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Mapping Congo Basin vegetation types from 300 m and 1 km multi-sensor time series for carbon stocks and forest areas estimation

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Abstract. This study aims to contribute to the understanding of the Congo Basin forests by delivering a detailed map of vegetation types with an improved spatial discrimination and coherence for the whole Congo Basin region. A total of 20 land cover classes were described with the standardized Land Cover Classification System (LCCS) developed by the FAO. Based on a semi-automatic processing chain, the Congo Basin vegetation types map was produced by combining 19 months of observations from the Envisat MERIS full resolution products (300 m) and 8 yr of daily SPOT VEGETATION (VGT) reflectances (1 km). Four zones (north, south and two central) were delineated and processed separately according to their seasonal and cloud cover specificities. The discrimination between different vegetation types (e.g. forest and savannas) was significantly improved thanks to the MERIS sharp spatial resolution. A better discrimination was achieved in cloudy areas by taking advantage of the temporal consistency of the SPOT VGT observations. This resulted in a precise delineation of the spatial extent of the rural complex in the countries situated along the Atlantic coast. Based on this new map, more accurate estimates of the surface areas of forest types were produced for each country of the Congo Basin. Carbon stocks of the Basin were evaluated to a total of 49 360 million metric tons. The regional scale of the map was an opportunity to investigate what could be an appropriate tree cover threshold for a forest class definition in the Congo Basin countries. A 30 % tree cover threshold was suggested. Furthermore, the phenology of the different vegetation types was illustrated systematically with EVI temporal profiles. This Congo Basin forest types map reached a satisfactory overall accuracy of 71.5 % and even 78.9 % when some classes are aggregated. The values of the Cohen's kappa coefficient, respectively 0.64 and 0.76 indicates a result significantly better than random.

1 Introduction

Central Africa contains the second largest and the least degraded area of contiguous moist tropical forest in the world (de Wasseige et al., 2009). It provides huge ecosystem services from the local scale to the global one, in various economic, social and ecological domains (Mayaux et al., 2009). Reliable, consistent and updated land cover information in the humid tropics is therefore essential in studies concerning development policies, habitat and biodiversity monitoring, forest resources management, Carbon (C) accounting, human livelihoods, biogeochemical cycles and climatic modeling (Hansen et al., 2008a; Loveland et al., 2000; Mayaux et al., 2004; Sellers et al., 1996; Townshend et al., 1992).

In recent years, improving regional and national capabilities to monitor forest extent has been an important concern in tropical areas. In Central Africa, several initiatives to monitor and protect forests have emerged. Specifically, the

Observatory for Forests of Central Africa (OFAC), an initiative of multiple stakeholders of the Congo Basin Forests Partnership (CBFP, 2006), aims at pooling the knowledge and available data necessary to monitor the different aspects of forests of Central Africa (Mayaux et al., 2009).

This study aims to contribute to the delivery of a detailed vegetation types map with an improved spatial discrimination and spatially coherent for the whole Congo Basin region. This work will take advantage of the fine spatial resolution of MERIS Full Resolution (FRS) and of the temporal consistency of 8 yr of daily SPOT VEGETATION (VGT) observations to achieve a better land cover discrimination in very cloudy areas. The spatial patterns of the different vegetation types will be better delineated in support to biodiversity habitat characterization and deforestation monitoring. Based on this new map, a specific objective is to produce improved estimates of the forest types areas in Congo Basin countries. These enable evaluating the Carbon stocks of the Basin. The regional scale of the map is an opportunity to investigate the impact on the surface covered by forests of a 10 or 30 % tree cover threshold in the forest definition in the Congo Basin countries. Furthermore, the phenology of the different vegetation types will be quantified systematically to support dynamic vegetation modeling.

2 Background

2.1 Land cover maps of Central Africa

In the last 20 yr, most vegetation maps of Central Africa have been derived from satellite images (Laporte et al., 1998; Mayaux et al., 1999, 2004). Satellite images are a powerful source to map the vegetation cover in remote areas and overcome the limitations due to the large spatial extent and the difficult accessibility of the territory (Hansen et al., 2008b; Vancutsem et al., 2009). However, with optical satellite data, an important issue for humid tropical forest monitoring is persistent cloud cover. As land cover maps provide a static depiction of land surface (Achard et al., 2007) and because of the technological improvement and constant increase of spatial resolution for large areas, the products need to be updated often.

Before the generalization of remote sensing for land cover mapping, continental cartographic syntheses of Africa were based on the compilation of national and local maps enriched by the consultation of many experts (Sayer et al., 1992; White, 1983). In the early nineties, the first global land cover maps were derived from satellite observations using Advanced Very High Resolution Radiometer (AVHRR) NDVI data (DeFries and Townshend, 1994; DeFries et al., 1998; Hansen et al., 2000; Loveland et al., 1999). Regional land cover maps over Central Africa were derived from AVHRR as well (Laporte et al., 1998; Mayaux et al., 1999). Then, more dedicated sensors appeared with enhanced spatial and spectral characteristics, such as the SPOT VGT and the MODerate resolution Imaging Spectroradiometer (MODIS), leading to the production of the first MODIS Land Cover map (Friedl et al., 2002) and the Global Land Cover 2000 project (GLC 2000) using data from the VGT sensor for the year 2000 (Bartholome et al., 2002). The GLC 2000 for Africa capitalized on local expert knowledge (Mayaux et al., 2004). More recently, the GlobCover initiative has produced a global land cover map based on an automatic method using the 300 m resolution mode from the MERIS sensor onboard the Envisat satellite (Defourny et al., 2009). The MODIS Global Land Cover map has been quite improved recently, generated at 500 m spatial resolution over the Modis Collection 5 (Friedl et al., 2010).

At a regional scale, Hansen et al. (2008a) developed a multi-resolution (MODIS and Landsat) methodology for a binary forest/non-forest mapping at 250 m of the Congo Basin. Vancutsem et al. (2009) presented a 1 km resolution map of the vegetation types of the Democratic Republic of Congo produced with a semi-automatic method applied on one year of SPOT VGT data. Concerning DRC, the FACET atlas (Mane et al., 2010) was released in 2011, mapping vegetation cover and forest loss from 2000 to 2010 with Landsat imagery.

In other words, a wide variety of land cover maps products exists over Central Africa (Table 1). Global land cover products, such as GlobCover, present the disadvantage of being rather unspecific to the region studied. The GLC 2000 of Africa is more specific in the thematic description but the 1 km spatial resolution smooths some fine limits between land cover classes. The product of Hansen et al. (2008a) presents the advantage of a fine spatial resolution but with a limited land cover legend. The map of Vancutsem et al. (2009) is very well adapted to the Central African vegetation but does not cover the whole region and is at a 1 km spatial resolution. Given the high landscape fragmentation, many stakeholders in Central Africa would much benefit from a land cover map derived from a fine spatial resolution with a high number of vegetation classes.

2.2 Carbon stocks of Central African forests

Assessing the Carbon stocks in tropical forest is of considerable concern nowadays. Tropical forests are an important carbon sink (Lewis et al., 2009) and tropical deforestation contributes about 12 % to total anthropogenic CO_2 emissions to the atmosphere (van der Werf et al., 2009). The important role in the global carbon cycle provided by the Congo Basin Forests appears prominently through the Reducing Emissions by Deforestation and Forest Degradation (REDD) initiative of the United Nations Framework Convention on Climate Change (UNFCCC). Despite this, the African tropical forest is the least known in terms of carbon stocks and rates of forest conversion (Djomo et al., 2010; Lewis et al., 2009).

