AN UPDATE ON THE GLOBCARBON INITIATIVE:
MULTI-SENSOR ESTIMATION OF GLOBAL BIOPHYSICAL PRODUCTS
FOR GLOBAL TERRESTRIAL CARBON STUDIES

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ABSTRACT
The ESA GLOBCARBON project aims to generate fully calibrated estimates of at-land products quasi-independent of the original Earth Observation source for use in Dynamic Global Vegetation Models, a central component of the IGBP-IHDP-WCRP Global Carbon Cycle Joint Project. The service features global estimates of: burned area, fAPAR, LAI and vegetation growth cycle. The demonstrator focused on six complete years, from 1998 to 2003 when overlap exists between ESA Earth Observation sensors (ATSR-2, AATSR and MERIS) and the French SPOT VEGETATION sensor and was extended to process 10 years up to 2007. After analysis, by the beta user community, of the first products the implementation of the algorithms was revisited and a reprocessing initiated. This paper provides details of the GLOBCARBON project and its revised algorithms, describes the re-processed products and gives initial results of their validation.

1 INTRODUCTION
‘Greenhouse gases’, especially carbon dioxide, are intimately connected to climate change. To predict future climate change accurately and find ways to manage the concentration of atmospheric carbon dioxide, the processes and feedbacks that drive the carbon cycle must first be understood. However, our current knowledge of spatial and temporal patterns of carbon pools and fluxes is uncertain, particularly over land. Recent inter-comparisons have shown that with best predictive vegetation models, such as the Lund-Potsdam_Jena (LPJ) model, there is general agreement on global carbon balance but disagreement on how the carbon is distributed despite running models with the same data (McGuire et al. 2001). Further progress in understanding of the global carbon cycle and its likely future evolution depends, in particular, on improved observations of the terrestrial carbon processes (Cramer et al., 1999) to narrow the large uncertainties in the magnitudes and locations of carbon fluxes between the land, oceans and the atmosphere.
However, this requires a holistic approach combining models, observations and process studies, not just focusing on the terrestrial component, but coupling it with atmosphere and ocean as advocated by the Integrated Global Observing Strategy Partnership (IGOS-P) Carbon Theme Team (Ciais et al. 2003). In tandem with this initiative an overarching global carbon observation project, the Earth System Science Partnership (ESSP) Global Carbon Project (www.globalcarbonproject.org), has been initiated with the objective:

‘to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them’

To aid this process the ESA GLOBCARBON project (Plummer et al. 2006) was initiated to generate fully calibrated estimates of at-land products quasi-independent of the original Earth Observation source, for use primarily in Dynamic Global Vegetation Models, as a contribution to the Global Carbon Project. While a large number of potential methods exist in the scientific literature for generating carbon-related information from Earth Observation (EO) data, the vast majority of them have not been applied rigorously or comprehensively across space and time. Unfortunately, these methods and their outputs have also not been well publicised to the very community at which they are aimed and it is important to recognise that the Global Carbon community is interested in derived products that are consistent, contain information on the potential error and are over the greatest temporal range possible.

Prior to initiating GLOBCARBON a targeted user requirements survey was conducted through direct contact with a small group of expert users who are specifically tied to the project. The results of this survey can be summarised as:

- a system to estimate burned area, vegetation amount and vegetation variation.
- a long temporal sequence (at least 5 years
- cover multiple satellite sensors
- be applicable to existing archives and future satellite systems
- be available at resolutions of 10 km, 1/4, and 1/2 degree
- have as accompanying layers of confidence information and spatial heterogeneity
- be available as a suite of products from a single source

The GLOBCARBON Initiative therefore features estimation of global burned area, the fraction of absorbed photosynthetically active radiation ($f_{\text{APAR}}$), leaf area index (LAI) and Vegetation Growth Cycle (VGC) for 10 complete years, from 1998 to 2007.

## 2 PRODUCTS AND THROUGHPUT

The baseline inputs are 1 km satellite sensor data, in the first instance data from sensors on the second ESA European Remote Sensing (ERS-2) and ENVISAT satellites and from the fourth and fifth Système Pour l’Observation de la Terre (SPOT) satellites but designed to be flexible so that other input data sets can be used (e.g. the Advanced Very High Resolution Radiometer, AVHRR or the Moderate Resolution Imaging Spectrometer, MODIS). The total throughput and product handling required to produce the GLOBCARBON outputs is summarised in Tab. 1.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Nr. Years</th>
<th>Throughput (Tbyte)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR-2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Vegetation</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>AATSR</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>MERIS</td>
<td>4</td>
<td>11</td>
</tr>
</tbody>
</table>

|          | 50        |

## 3 GLOBCARBON PRE-PROCESSING

Two fundamental pre-cursors to the generation of global biophysical estimates of LAI, $f_{\text{APAR}}$, vegetation phenology and burned area are the detection and removal of non-valid pixels – specifically those affected by cloud, cloud shadow and snow and then the correction of ‘valid’ pixels for the effects of the atmosphere on the signal detected by satellites.

