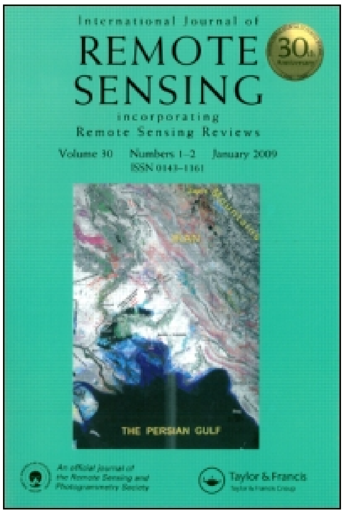

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Letter

Temporally smoothed and gap-filled MODIS land products for carbon modelling: application of the *f*PAR product

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TIMESAT software is used to produce a temporally and spatially Gap-Filled and Smoothed (GFS) version of the MODIS (Moderate Resolution Imaging Spectroradiometer) fPAR (fraction of absorbed photosynthetically active radiation) product (MOD15). We apply this new *f*PAR product within two commonly used carbon and vegetation productivity models, CASA (Carnegie-Ames-Stanford Approach) and the MODIS GPP (Gross Primary Production) algorithm (MOD17). The GFS product removes noise present within the original MOD15 fPAR dataset, yet is comparable to the linearly interpolated UMT (University of Montana) fPAR used in the MOD17 algorithm. However, the GSF data provides a realistic fPAR time-series in relation to magnitude and seasonality associated with radiation in regions where persistent cloud cover is an issue. It is available for North America and the northern part of South America covering the Amazon basin for the MODIS acquisition period (2000–2005).

1. Introduction

Remotely sensed datasets are frequently used to derive biophysical parameters to calibrate and drive ecological models. The MODIS (MODerate Imaging Spectroradiometer) sensor provides an extensive archive (2000 to present) of land products that can be applied to global environmental and carbon modelling issues. Cloud contamination and moderate to high atmospheric aerosol levels can reduce data retrieval quality and result in periods of missing data. Of particular importance for ecosystem/carbon models are the LAI (leaf area index) and *f*PAR (fraction of absorbed photosynthetically active radiation) products. These biophysical parameters describe canopy structure and are related to functional process rates of energy and mass exchange. The MODIS LAI and *f*PAR product algorithms (MOD15) will produce results even under sub-optimal atmospheric conditions and these values are flagged as low quality (figure 1).

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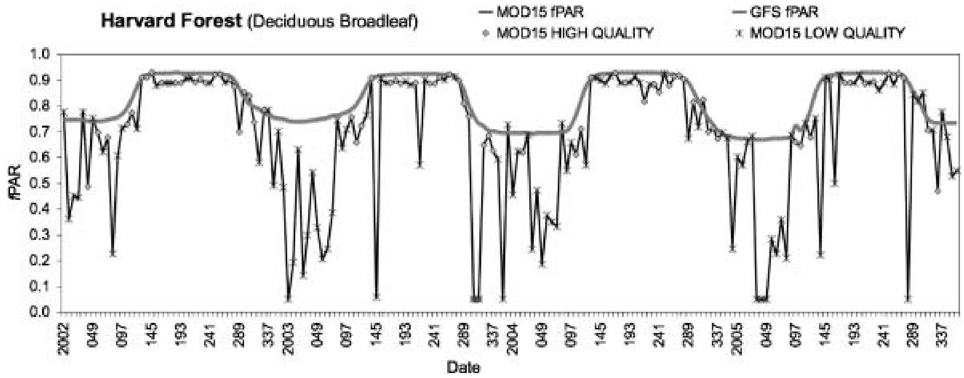

Figure 1. MOD15 *f*PAR (showing data quality flags) and the GFS *f*PAR time-series, for the Harvard Forest site.

Ecosystem models require high quality, temporally and spatially continuous measurements. All MODIS products have quality assessment layers, which if used require the user to pre-process the data. However, quality assessment information is often ignored, and the time series data used as is. The TIMESAT program (Jonsson and Eklundh 2006) was applied to temporally smooth and spatially gap-fill MODIS collection 4 land products including the LAI, *f*PAR as well as the EVI and NDVI (enhanced and normalized difference vegetation index). Details of this procedure can be found in Gao *et al.* (2008). TIMESAT GFS (gap-filled and smoothed) datasets can be retrieved through the MODIS-for-NACP website at http://www.accweb.nascom.nasa.gov/. This system facilitates: (1) data reprojection; (2) mosaicking; (3) image subsetting; (4) data aggregation; (5) resampling; and (6) format conversion.