Table 1. Land cover maps with a specific focus on Africa and recent global land cover maps

Author (year)	Title (data)	Spatial focus
Consultation of experts and compilation of local information		
White (1983)	Vegetation of Africa	Africa
Sayer et al. (1992)	Conservation atlas of tropical forests	Africa
Olson et al. (2001)	Terrestrial ecosystems WWF	Global
Satellite-based analysis		
Laporte et al. (1998)	A new land cover map of central Africa (AVHRR)	Central Africa
Mayaux et al. (1999)	A vegetation map of Central Africa derived from satellite imagery (AVHRR 1 and 5 km)	Central Africa
Mayaux et al. (2004)	GLC 2000 for Africa (1 km SPOT VGT 2000)	Africa
Hansen et al. (2008)	Regional forest/non-forest cover map (MODIS 250 m)	Central Africa
Defourny et al. (2009)	GlobCover (MERIS 300 m for 2005 and 2009)	Global
Vancutsem et al. (2009)	The Democratic Republic of Congo vegetation types map (1 km SPOT VGT)	DRC
Friedl et al. (2010)	Modis Land cover map (Modis collection 5 500 m)	Global
Mane et al. (2010)	FACET altas (Landsat 2000 to 2010)	DRC

Developing countries are requested to produce robust estimates of forest carbon stocks to implement REDD mechanisms. The existing biomass estimates are derived from local forest inventories that provide precise and accurate estimates at the plot or concession levels, but less accurate information over broader spatial scales (Baccini et al., 2008). Refining these estimates requires improved knowledge of the density and spatial distribution of forests above and below ground biomass. Because of the lack of data over large areas in the region, SAR and Lidar remote sensing is expected to be used more and more to capture the biomass variability over the Congo Basin or even globally. Alternatively, regional estimates have been extrapolated from local field measurements to forest cover type classes (Gibbs et al., 2007). However, this approach misses information on the variability of the density of forest biomass within land cover types classes. Combining remote sensing and field data, Baccini et al. (2008) and Saatchi (2011) recently delivered maps of Biomass and Carbon stock in African and world tropical forest, respectively.

2.3 Study area

The study area covers 8 countries in Central Africa, i.e. Cameroon, Congo, Gabon, Burundi, Central African Republic (CAR), Equatorial Guinea, Republic Democratic of Congo (DRC) and Rwanda.

The Congo Basin covers an area of nearly 2 million km^2, stretching from the coast of the Gulf of Guinea to the mountains of the Albertine Rift and covering about seven degrees of latitude on either side of the Equator (CBFP, 2006).

Seasons and cloud cover are influenced by the movement of the intertropical convergence zone (ITCZ). The nebulous state of the sky is relatively permanent in the area and influences insolation directly. This justifies a low value for insolation that does not exceed 2000 h (Mpounza and Samba-Kimbata, 1990). Some coastal parts of the western Basin are presenting even lower values of insolation as well as a permanent cloud cover due to the warming and rising of moisture-laden air as it moves from the Gulf of Guinea onto the central African land mass (Camberlin et al., 2001; Hansen et al., 2008a).

Precipitation is a main factor driving vegetation distribution in tropical environments. The most important precipitations are linked with the ITCZ. Central Africa presents large variations in annual average precipitation; some areas largely confined to a narrow coastal region of Cameroun adjacent to the Gulf of Biafra are receiving up to 10 000 mm, while for instance Loudima in the Bouenza region (Congo) is receiving about 1000 mm (Mpounza and Samba-Kimbata, 1990; White, 1983). Over all the major part of the region, precipitation varies between 1.600 and 2.000 mm a year on average. This is lower than other tropical regions (CBFP, 2006).

The seasonal distribution of precipitation is bimodal in areas close to the Equator but becomes unimodal further north or south (CBFP, 2006). Bimodal rainfall regimes are the vast majority. They are characterized by two equinoctial maxima and two minima corresponding to the solstices. In the major part of the dense moist forest, rainy seasonal contrasts are imperceptible, so that in most cases it is a constantly humid regime. On the coast of Congo and DRC, the minima are more pronounced. During the principal minimum, up to 3 consecutive dry months can be observed (Mpounza and Samba-Kimbata, 1990). The unimodal rainfall regime is characterized by a single maximum rainfall centered on the summer and a minimum centered on the winter. The length of the dry season increases with latitude: it lasts one to two months on the Equator, but as long as three to four months at the northern and southern edges of the forest block (CBFP, 2006).

3 Data and methods

3.1 Data selection

In order to discriminate the vegetation types, this study is based on the spatial, temporal and spectral information of two major dataset. The first one consists of 19 months, i.e. December 2004 to June 2006, of Envisat MERIS FRS at 300 m spatial resolution composited in 15 days. The second one consists of 8 yr of daily (S1 products) SPOT VGT data, 2000 to 2007, at a spatial resolution of 1 km. Many other classification approaches are based on vegetation indices. Here, the spatially consistent surface reflectances delivered by the data preprocessing have allowed using directly spectral signatures to separate the different vegetation types. Data were georeferenced in Plate Carrée projection using the World Geodetic System 1984 (WGS84) system.

MERIS is a push-broom imaging spectrometer that measures the solar radiation reflected by the Earth's surface in 15 spectral bands from the visible to the near infrared wavelengths. The MERIS swath is 1.150 km and a global coverage is obtained in 3 days. The ESA GlobCover initiative demonstrated the advantage of the MERIS FRS capabilities for global land cover mapping (Defourny et al., 2009). The 19 months of data were available for this study as preprocessed according to the GlobCover processing chain. These data are providing high geolocation accuracy (Bicheron et al., 2011).

The spatial resolution of the VGT instrument, onboard the SPOT-4 satellite, is almost consistent across the whole swath. The four spectral bands of the sensor allow characterizing the main features of the plant canopy: (i) the red band centred on the absorption peak of chlorophyll (0.61–0.68 µm); (ii) the near-infrared (NIR) band (0.78–0.89 µm) corresponding to maximum vegetation spectral reflectance; and (iii) the shortwave infrared (SWIR) band centred around 1.65 µm for reflectance related to the water content of canopy components and to its structure. An additional band in the blue region (0.4 and 0.50 µm) is used for the cloud screening and the atmospheric correction. More details are available in the VGT Users Guide (1999).

Complementary types of data were used to interpret the classification: the Landsat Geocover 2000 ETM+ data set (30 m spatial resolution) (MDA Federal, 2004) and reference vegetation maps and documents of the region, i.e. a vegetation map of the Republic of Congo (Laudet, 1967), of Cameroon (Mertens et al., 2007), of the Central African Republic (Boulvert, 1986), a vegetation map of Africa (White, 1983) and Africover maps (Latham, 2001) for Rwanda and Burundi, GlobCover (Defourny et al., 2009), GLC 2000 on Africa (Mayaux et al., 2004), and a vegetation map of the Republic Democratic of Congo (Vancutsem et al., 2009). The Shuttle Radar Topography Mission (SRTM) data (http://srtm.usgs.gov/) was used to discriminate the altitudinal land cover classes and the Global Insight database for the urban sprawls. Moreover, the hydrographic network was produced by the OFAC (http://www.observatoire-comifac.net/).

3.2 Methodology

The cornerstone of this research is to combine the advantages of MERIS and SPOT VGT time series in various ways and according to the persistence of cloud coverage.