### 3.1 Cloud, cloud shadow and snow detection

The GLOBCARBON system uses an adapted version of the APOLLO method (Saunders and Kriebel, 1988) for A/ATSR-2 (Plummer, in review, 2007). Snow was screened as a precursor to application of the cloud detector, adopting the approach developed for MODIS (Hall et al. 2001). The system adopted for cloud and snow screening for VEGETATION data is that developed in the standard processor at CTIV (Kempeeneers et al. 2000). The snow and cloud testing for MERIS relies on the so-called Bright Layer and adaptive thresholds derived from statistical parameters of the bright flagged pixels in ratios of blue (443nm) and near-infrared (750nm) and far-red (705nm) and near infrared (865nm). The former ratio allows land to be discriminated from cloud and ice/snow while the latter provides separation of snow from land/cloud (Ranera et al. 2005). Cloud shadow detection for all sensors uses the cloud mask in a combined geometry-
threshold technique to locate cloud shadow using the method described in Kempeneers et al. (2000).

3.2 Atmospheric Correction
The atmospheric correction adopted for GLOBCARBON is SMAC (Rahman and Dedieu, 1994) v4 populated by aerosol derived from a latitude-based formulation in the absence of a global dataset covering all 10 years or even 1 year, ozone derived from GOME level 3 total column thickness generated by DLR, pressure derived from the ACE global digital elevation model and water vapour from ECMWF.

4 THE GLOBCARBON PRODUCTS

4.1 The Burned Area product
The fire product builds on the extant methods, experience and information from GLOBSCAR (ESA) (Piccolini, 1998, Simon et al. 2004) and EC Global Burned Area Assessment (GBA-2000) (Tansey et al. 2004). The approach brings together the two processing chains plus active fire location information (e.g. World Fire Atlas (WFA), Tropical Rainfall Mapping Mission (TRMM) fire product and the Canadian FireM3 product). For GBA 2 of the algorithms used in the GBA-2000 chain have been implemented globally. These are the Technical University of Lisbon (UTL) Africa (UTL-Africa) algorithm (Silva et al. 2002) and the Russian International Forest Institute (IFI) (Ershov and Novik, 2001). The three burned area mapping algorithms are used independently and then provided along with the fire location information as a bit-encoded product on a monthly time step derived from detection by the three approaches and the presence of detected fires. Fig. 1 shows the co-location of the GLOBCARBON burned area and active fires from the World Fire Atlas around Sakhalin Island in 1998.

4.2 LAI estimation
4.2.1 Methodology
Leaf area index (LAI) and the instantaneous fraction of absorbed photosynthetically active radiation (fAPAR) are derived using a constrained model-based look-up table (LUT) as described in Deng et al. (2006). This relies on relationships between LAI and reflectances of various spectral bands (red, near infrared, and shortwave infrared). These relationships have been established for different types of vegetation types using a physically based geometrical model complete with a multiple scattering scheme (denoted Four-Scale by Chen and Leblanc, 2001).

For every land cover type, a large number of Four-Scale simulations are made to determine all the parameters of the algorithm, including bidirectional reflectance distribution function (BRDF) kernel coefficients. The methodology proceeds through a simple iteration procedure: (1) a precursor effective LAI value for a pixel is first estimated from a general cover-type dependent Simple Ratio (SR) to LAI relationship, assuming \( f_{BRDF}(\theta_{vi}, \theta_{si}, \phi_i) = 1 \). (2) BRDF kernels are calculated using the precursor effective LAI value. Given these relations, it is possible to write the BRDF modification functions \( f_{BRDF} \) and \( f_{SWIR\cdotBRDF} \) that can be used to cast the SR and SWIR bands of a pixel at any angle combination \( (\theta_{vi}, \theta_{si}, \phi_i) \) to a new angle combination \( (\theta_{vn}, \theta_{sn}, \phi_n) \): where subscript \( i \) represents an image pixel, subscript \( n \) represents the new angle combination from which we intend to calculate the LAI value given the LAI–SR or SWIR adjusted SR (RSR) relationship at that angle combination, (3) final effective LAI is calculated from the BRDF kernels and SR/RSR, and (4) empirical clumping index of different land cover is used to calculate the final LAI. Two separate algorithms have been developed for the retrieval of the effective leaf area index (\( L_E^\cdot \)):