In this letter we evaluate the use of the TIMESAT GFS *f*PAR product in two carbon models that estimate terrestrial GPP, including CASA (Carnegie-Ames-Stanford Approach) and the MOD17 GPP (Gross Primary Production) algorithm, to determine the sensitivity and suitability for widespread usage of this model parameter.

2. Application of TIMESAT *f*PAR product

Gross primary production (GPP) is an important variable in the global carbon cycle and the accuracy of model-derived estimates is dependent on the quality of input datasets used. We applied both the CASA and MOD17 GPP algorithm, using both the original MODIS and GFS *f*PAR while holding all other model inputs constant. Model sensitivity to *f*PAR was assessed by comparing GPP estimates at 30 sites across North and South America, selected to capture different vegetation types and climate regimes (figure 2). We hypothesize that removing the low quality *f*PAR values in the time-series should improve the model derived estimates of GPP when compared to flux tower productivity estimates as demonstrated by Heinsch *et al.* (2006).

CASA (Potter *et al.* 1993) and the MOD17 algorithm (Running *et al.* 2004) are both radiation-use efficiency (RUE) based models that operate at monthly and 8-day temporal resolutions, respectively. Satellite-derived estimates of *f*PAR and independent estimates of PAR are related by a RUE term, which is scaled by

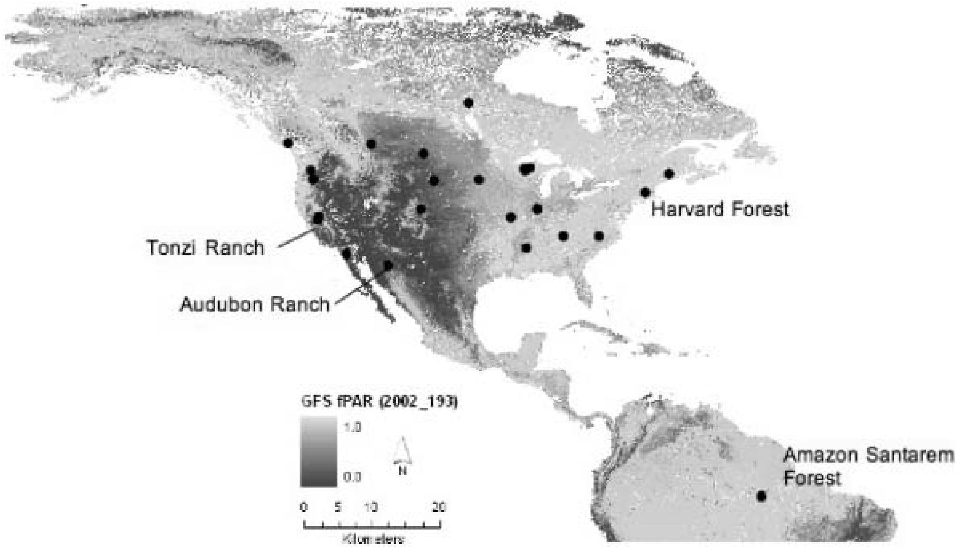

Figure 2. Spatial availability of TIMESAT GFS land products. Field sites used for dataset comparison are shown over the GFS *f*PAR for day 193 (12 July), 2002.

temperature and moisture stresses. Cloud contaminated and missing data within the MOD15 *f*PAR product were found to reduce the quality of the MOD17 product, therefore the standard MOD17 product uses linear interpolation to gap-fill and remove low quality retrievals (Zhao *et al.* 2005) and will be referred to as UMT (University of Montana) *f*PAR throughout. We compare estimates of GPP for four years (2002–2005) from: the MOD17 GPP dataset to MOD17 run with GFS *f*PAR; and GPP derived from net primary production modelled using CASA run with both the original MOD15 and GFS *f*PAR data. Results are presented for four representative sites across North and South America (figure 2).