3.2.1 Map production

The study area is stratified in order to account for the difference of seasonality between the north and the south. The spatial delineation of the vegetation types is obtained from spatially consistent and cloud-free composites compiled for specific seasons. Temporal information derived from multi-year time series is used to improve the discrimination of vegetation types. The land cover mapping methodology involves 4 steps: (a) selection and processing of seasonal composites, (b) stratification of the study area according to seasonality and cloud coverage, (c) unsupervised multispectral clustering of one or several composites for each stratum, (d) automatic prelabelling, visual interpretation and interactive editing of each stratum. The method capitalized on a previous 1 km mapping effort for the Democratic Republic of Congo using one year of VGT data (Vancutsem et al., 2009) and on the ESA-GlobCover global automatic land cover mapping.

Data compositing

In equatorial areas the persistent cloud cover is the main challenge for land cover mapping. Compositing methods are therefore used to produce cloud-free and spatially consistent images, called temporal syntheses or composites (Vancutsem et al., 2009). The methodology selected is the mean compositing (MC) which improves the radiometric quality of temporal syntheses by reducing atmospheric and directional variations. The MC method involves averaging for each pixel and in each spectral band all the valid reflectance values acquired during the chosen period (Vancutsem et al., 2007). For the centre of the study area, an annual composite is the most relevant duration, as the tropical forest variation is very low during the year. For the north and the south, the clearer information is available during the period going from one month after the last rainfall to the beginning of the savannas fires. Dry season image selection provides a good contrast between forest and other more seasonal land cover types. Three syntheses were generated for each SPOT VGT and MERIS FRS sensor from all available time series: (i) a seasonal composite for December–January corresponding to the dry season in the northern part; (ii) an annual composite; and (iii) a seasonal composite for May–June corresponding to the dry season in the southern part. To ensure the coherence of the product, the SPOT VGT 1 km pixels were resampled to 300 m.

To characterize the seasonality of the vegetation types, 10 day composites were also produced from the SPOT VGT daily dataset acquired over the 8 yr. Two vegetation indices, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) were computed on the basis of these 10-day reflectance averages. The NDVI is well recognized for the characterization of the chlorophyll activity of vegetation cover over time (Tucker, 1979). The EVI was developed to optimize the vegetation signal with improved sensitivity in high biomass regions and improved vegetation monitoring through a de-coupling of the canopy background signal and a reduction in atmosphere influences (Huete et al., 2002). The respective equations are as follows,

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{RED}}} \quad (1)$$

$$\mathrm{EVI} = G \times \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{R}}}{\rho_{\mathrm{NIR}} + C1\rho_{\mathrm{R}} - C2\rho\mathrm{B} + L}, \quad (2)$$

where $\rho_{\mathrm{NIR,R,B}}$ are surface reflectances in the near-infrared (NIR), red (R) and blue (B) bands, respectively. L is the canopy background adjustment factor, $C1$ and $C2$ are the coefficient of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in the EVI equation are, $C1 = 6$, $C2 = 7.5$, $L = 1$ and G (gain factor) = 2.5 (Huete et al., 2002).

Spatial stratification

Central Africa experiences an inversion of seasonality between the northern and southern part across the Equator (White, 1983), the same land cover types in the north and south of the region will therefore present different phenological stages at the same time. This makes the classification step more complex as it is difficult to classify the whole region in a single zone. To consider this particularity of the study area, the region has been stratified into 4 zones (Fig. 1). First, the area has been stratified in three seasonal zones as it was done in (Vancutsem et al., 2009). This stratification was based on vegetation limits identified by thresholding the NDVI values of the SPOT VGT time series. The first zone (N) corresponds to the dry forest and savannas of the north, the second zone (C) to the dense tropical forests of the centre and the third (S) to the open dry forests and savannas of the south. The composites processed at the previous step are attributed according to the specificity of the seasonality of each zone; seasonal composites are therefore used for the north and the south zones. The central stratum, where an annual composite is used, is further divided in two parts in order to deal with high cloud coverage (CW and CE, hatched zone in Fig. 1). The 8 yr of SPOT VGT data were required to map the western central seasonal zone (CW) in Gabon, Cameroon and Equatorial Guinea. Indeed, 19 months of MERIS data were not enough to build consistent temporal syntheses for some areas near the Atlantic coast, where the cloud coverage is the highest. Figure 2 presents the consistent image obtained by combining the specific composites for each zone. Each stratum is spatially extended by 3 km in order to provide strata overlap and avoid sharp limits when mosaicking the four classifications. If different labels are obtained for a given location, the more coherent one will be chosen according to the location and the label of the neighbouring pixels.

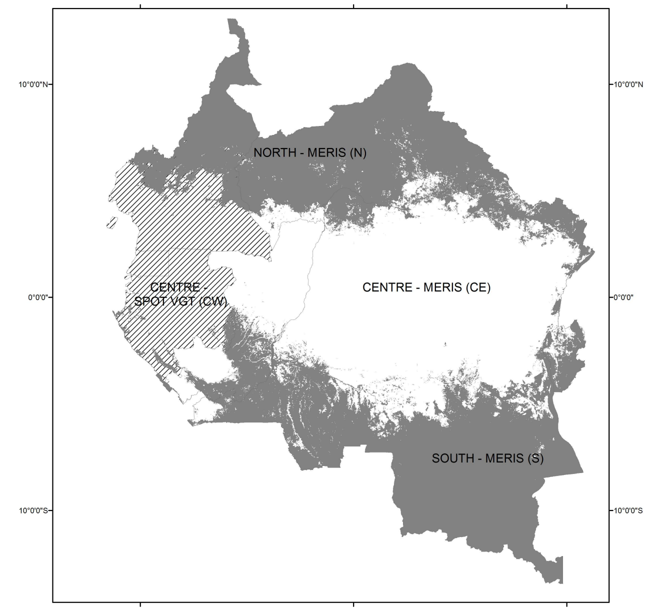

Fig. 1. Stratification of the study area in four zones: North (N), South (S), Western Centre (CW) and Eastern Centre (CE). SPOT VGT is used for hatched countries while MERIS is used for the rest.

Clustering

An unsupervised classification based on the k-means algorithm is performed for each of the four zones separately. More than 200 initial cluster seeds have been used for each zone, which is ten times the number of land cover classes to discriminate. This permits clusters that are generally interpretable as a single land cover class. For each stratum showing seasonality (Zone N and S), the dry season MERIS temporal synthesis of Red and NIR bands is used in addition to the annual MERIS composite as input to the unsupervised classification. MERIS is preferentially used for its spatial discrimination, but the MIR reflectance band of SPOT VGT resampled to 300 m is added for its great spectral contribution for the vegetation types discrimination. For the sub-strata of the Atlantic coast (Zone CW), only SPOT VGT composites are used (Red, NIR, MIR).

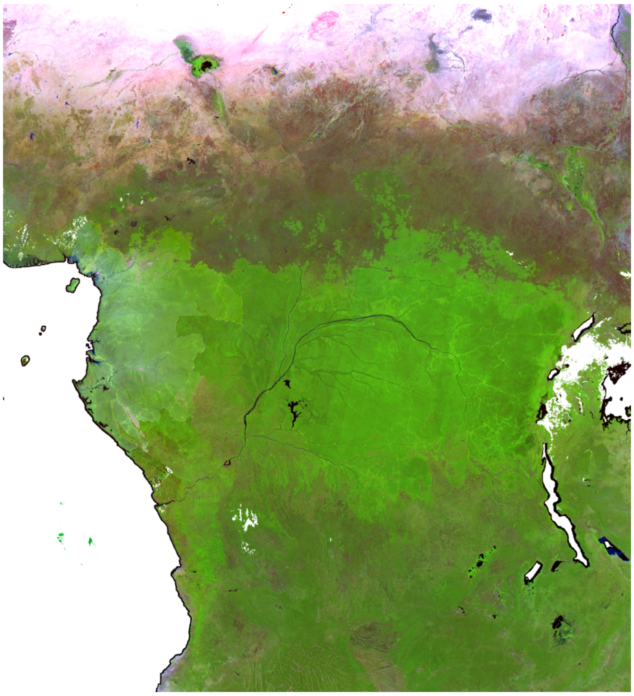

Fig. 2. The consistent image obtained by combining different composites for each zone; in the north a seasonal composite for December–January corresponding to the dry season in the northern part (MIR SPOT VGT, NIR and Red from Meris), in the south a seasonal composite for May–June corresponding to the dry season in the southern part (MIR SPOT VGT, NIR and Red from Meris), for the centre (DRC, Congo and RCA) an annual composite (MIR SPOT VGT, NIR and Red from Meris) and an exclusively SPOT VGT composite for the centre (Equatorial Guinea, Cameroon an Gabon).

