index algorithm retrievals over broadleaf forests. *IEEE Transactions on Geoscience and Remote Sensing*, **43**, pp. 1855–1865.

STEINBERG, D.C., GOETZ, S.J. and HYER, E., 2006, Validation of MODIS F_{PAR} products in boreal forests of Alaska. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 1818–1828.

TATEM, A.J., GOETZ, S.J. and HAY, S.I., 2004, TERRA and AQUA: new data for epidemiology and public health. *International Journal of Applied Earth Observation and Geoinformation*, **6**, pp. 33–46.

TIAN, Y., DICKINSON, R.E., ZHOU, L., ZENG, X., DAI, Y., MYNENI, R.B., KNYAZIKHIN, Y., ZHANG, X., FRIEDL, M., YU, H., WU, W. and SHAIKH, M., 2004, Comparison of seasonal and spatial variations of leaf area index and fraction of absorbed photosynthetically active radiation from Moderate Resolution Imaging Spectroradiometer (MODIS) and Common Land Model. *Journal of Geophysical Research-Atmospheres*, **109**(D1).

WANG, Y.J., WOODCOCK, C.E., BUERMANN, W., STENBERG, P., VOIPIO, P., SMOLANDER, H., HAME, T., TIAN, Y.H., HU, J.N., KNYAZIKHIN, Y. and MYNENI, R.B., 2004, Evaluation of the MODIS LAI algorithm at a coniferous forest site in Finland. *Remote Sensing of Environment*, **91**, pp. 114–127.

YANG, W.Z., HUANG, D., TAN, B., STROEVE, J.C., SHABANOV, N.V., KNYAZIKHIN, Y., NEMANI, R.R. and MYNENI, R.B., 2006a, Analysis of leaf area index and fraction of PAR absorbed by vegetation products from the terra MODIS sensor: 2000–2005. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 1829–1842.

YANG, W.Z., TAN, B., HUANG, D., RAUTIAINEN, M., SHABANOV, N.V., WANG, Y., PRIVETTE, J.L., HUEMMRICH, K.F., FENSHOLT, R., SANDHOLT, I., WEISS, M., AHL, D.E., GOWER, S.T., NEMANI, R.R., KNYAZIKHIN, Y. and MYNENI, R.B., 2006b, MODIS leaf area index products: From validation to algorithm improvement. *IEEE Transactions on Geoscience and Remote Sensing*, **44**, pp. 1885–1898.