3. Results and Discussion

3.1 *MOD17 algorithm*

There are relatively minor differences between the UMT and GFS *f*PAR datasets (figure 3). Variation of up to 0.3 *f*PAR units corresponds to negligible differences in GPP ($\pm 5\,gC\,m^{-2}$/8-day). The UMT *f*PAR dataset tracks high quality MOD15 values more closely than the TIMESAT method. The upper envelope fitting used by TIMESAT (Gao *et al.* 2008), smoothes some of the valid *f*PAR variation resulting in higher GPP values. This effect is prominent at the Audubon Ranch (AR) site during spring and early summer (figure 3(*a*)), but does not translate into great differences in modelled GPP. At both the AR and Tonzi Ranch (TR) sites, higher GFS *f*PAR values, in combination with greater precipitation experienced in this region during July, correspond to increases in GPP of up to $12.5\,gC\,m^{-2}$/8-day (figure 3).

At Harvard Forest (HF), considerable differences in *f*PAR ~0.25 units (and up to 0.8 units where the UMT data provides values of 0, not shown in the time series to reduce noise in the figure) occur during the winter months, yet do not translate to differences in modelled GPP, figure 3(*b*). This is an artefact of how

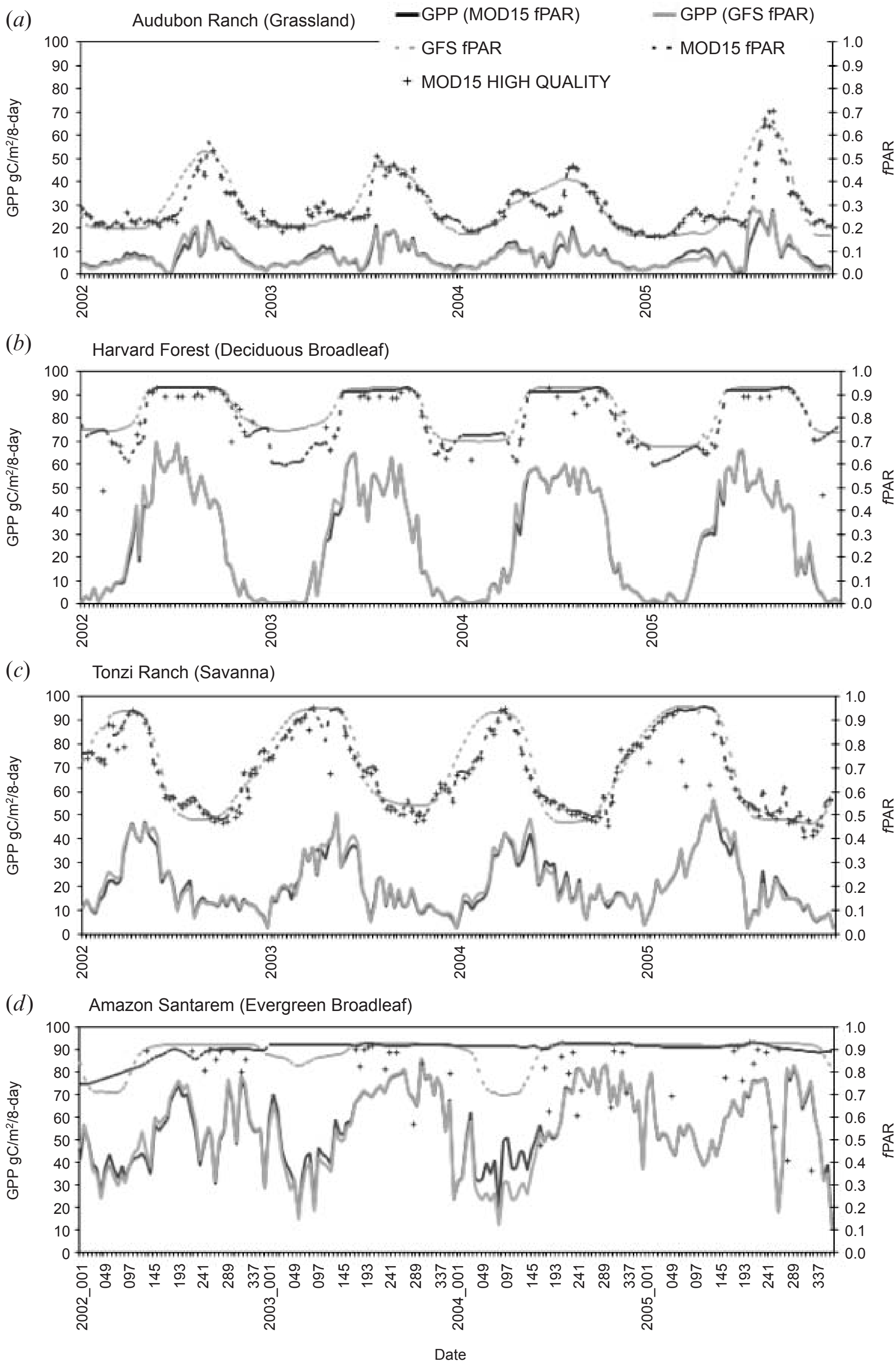

Figure 3. Time-series *f*PAR and MOD17 GPP (gC m^{-2}/8-day) for the selected sites. High quality MOD15 values (+symbols) indicated subsequent *f*PAR product quality.