Labelling

The clusters produced by the classification are labelled thanks to already existing maps as done for the GlobCover initiative (Defourny et al., 2009). The legends of these maps are translated to correspond to the legend of the vegetation map. The clusters are superimposed to the reference maps. A label is automatically allocated to the cluster according to the majority class (in term of area) of the reference map. A minimum threshold is set to 50 % to inherit a label.

Unlabelled clusters are then manually labelled by visual interpretation of the different composites with the help of expert knowledge, NDVI seasonal profiles and Landsat Geocover 2000 ETM+ data set. The annual NDVI composite was found very useful to discriminate some classes, e.g. the rural complex from the non-forest. Indeed the NDVI value for non-forest is expected to be lower than for rural complex, dominated by vegetation regrowth and croplands.

Mangroves are superimposed with light adaptations to the 300 m resolution from the GLC 2000 map and the Cameroon map (WRI). An interactive editing for land cover labels such as urban areas, aquatic grassland and swamp forests is required due to their low occurrence.

3.2.2 Temporal profiles

The 8 yr of EVI temporal profiles are used to describe the seasonal behaviour of the vegetation classes. The land cover classes are eroded by 300 m in order to guarantee pixel purity and resampled to a 1 km resolution to match the SPOT VGT resolution. The thus selected pixels are aggregated spatially and temporally by taking the median value decade by decade over 8 yr. This results in a series of 36 EVI values, representing the seasonal pattern over the years and the class level. The seasonal behaviour of the vegetation presents an inversion across the Equator and this aggregation is done separately for the north and the south part of the study area.

3.2.3 Confidence building and validation

Two assessments are considered to evaluate the quality of the output. The first evaluation proceeds by cross-comparison with already existing land cover maps to check for macroscopic errors and consistency. A second evaluation consists in the validation of the map based on expert interpretation of randomly spread points. The validation exercise took place in September 2009 during a FRA-FAO-OFAC workshop held in Kinshasa. A hundred random points were validated by national remote sensing experts from 6 countries. The experts were asked to determine to which land cover class the point belongs to, thanks to Landsat 30 m resolution images and an annual NDVI profile related to each point. The Landsat images used were acquired at the closest date possible to one of the MERIS composites. This dataset is completed by 51 validated points in Central Africa obtained through the GlobCover validation database (Defourny et al., 2009). Only points where the expert reported one single class, and this with a high degree of certitude, were selected. The final validation dataset was then composed of 151 points. Datasets can be combined easily after the conversion of the LCCS legend of the GlobCover points into the legend of the Congo Basin vegetation types map. The overall accuracy of the map and the Cohen's kappa coefficient are computed. Kappa can be used to determine if the values contained in a confusion matrix represent a result significantly better than random.

3.2.4 Choice of a 10 or 30 % tree cover threshold in the forest definition

In the context of REDD mechanisms, the UNFCCC requires that parties select a single value for the minimum forest area (0.05 to 1 ha), the potential to reach a minimum height at maturity in situ (2 to 5 m) and the minimum tree crown cover (10 to 30 %). Forest definition and related area are crucial for the REDD negotiations. The new Congo Basin vegetation map was an opportunity to evaluate which tree cover threshold seemed the most appropriate for the forest definition in the

Central Africa region. As a first investigation, the 10 % and 30 % tree cover threshold have been compared in terms of area covered by forest. The inclusion of a land cover class area into one threshold or the other was determined according to the canopy cover mentioned in the LCCS definition of the forest types classes.

3.2.5 Carbon content

The REDD mechanisms require data on how much C is stored in different standing vegetation types (especially forests) and soils and released through agriculture, forestry and other land use activities (Nasi et al., 2009). An indirect methodology of "stratifying and multiplying" is used here for assessing C stock in the Congo Basin. The Congo Basin vegetation types map, which is more detailed than existing maps, is used to stratify the different vegetation types. Then, C stock values from Nasi et al. (2009) are attributed to each category of vegetation. Nasi et al. (2009) established C stock estimates for the Congo Basin derived from plots in situ measurements, inventory, or GIS modelling techniques. Estimates of the aboveground (trees, lianas, understory vegetation, litter and dead wood) and belowground (roots and soil carbon) C pools are regrouped.

4 Results and analysis

4.1 Description and area of vegetation types

The Congo Basin vegetation types map is presented in Figure 3 in a Plate carrée projection with a WGS-84 Ellipsoid. The legend of 20 land cover classes (Table 2) is described by the composition of each vegetation type using the standardized Land Cover Classification System (LCCS) developed by the FAO (Di Gregorio, 2005). These 20 classes may not be representative of all the vegetation types present in Central Africa but they are a good trade-off between the reality in the field and what can be delineated by remote sensing. For instance, even if dense moist forest and riparian forests are different in their floristic composition, the boundary between the two is often unclear and they are therefore grouped together in one single class (class 1 – dense moist forest).

Table 3 contains the area estimates derived from the map, projected in an equal area projection, for the entire region and by country of the different land cover classes in hectares as well as their relative proportion. Class 1 – dense moist forest is the most represented vegetation type in the region covering 41.2 % of the territory with 1 690 000 km^2. More than three quarters of Gabon and Equatorial Guinea territory is covered by dense moist forest, 84.6 % and 75.9 % respectively. Class 1 is also the dominant land cover class in Cameroon (40 %), Congo (49.8 %) and DRC (43.7 %). In CAR, the dominant class is class 9 – savanna woodland/tree savanna, representing 55.5 % of the land, while Class 1 covers only 11.2 %. Besides these countries mainly covered by large patterns of forest or savanna, Burundi and Rwanda present a more fragmented landscape with 46 % of the land covered by class 15 – mosaic of cultivated areas and vegetation (herbaceous or shrubs). In the whole region, class 18 – bare areas, class 14 – sparse vegetation and class 19 – artificial surfaces, are very poorly represented.