\[
L_E^\cdot = \int_{SR\cdot \cdot} \cdot f_{BRDF}^\cdot (\theta_i^\cdot, \theta_s^\cdot, \phi^\cdot) \tag{1}
\]
where \( f_{\text{LE-SR}} \) and \( f_{\text{LE-RSR}} \) are functions defining the relationships between \( L_E \) and SR and between \( L_E \) and RSR at a specific view and sun angle combination \( (\theta_{\text{specific}}, \theta_{s}, \phi) \). These functions are expressed as Chebyshev polynomials of the second kind. Functions \( f_{\text{BRDF}} \) and \( f_{\text{SWIR-brdf}} \), quantifying the BRDF effects, depend on the angular behaviour of reflectances of the spectral bands involved, which are described mathematically based on a modified Roujean’s model (Chen & Cihlar, 1997; Roujean, Leroy, & Deschamps, 1992). The true LAI is then estimated according to the effective LAI and a clumping index. The relationship between the effective LAI and the true LAI is defined as:

\[
LAI = \frac{L_E}{\Omega}
\]  

The global application of the algorithm is achieved by reference to the GLC2000 global land cover map (Bartholome and Belward, 2005).

### 4.2.2 Smoothing of the annual LAI

Once an annual cycle of LAI\(_{\text{ten-daily}}\) products has been generated for the globe the data are filtered to produce a smooth trend in LAI consistent with the expected growth cycle using 54 decades of LAI estimates. The smoothing process is accomplished using the locally weighted regression method LOESS (Chen et al. 2006) to produce an effective capping for the original data series. This involves smoothing using cubic Bezier curves replacing observations by values of the predicted curve. The objective of this exercise is to allow the identification of problematic data points while not eliminating systematic large changes such as those at the beginning and end of the growing season.

### 4.2.3 Results

The resulting output of these algorithms is provided as a series of images which record, in the 1 km product, for the given month, the average LAI after smoothing, the original LAI for the month, their respective standard deviations, the number of valid estimates sourced from each given sensor (VEGETATION, ATSR-2, MERIS, AATSR), the number of LAI values replaced in the smoothing expressed in two fields LOW10 and LOW20 when the difference between final and original LAI was greater than 10 and 20% respectively and finally a series of flag values. Low resolution products are produced from the smoothed values of LAI and contain information on this value and its spatial standard deviation, the number of valid pixels from each sensor again expressed spatially, quality flags and the predominant land cover for the low resolution grid as defined from the GLC2000 map.

### 4.3 f\(_{\text{APAR}}\) estimation

The fraction of photosynthetically active radiation absorbed by the canopy (f\(_{\text{APAR}}\)) is 1-reflection-penetration+absorption of PAR reflected by the background:

\[
f_{\text{APAR}} = (1 - \rho_1) - (1 - \rho_2) e^{-G(\theta)f_{\text{LE}}/\cos\theta_s}
\]

where \( \rho_1 \) and \( \rho_2 \) are the PAR reflectances above and below the canopy; \( G(\theta) \) is the light extinction...
coefficient, $\beta$ is a parameter to consider the light multiple scattering effect in the canopy and is taken as a constant of 0.9; and $L_E$ is the result of LAI algorithm. The reflectance in the red band $\rho_{\text{red}}$ is proportional to and smaller than the PAR reflectance above the canopy, and $\rho_\lambda$ is assumed to correspond to $1.5^*\rho_{\text{red}}$. While, measured $\rho_{\text{red}}$ includes the BRDF effect, this effect is not important as $\rho_{\lambda}$ is generally small in comparison with $f_{\text{APAR}}$.

The $f_{\text{APAR}}$ is calculated for pixels after the smoothing of LAI has taken place using the $L_e$ smoothed value in tandem with the original reflectance values and view angles. The $f_{\text{APAR}}$ is only calculated where all reflectance values and view-solar angles are available. While nominally this is described as a ‘daily’ product no integration over the diurnal cycle has been performed and the value represents solely the instantaneous $f_{\text{APAR}}$ for the satellite overpass. Each satellite product is maintained separately (VEGETATION, ATSR-2, AATSR, MERIS) and each day contains 6 planes for the $f_{\text{APAR}}$ product: Value, Solar Zenith Angle (SZA), View Zenith Angle (VZA), Azimuth Angle Difference (AAD), Status Map (SM) and Quality Flag. The $f_{\text{APAR}}$ is aggregated to the 10km, 0.25° and 0.5° grid sizes as for LAI using all available valid values plus the solar-view geometry values. The separation between Sensors is maintained and no temporal averaging takes place. Values are provided also for the standard deviation associated with the spatial mean and a quality flag, is provided as a binary file which indicates when less than 30% of the pixels in the grid box have an associated $f_{\text{APAR}}$ value. In such a case it is not possible to calculate a $f_{\text{APAR}}$ value at low resolution.