snow-contaminated pixels are treated by the smoothing/gap-filling methods (Gao *et al.* 2008, Zhao *et al.* 2005). Environmental modifiers applied within the algorithm (minimum temperature and water stress) constrain growth during this period more severely than light availability (Jolly e*t al.* 2005, Running *et al.* 2004). UMT gap-filling of cloud-contaminated *f*PAR pixels within the Amazon region resulted in a fairly high and uniform value across the time-series (figure 3(*d*)). The GFS product reveals more seasonality in the Amazon *f*PAR signal, which may in fact relate to the endogenously controlled vegetation phenology that is timed to the seasonality of solar radiation across this region (Myneni *et al.* 2007). Reduced vegetation productivity (up to 15 gC m^{-2}/8-day) during the wet season occurs when radiation loads decline due to cloud cover, as captured in the GFS *f*PAR time-series.

Annual estimates of GPP derived from the MOD17 GPP algorithm run with both UMT and the GFS products are highly correlated at each of the 30 sites analysed (r^2>0.98). Overall differences in the *f*PAR datasets were not significant enough to change the nature of the association between the UMT dataset and annual GPP derived from flux measurements as described in Heinsch *et al.* (2006).

3.2 *CASA model*

Monthly averaging of the 8-day MOD15 *f*PAR dataset tends to naturally smooth the time-series and lower overall values (figure 4). Several sites (such as TR; see figure 4(*c*)) retain a degree of seasonal variation in *f*PAR. At the HF and TR sites, the greatest differences between MOD15 and GFS *f*PAR occur during winter (November–April), and between May and August at the AR site. There is considerable divergence between the two datasets with respect to *f*PAR magnitude and seasonality, for the entire time-series at the Amazon site (figure 4). In all cases, *f*PAR differences relate closely to precipitation regimes and cloud contamination forcing the use of the backup empirical algorithm rather than the main radiative transfer algorithm (Ahl *et al.* 2006; Gao *et al.* 2008).

The CASA model is relatively sensitive to input *f*PAR data. Relatively small variations in summer *f*PAR (within $\pm$0.2 units) result in substantial differences in GPP for many of the sites analysed (figure 4). At both the HF and TR sites, the greatest *f*PAR differences occur during winter when low temperatures and light limitations constrain plant growth (GPP) (Jolly *et al.* 2005). However, at Audubon Ranch, the driest site (least cloud cover), small variations in *f*PAR and hence monthly GPP estimates remained within $\pm$5 gC m^{-2}/month. At the wettest site, in the Amazon, differences in the input fPAR data types resulted in GPP differences of up to as much as 140 gC m^{-2}/month.

CASA annual GPP estimates using TIMESAT and MOD15 fPAR were very similar for the AR site (within 16 gC m^{-2}/year). However, average annual differences of up to 100 gC m^{-2}/year at HF, 270 gC m^{-2}/year at TR, and greater than 760 gC m^{-2}/year at the Amazon rainforest site were measured (figure 4). CASA estimates of annual GPP, using both the GFS and the MOD15 *f*PAR data, were compared to flux tower derived estimates of GPP (Heinsch *et al.* 2006) and yielded similar results as outlined in this article. This finding stressed the requirement for further refinement of the *f*PAR datasets, and using field measured *f*IPAR (fraction of radiation intercepted by the canopy) as demonstrated by Ahl *et al.* (2006) is required to improve satellite-derived estimates.