Class 1 – dense moist forest is mainly situated in the central stratum. These forests are known as the Lower Guineo – Congolian forests as defined by White (1983). Some small patches of dense moist forest are also present in North CAR. Class 2 and 3 – submontane and mountain forest, covering a total of 1.2 % of the region, are mostly present in the mountain chain of Eastern Congo and for some small areas in coastal Central Africa (Mont Cameroon). The class 4 – edaphic forest, covering 3 % of the whole region, follows the dense hydrographic network of the Congo river. Edaphic forest is also found in western Congo. The Congolian Swamp forest contains the largest areas (126 800 km^2) of swamp forest on the planet. Class 5 – mangrove are forest formations associated with marine alluvium, partially steeped in salt water (Mayaux et al., 2003). It is present on the Atlantic coast mainly in Gabon and Cameroon. Mangrove is a scarce (4404 km^2, 0.1 % of the whole region) and fragile ecosystem. Class 6 – forest savanna mosaic is a formation including both forest and savanna elements. It is found at the edges of the dense moist forest (5.2 % or 213 800 km^2) and represents an important transition zone in the north of the Congo basin, the higher amount of class 6 are indeed found in CAR (111 900 km^2) and in DRC (69 560 km^2). Class 7 – rural complex is formed by a mosaic of secondary regrowth, fallow, home gardens, agricultural areas and village plantations in the forest domain (Vandenput, 1981 in) (Mayaux et al., 1997). In dense moist forest, mapping the 322 600 km^2 of rural complex highlights the road network as well as the population footprint in the forest. In spite of cloudiness, the network of rural complex patches near the Atlantic coast is very clear thanks to the compositing of 8 yr of daily data. In North Congo, because of their similar spectral reflectance, the rural complex class wrongly includes a specific forest class: open forest with Marantaceae. These forests have a more open canopy than the dense forests, and their floor is covered with grasses from the Marantaceae family (Heckestweiler et al., 1991). Class 8 – closed to open deciduous woodland includes the dense dry forests of the Central African Republic and the open dry forests (Miombo woodland) of the southern part of Congo-Kinshasa for a total area of 290 100 km^2 or 7 % of the territory. Only some relics of dense dry forests are present in south DRC (Muhulu). Class 9 – savanna woodland and tree savanna is widely represented as covering 21.3 % of the area with important representation in DRC (370 700 km^2), CAR (344 700 km^2) and Cameroon (119 500 km^2). Class 9 is gathering savanna woodland and tree savanna of the North and the South. Tree and woodland savanna could be presented as two separate ecosystems but are difficult to discriminate, as the delineation between

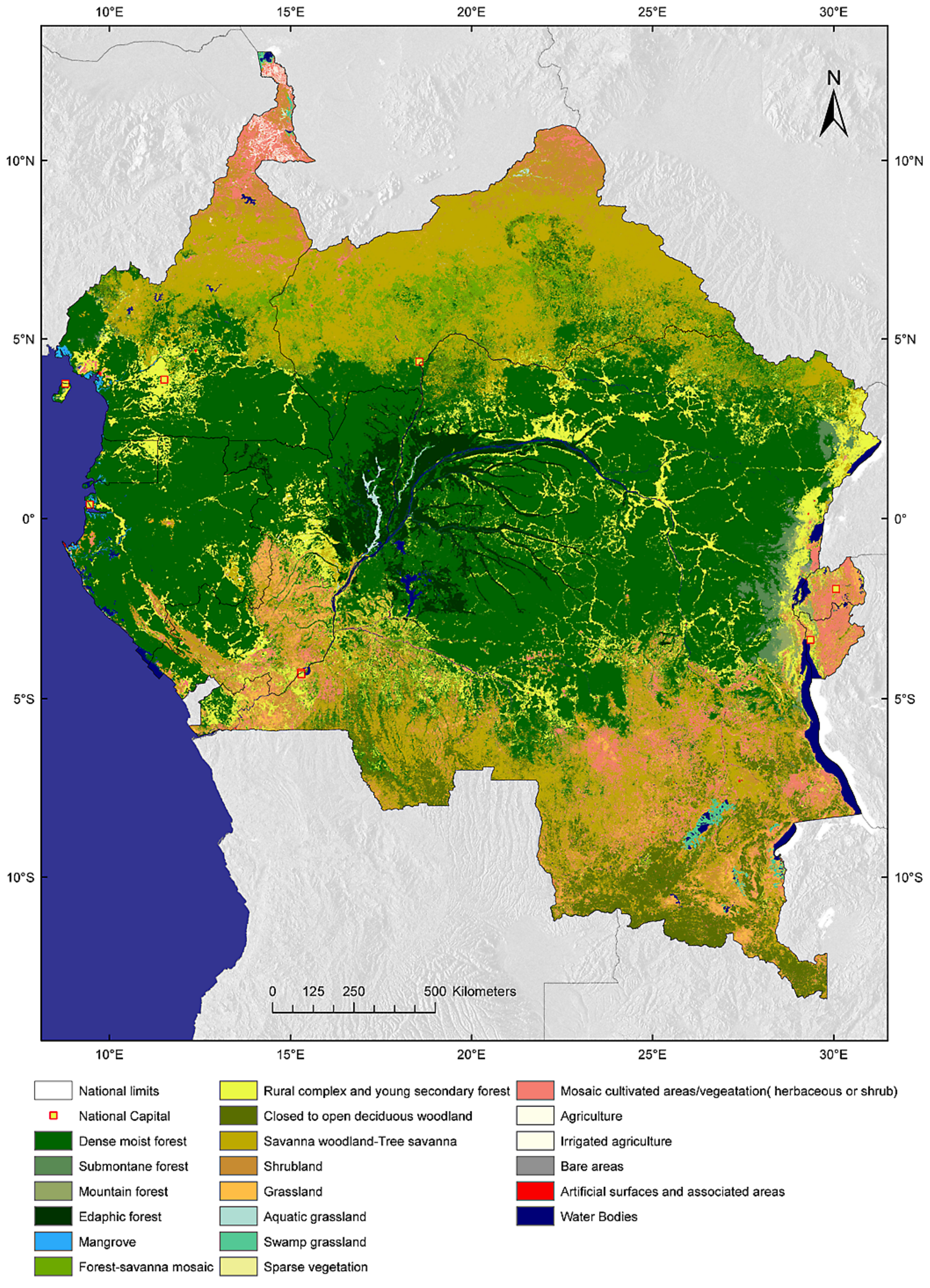

Fig. 3. The Congo Basin vegetation types map.

Table 2. User label and LCCS legends for the Congo Basin vegetation types map.

No.	User's label	LCCS label
1	Dense moist forest	broad-leaved evergreen high trees with closed high shrubs / broad-leaved semi-deciduous high trees with closed high shrubs
2	Submontane forest	closed (> 65 %) broad-leaved semi-deciduous (> 14 m) forest, altitude: 1100–1750 m
3	Mountain forest	closed(> 65 %) broad-leaved semi-deciduous (> 14 m) forest, altitude > 1750
4	Edaphic forest	semi-deciduous high trees on permanently flooded land water quality: fresh water/ semi-deciduous high trees on temporarily flooded land water quality: fresh water
5	Mangrove	closed to open (100–40) % semi-deciduous high trees on permanently flooded land water quality: saline water
6	Forest/savanna mosaic	mosaic closed (> 65 %) semi-deciduous high (> 14 m) forest-closed grassland with sparse trees
7	Rural complex (forest area)	cultivated and managed terrestrial area(s) / broad-leaved semi-deciduous woodland with closed shrubs and closed herbaceous layer
8	Closed to open deciduous woodland	broad-leaved deciduous high trees
9	Savanna woodland/tree savanna	broad-leaved deciduous woodland with closed medium to tall herbaceous layer
10	Shrubland	broad-leaved deciduous (40–(20–10) %) high shrubland with closed herbaceous
11	Grassland	closed tall herbaceous vegetation with medium sparse trees
12	Aquatic grassland	closed tall herbaceous vegetation on permanently flooded land// closed tall herbaceous vegetation on temporarily flooded land
13	Swamp grassland	closed tall herbaceous vegetation on waterlogged soil
14	Sparse (< 15 %) vegetation	sparse trees // sparse shrubs // herbaceous sparse vegetation
15	Mosaic cultivated areas/ vegetation (herbaceous or shrubs)	cultivated and managed terrestrial area(s) // closed to open shrubland (thicket) // herbaceous closed to open vegetation
16	agriculture (> 70 %)	rainfed herbaceous crop(s)
17	Irrigated agriculture (> 70 %)	irrigated herbaceous Crop(s)
18	Bare areas	bare area(s)
19	artificial surfaces and associated areas (Urban areas > 50 %)	artificial surfaces and associated area(s)
20	Waterbodies	natural waterbodies // artificial waterbodies