4.4 Vegetation Growth Cycle estimation

4.4.1 Methodology
Analysis of NDVI data has indicated a progressive greening of the boreal zone associated with advances of spring budburst and delay of autumn leaf fall (Myneni et al. 1997, Slayback et al. 2003). This has recently been confirmed as being a real phenomenon as opposed to instrument effects by comparison with a dynamic vegetation growth model and both tree phenology trends and changes in temperature (Lucht et al. 2002). For GLOBCARBON the generation of growth cycle parameters is based on the previously calculated LOESS smoothed profiles of LAI instead of the usual NDVI. This approach is taken as it should be less sensitive to extraneous effects which are often seen on vegetation index time series. The LAI values a 54 decade period, are used to calculate the leaf-on and leaf-off dates, the peak value of the LAI and its date, the mean LAI between leaf-on and leaf-off dates along with associated flags. The date of leaf-on is defined to be the date with the highest first derivative of the smoothed LAI time series before the maximum LAI is reached. This value is derived for the limited temporal period bounded by the values of LAI $1/4$ and $3/4$ of the maximum LAI, prior to the location of the maximum LAI. The leaf-off date is defined to be the location in time after the maximum when the LAI is reduced to the mean of maximum and minimum values.

4.4.2 Results
For the 1 km product the values provided comprise the leaf-on (Figure 3a) and leaf-off dates, the peak value of the LAI and its date, the mean LAI between leaf-on and leaf-off dates and the associated flags. In addition, with respect to the leaf-on date, the dates just before and just after the highest first derivative (with a first derivative equal to the 90% of this maximum) and the date with the highest second derivative are also provided. The values lie in the range 1-550 but are

Figure 3: Leaf-on dates for 1998 for Switzerland and the associated flags. The +1 term indicates the following year as the scale is applicable to the globe while the flag codes are confidence values for the estimate (0 is water, 1, 3-7, 9-15, 17-23 and 25-31 are indicative of the availability of data to the smoothing process, 6 is no data, 33-63 are pixels near water bodies and 129-161 evergreen vegetation).
provided in the year when growth started even if the value actually falls in the subsequent year.

The flags accompanying the VGCP products correspond to those for which no LAI estimate could be made (water, artificial surfaces, bare areas and permanent snow and ice in the GLC’2000 product), those where missing data caused a problem in the calculation, where the calculation should be treated with caution owing to limited data in the time period around the leaf-on date and finally pixels which, although a value is generated, correspond to an evergreen land cover class (Figure 3b).

5 VALIDATION

5.1 Leaf Area Index

Version 2 of GLOBCARBON will be subjected to a comprehensive validation of LAI spatially, temporally and over a range of land covers using estimated LAI fields, via the translation of in situ point observations to spatial fields with Landsat TM and SPOT HRV data, provided by the principal validation networks (VALERI, CCRS, BigFoot). Fig. 4 shows an early result over boreal forest in July 1998 with GLOBCARBON generally being within one standard deviation of the Landsat estimate.

5.2 Burned Area

To achieve a comprehensive validation of burned area estimated from low or medium resolution sensors the methodology used within GLOBCARBON reports on the ability of each of the algorithms to represent the area that has been burned within a hexagonal grid with a spacing of 60km. This grid is projected over the Earth’s surface providing uniform global coverage. Burned area in each grid cell is computed from high-resolution (Landsat TM and SPOT HRV) images and a selection of available burned area vectors (e.g. USFS) and the GLOBCARBON products.

Figure 4: Inter-comparison between estimated LAI along a transect in Quebec in July 1998 using Landsat TM data (red) and that from version 2 of GLOBCARBON (blue). The values for GLOBCARBON lie within 1 SD of those generated from Landsat taking into account the averaging across 1 km.

Figure 5: 60km spaced grid hexagons indicating percentage of burned area for the GLOBCARBON project.

Fig 5 shows an example of the hexagonal grid indicating percentage area burned for an area in NE sub-Saharan Africa. This method allows a robust inter-comparison of global products across a range of vegetation types and fire regimes.

While the comprehensive assessment has not yet been conducted clear improvements in the GLOBCARBON BAE are evident in version 2. Fig 6 highlights the improvements that have been made between version 1 and 2 in Australia showing the correspondence between burned areas detected using the Firewatch Fire Mapping Service (red) and those observed in GLOBCARBON version 2 (blue).
Figure 6: Burned area detection in NW Australia. GLOBCARBON burned area vectors (blue) for July 1999 compared against those (red) obtained from AVHRR in the Firewatch operational fire detection system (http://firewatch.dli.wa.gov.au/landgate_firewatch_public.asp).

6 CONCLUSIONS

The ESA GLOBCARBON project (Plummer et al. 2006) was initiated to generate fully calibrated estimates of at-land products quasi-independent of the original Earth Observation source. After undergoing beta testing of the first products a re-processing was undertaken to produce version 2. These data are currently being analysed through an extensive validation exercise but early results are promising. The version 2 data themselves are now being made available through the GLOBCARBON website (www.globcarbon.info).

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