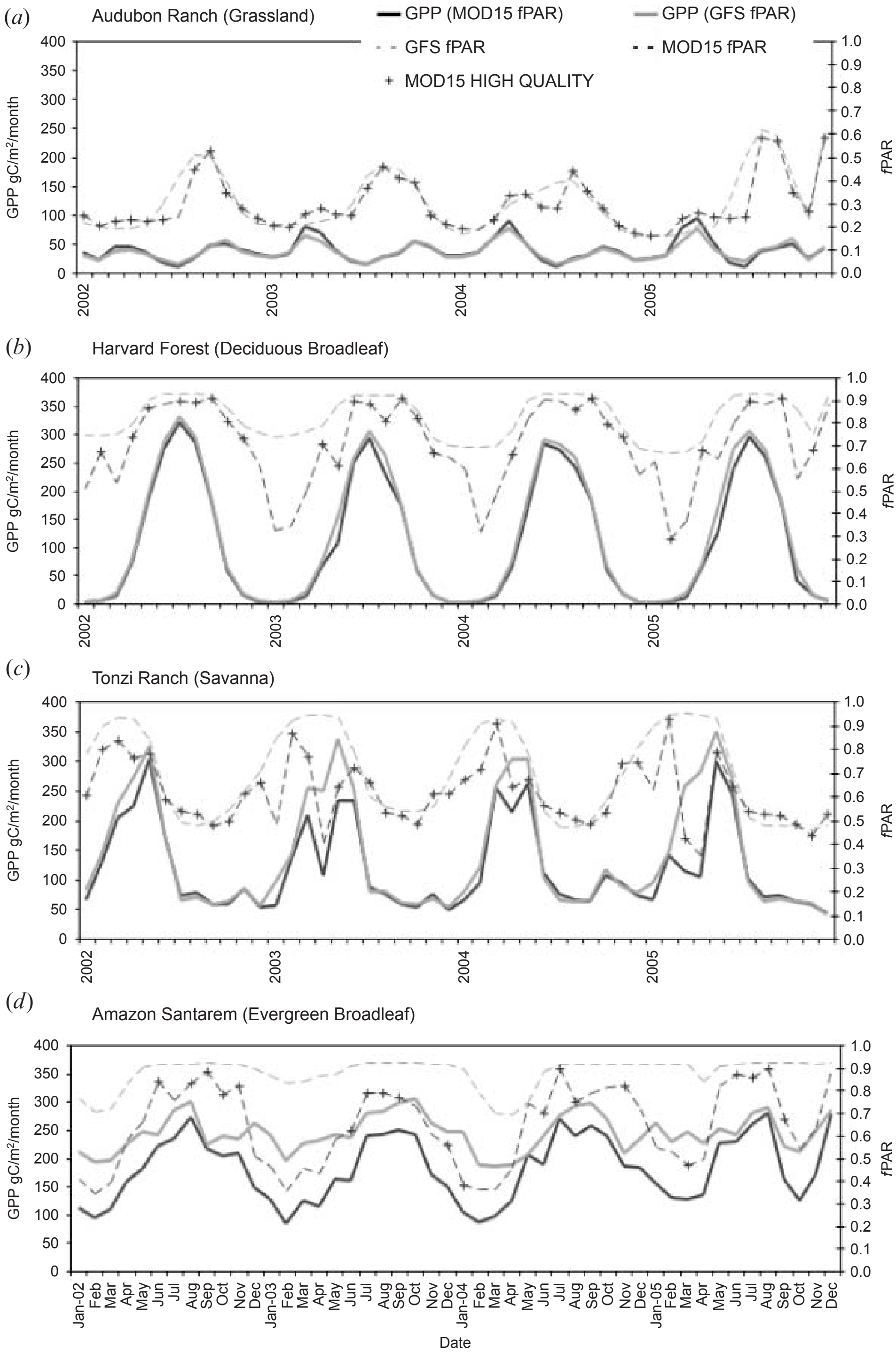

Figure 4. Time-series *f*PAR and CASA GPP (gC m^{-2}/month) for the selected sites. High quality MOD15 values (+symbols) indicated subsequent *f*PAR product quality.

4. Conclusions

The GFS product removes the noise present within the original MOD15 *f*PAR dataset. While this technique may also smooth over some of the valid variation in the data, this does not significantly affect modelled productivity estimates. Large differences between the GFS and both the UMT and MOD15 *f*PAR datasets tend to occur during the winter period as a result of how the algorithms handle pixel snow contamination. In general, model imposed growth constraints (minimum temperature and water deficit) limit plant growth more rigidly than light availability. In the Amazon these constraints are minimal and light availability plays a greater role in limiting productivity. In such regions where persistent cloud cover is an issue, the GFS product provides more realistic *f*PAR time-series in relation to magnitude and radiation seasonality than is offered by the original or UMT *f*PAR datasets.

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