the two would be better described through a gradient of tree cover density than with a strict border. Class 10 – shrubland is present over 4 % or 164 110 km^2 of the whole area, where the tree layer disappears progressively due to a lack of rainfall, mainly in the north of CAR and Cameroon as well as in the south of DRC. Class 11 – grassland, 1.6 % or 65 310 km^2, is found in the Bateke plateau on sand soils and in dry regions of South DRC. Class 12 – aquatic grassland is present in 0.1 % of the region, where flooding persists and drainage conditions are unfavourable. It is mainly distributed along the Congo and Ubangui Rivers, at the periphery of the edaphic forest and between the Congo and Ubangui Rivers (Vancutsem et al., 2009). It is also found in the north of CAR. Class 13 – swamp grassland is a scarce land cover class as well (0.2 %) and is present in the south of DRC and in the north of Cameroon, in the region of Lake Chad. It is more dependent on soil than aquatic grassland (Schmitz, 1977 in (Vancutsem et al., 2009). Class 15 – mosaic cultivated areas/shrub or herbaceous vegetation covers 221 100 km^2 or 5.4 % and is found in the south of DRC, Rwanda, Burundi, south of Cameroon and RCA. Class 16 – agriculture is a class that is difficult to map due to the small size of the fields in the Congo basin region. Agriculture patches are identified in the north of Cameroon, but agriculture is mainly represented here in mosaic classes mixed with forest or shrub and herbaceous vegetation. Irrigated agriculture is only taking into account the fields near Lake Chad in Cameroon.

4.2 Phenological profiles of the vegetation classes

Vegetation types can be characterized by their temporal EVI profile. The vegetation types have a different phenological pattern, corresponding to the foliage cycle as depicted by the vegetation index and characterized by a vegetation season

Table 3. Area estimates (in hectares) and proportion (%) of the vegetation types for 8 countries as derived from the Congo Basin vegetation types map (in an equal area projection).

Class	CAMEROON		CONGO		CAR		DRC		GABON		EQ. GUINEA		BURUNDI		RWANDA		Total Congo Basin	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Dense moist forest	18 660 000	40	17 140 000	49.8	6 981 000*	11.3	101 800 000	43.7	22 280 000	84.6	2 097 000	75.9	8792	0.3	176	0.01	169 000 000	41.2
Submontane forest	195 800	0.4	0	0	7557	0.01	3 274 000	1.4	0	0	24 400	0.9	36 070	1.3	39 120	1.6	3 577 000	0.9
Mountain forest	28 450	0.1	9	0	0	0	929 200	0.4	46	0	6 684	0.2	58 110	2.2	183 400	7.3	1 206 000	0.3
Edaphic forest	0	0	4 157 000	12.1	223	0	8 506 000	3.7	15 800	0.1	0	0	0	0	0	0	12 680 000	3.1
Mangrove	236 500	0.5	11 860	0.03	0	0	37	0	164 400	0.6	27 550	1	0	0	0	0	440 400	0.1
Total dense forests	19 120 000	41	21 310 000	62	7780	11	114 500 000	49	22 460 000	85	2 156 000	78	103 000	4	222 700	9	186 900 000	46
Forest/savanna mosaic	2 546 000	5.5	516 200	1.5	11 190 000	18	6 956 000	3	50 900	0.2	9	0	70 530	2.6	54 820	2.2	21 380 000	5.2
Rural complex (forest domain)	3 929 000	8.4	3 671 000	10.7	717 100	1.2	21 440 000	9.2	1 390 000	5.3	512 800	18.6	300 200	11.2	308 900	12.3	32 260 000	7.9
Closed to Open Deciduous Woodland	1 300 000	2.8	296 500	0.9	3 426 000	5.5	23 920 000	10.3	31 130	0.1	306	0.01	35 390	1.3	4373	0.2	29 010 000	7.1
Savanna woodland/ Tree savanna	11 950 000	25.6	2 695 000	7.8	34 470 000	55.5	37 070 000	15.9	749 200	2.9	5292	0.19	297 300	11.1	355 500	14.1	87 590 000	21.4
Shrubland	2 610 000	5.6	2 169 000	6.3	4 023 653	6.5	6 727 000	2.9	545 500	2.1	1328	0.05	224 900	8.4	109 000	4.3	16 410 000	4
Grassland	178 000	0.4	1 193 000	3.5	62 277	0.1	4 405 000	1.9	335 700	1.3	186	0.01	203 900	7.6	153 300	6.1	6 531 000	1.6
Aquatic grassland	20 230	0.04	327 200	1	99 079	0.2	74 200	0.03	19 090	0.1	1077	0.04	0	0	0	0	540 900	0.1
Swamp grassland	148 000	0.3	0	0	0	0	700 900	0.3	0	0	0	0	0	0	0	0	848 900	0.2
Sparse vegetation	0	0	56	0	0	0	2191	0	0	0	0	0	0	0	0	0	2247	0
Mosaic cultivated areas/ vegetation (herbaceous or shrubs)	3 678 000	7.9	1 797 000	5.2	970 476	1.6	12 950 000	5.6	297 600	1.1	1198	0.04	1 256 000	46.7	1 161 000	46.1	22 110 000	5.4
Agriculture	766 700	1.6	60 180	0.2	8523	0.01	0	0	19 780	0.1	167	0.01	0	0	0	0	855 400	0.2
Irrigated agriculture	61 270	0.1	9	0	26 831	0.04	102	0	0	0	0	0	0	0	0	0	88 210	0.02
Bare areas	0	0	0	0	0	0	42 210	0.02	0	0	0	0	0	0	325	0.01	42 530	0.01
Artificial surfaces and associated areas	38 790	0.1	2952	0.01	7288	0.01	42 430	0.02	18 530	0.1	622	0.02	0	0	28	0	110 600	0.03
Waterbodies	281 400	0.6	362 200	1.1	72 960	0.12	4 032 000	1.7	412 700	1.6	83 130	3	200 800	7.5	148 600	5.9	5 594 000	1.4

* For RCA, 3 994 399 ha of the dense moist forest belongs to the Congo-Guinean domain as defined by Boulvert (1986) the rest belonging mainly to the edaphic domain.

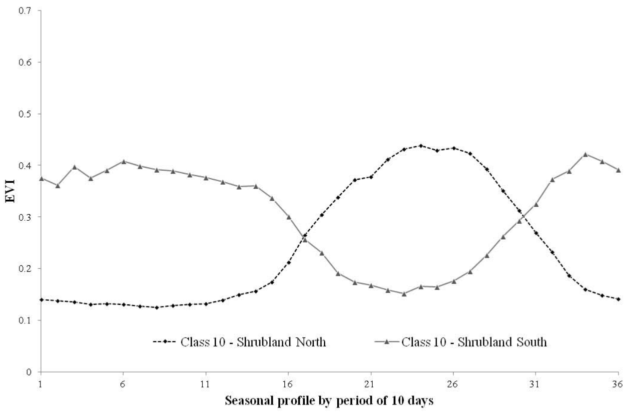

Fig. 4. January to December EVI temporal profile for class 10 – shrubland in the North and the South. This illustrates the inversion of seasonality between the North and the South.

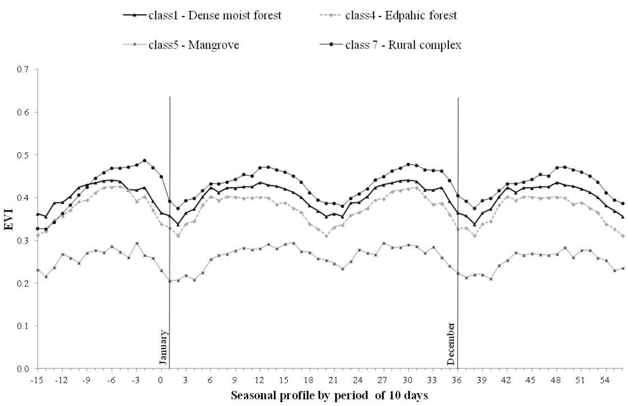

Fig. 5. EVI Seasonal profile by period of 10 days (January to December between the vertical lines) for classes (1, 4, 5 and 7) situated in the central forest zone.

length, a maximum and minimum value. The inversion of seasonality across the Equator is clearly illustrated by very similar but inverse temporal profiles for class 10 – shrubland in Fig. 4. This is observed for all vegetation classes showing a seasonal signal.

Dense forests (dense moist, submontane, mountain, edaphic forests and mangrove) present similar profiles of EVI that show low seasonal variation (less than 0.1 amplitude). Mangrove presents a profile with lower EVI values. The rural complex presents a seasonal profile with a similar pattern but with higher values of EVI. The presence of pioneer species, strictly light-demanding, shows indeed a rapid height growth in the clearings and permanent high photosynthetic activity (high near-infrared reflectance) (Mayaux et al., 1999). In Fig. 5, smooth profiles obtained by the spatial aggregation over the whole forest type and years present two decreases in EVI values, one in July and a second in December. In order to better visualize the cycle over these reference profiles, part of the year is reproduced at the beginning and at the end of the year (delimited by vertical lines). These EVI variations can be related to the variations of rainfall currently observed for an equatorial bimodal rainfall regime and the cloudiness associated. Indeed in this kind of regime, found in the immediate neighbourhood of the Equator between about 4° N and 3°5′ S (with the exception of the coast of Gabon), two rainfall maxima take place: one in April or May and the second in October or November, while minima take place one in January or February and the other in June or July (Mpounza and Samba-Kimbata, 1990). Wide clearings are associated with heavy rainfall, while July and August are known as being the most nebulous months of the year. It would be of great interest to analyse these patterns highlighted by recent studies in the Amazon Basin. These have shown that the photosynthetic behaviour of the tropical forest varies during the season. Studies suggest that the canopy of the Amazon rainforest plants flush their new leaves to maximize photosynthetic assimilation when the cloud cover is minimal and the photoperiod is maximal, that is, during the dry season (Huete et al., 2006; Pennec et al., 2011; Xiao et al., 2006). In the same way, EVI seems here to reach its highest values when the cloudiness is minimal. However, in Central Africa the cloud cover seems less important during the wet and not the dry season. Figures 6 and 7 show the difference in seasonality between the dense moist forest and the savanna classes for the northern and southern zones. The temporal profiles are directly linked with the composition of the vegetation layers. Formations with a dominant grass layer, such as grassland, have EVI values close to the bare soil signature in the dry season, while formations where a shrub or a tree layer remains have higher EVI values during the dry season. The growing season starts earlier for vegetation type with an important tree layer (deciduous woodland) than with a continuous shrub layer with sparse trees (Mayaux et al., 2004; Vancutsem et al., 2009).

This is clearly illustrated in the North. A gradient is observed between the forest and savanna types according to the tree cover. Minimum EVI values are found in December–January, concurring with the minimum of rainfall. A maximum of EVI is found for each vegetation type in July, the period with the maximum rainfall. Closed to open deciduous woodland EVI varies between 0.25 and 0.45. The length of the season of vegetation is 10 months. Savanna woodland/tree savanna, which presents a more open tree cover, has lower values of EVI, varying between 0.15 and 0.41. The length of the season of vegetation is 9 months. Then surprisingly, grassland has a longer season of vegetation than shrubland, as grassland growing season starts earlier. This is explained by the spatial location of shrubland, much farther north than grassland and therefore undergoing a longer dry season of 7 to 8 months.

In the South, the difference between the savannas types is less evident. Minimum values are found in July, the period of smallest rainfall, and maximum EVI during the wet season

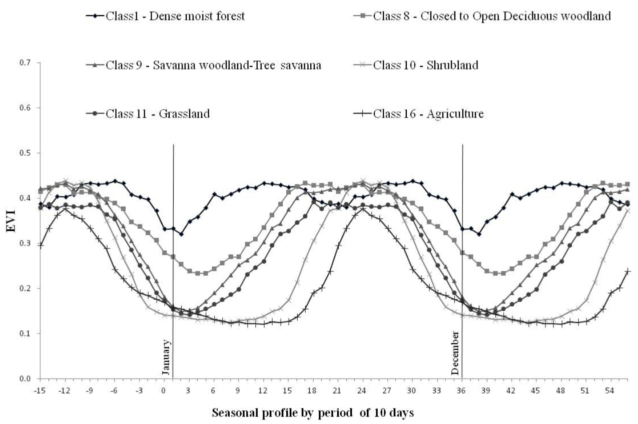

Fig. 6. EVI Seasonal profile by period of 10 days (January to December between the vertical lines) for classes (1, 8, 9, 10 11 and 16) situated in the northern zone.

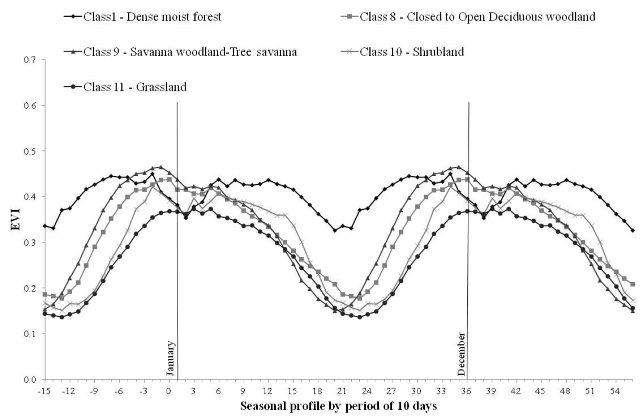

Fig. 7. EVI Seasonal profile by period of 10 days (January to December between the vertical lines) for classes (1, 8, 9, 10 11) situated in the southern zone.

(November to April). Closed to open deciduous woodland and savanna woodland/tree savanna are very similar in their phenological behaviour. A major part of closed to open deciduous woodland is present as Miombo in the South of DRC, where the length of the dry season is about 7 to 8 months whether savanna woodland/tree savanna is undergoing a shorter dry season more north. Grassland is, in the south, as expected, the formation with the lower values of EVI in June–July and the shorter season of vegetation.

In both the North and South, the following behaviour is observed. There is a maximum value of EVI (0.40–0.45) reached by every temporal profile except for the class 12 – aquatic grassland and class 5 – mangrove where water is present throughout the whole year. This maximum probably represents a maximum photosynthetic capacity reached when the conditions are favourable. As already mentioned, Class 7 – rural complex reaches a value a little higher than all the other profiles.

4.3 Confidence-building and validation

Large regional maps pose problems of validation. Indeed, the scale and the extent of such documents preclude any classical ground truthing at an acceptable cost (Mayaux et al., 2004). This gives extra value to the points validated with experts in Kinshasa allowing evaluating the map with another method than intercomparison with previous maps.

4.3.1 Visual comparison

Visual comparison confirms that the spatial resolution of MERIS (300 m) (Fig. 8a and c) better discriminates details in forest/savanna zones or rural complex than GLC 2000 (Fig. 8b), and is comparable to what is mapped in the FACET atlas with a Landsat resolution (Fig. 8d). In the forest domain near the Atlantic (Fig. 9), where the 8 yr of SPOT VEGETATION data were used, the spatial resolution is lower but the consistency of the signal improves the discrimination of the spatial extent of rural complex, whereas GlobCover presents patches that reflect the noise of the data instead of the land cover state, and GLC 2000 shows some inconsistencies. In dense moist forest of DRC, the deforestation patterns (Fig. 10) are similar to the patterns observed on the DRC map of Vancutsem et al. (2009), for example around Kisangani. The Miombo is slightly better identified in the DRC map, while our map presents some confusion between "deciduous woodland" and "savanna woodland". The deforestation spots identified in the forest domain near the Atlantic coast are consistent and confirmed by the presence of road networks (Fig. 11). The stratification in four zones used in the methodology do not create sharp boundaries between land cover classes due to the different strata. Figure 12 illustrates this for the boundary between the central eastern zone (CE) and the south (S) zone.

4.3.2 Validation by experts

According to the recommendations of the Committee on Earth Observation Satellites (CEOS), the user's accuracy values are weighted by the proportions of area of the various land cover classes. The weighting factor corresponding to the proportion of area of the given class is derived from the map, projected in an equal area projection. This allows for the correction of a possible overrepresentation in the sampling set of classes covering only small surfaces, and an underrepresentation of classes that cover large surfaces (Bicheron et al., 2008). It is important to mention that the confusion matrix contains several classes for which the producer and user's accuracy are null. However, these land cover classes are classes that are representing a very small spatial extent compared to the total area. As the accuracy is weighted by the proportions of area of the various land cover classes, this should not significantly affect the overall accuracy of the map. The weighted numbers are presented in Table 5.

Table 4. Confusion matrix that consider the product and the validation dataset. Italic cells are cells that show agreement between classification and validation (1). Bold cells show cells that have been considered to show agreement (2).

map derived from image classification

reference data / "ground truth" data	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	total	Producer accuracy (1)	Producer accuracv (2)
1	*52*			1											1						54	1.00	96.3
2		*1*																			1	1.00	
3			*0*																		0		
4	1			*0*																	1	0.0	0.0
5					*4*																4	1.0	100.0
6						*9*															9	1.0	100.0
7							*4*														4	1.0	100.0
8	1							*11*	5												17	0.7	64.7
9									*16*	**3**											19	0.8	84.2
10							1	1	**12**	*5*	1				3						23	0.2	21.7
11									5		*1*										6	0.2	16.7
12	1											*0*									1	0.0	0.0
13					1								*0*								1	0.0	0.0
14									1					*0*							1	0.0	0.0
15															*2*						2		
16									2	1						*0*					3	0.0	
17																	*0*				0		
18																		*0*			0		
19																			*0*		0		
20	1				1				1											*2*	5	0.2	20.0
total	56	1	0	1	6	9	5	12	42	9	2				6					2	151		
User accuracy (1)	92.7	100.0		0.0	66.7	100.0	80.0	91.7	38.1	55.6	50.0				33.3					100			
User accuracy (2)	92.7	100.0		0.0	66.7	100.0	80.0	91.7	66.7	88.9	50.0				33.3					100			

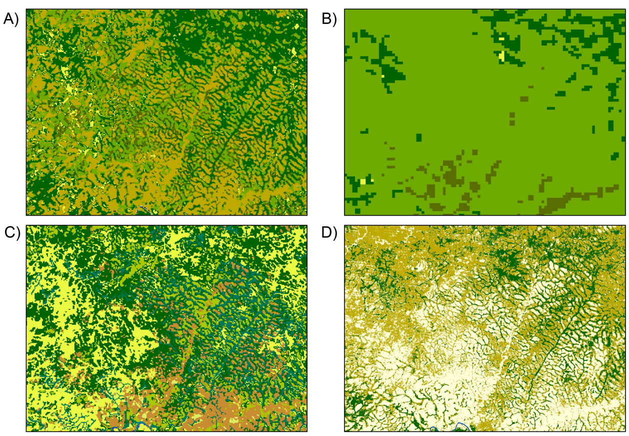

Fig. 8. Visual comparison of the new Congo Basin vegetation map with earlier maps in a forest/savanna zone in Haut-Uele (Zigbi). **(A)** Congo Basin Vegetation types map. **(B)** GLC 2000 (1 km resolution). **(C)** GlobCover (300 m resolution). **(D)** DRC Facet Atlas (OSFAC, 2010).

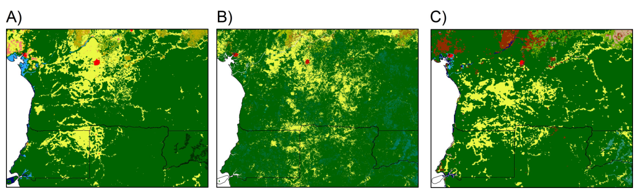

Fig. 9. Example of the improved discrimination of vegetation classes using the 8-yr SPOT VGT time series analysis depicting networks of deforested areas usually not detected due to the persistent cloud coverage. **(A)** Congo Basin Vegetation types map **(B)** GlobCover (300 m resolution) **(C)** GLC 2000 (1 km resolution).

The global accuracy weighted by area reached 71.5 % and appears quite satisfactory for Central Africa. The result of the validation is greatly improved if classes 9 and 10 are aggregated for the validation. The overall accuracy then reaches 78.9 %. These savanna classes, even if thematically different, present similarities in their reflectance and are difficult to discriminate. Moreover, sharp limits are not easy to find between savanna classes. Looking at the user accuracy for each class separately, dense moist forest is the class that performs best. This is not surprising as this class is homogeneous, unambiguous and recognizable. High values are also reached for deciduous forests, rural complex and mangrove. Classes 9 and 10 also reach high values of user accuracy when considered as a similar class for validation. The Cohen's kappa coefficient indicates a result significantly better than random classification with a value of 0.64 for the confusion matrix and a value of 0.76 when classes 9 and 10 are aggregated (Table 6).

4.4 Choice of a 10 or 30 % tree cover threshold in the forest definition

The spatial extent of forest according to two tree cover thresholds (10 % or 30 %) for forest definition in Central Africa are illustrated in Fig. 13 and reported in Table 7.

Table 5. Accuracy of the Congo Basin vegetation types map based on surface area figures per class and the user's accuracy.

		Overall accuracy
1	151 points	71.5 %
2	151 points (assembling classes 9–10)	78.9 %

Table 6. Cohen's kappa coefficient for the Congo Basin vegetation types map.

		kappa coefficient
1	151 points	0.64
2	151 points (assembling classes 9–10)	0.76

Table 7. Forest areas for 10 % or 30 % tree crown cover.

	Area (ha)
Total Forest 10 %	330 600 000 (81 %)
Total Forest 30 %	226 610 000 (55 %)

A) B)

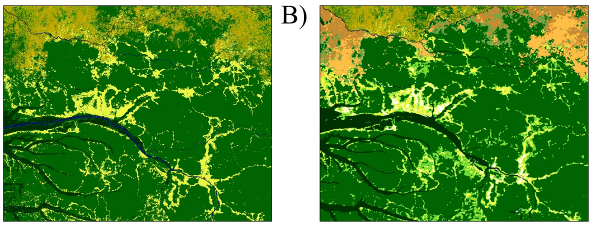

Fig. 10. Rural complex patches in forest of DRC **(A)** Congo Basin Vegetation types map, **(B)** Vegetation types map of DRC (Vancutsem et al., 2009).

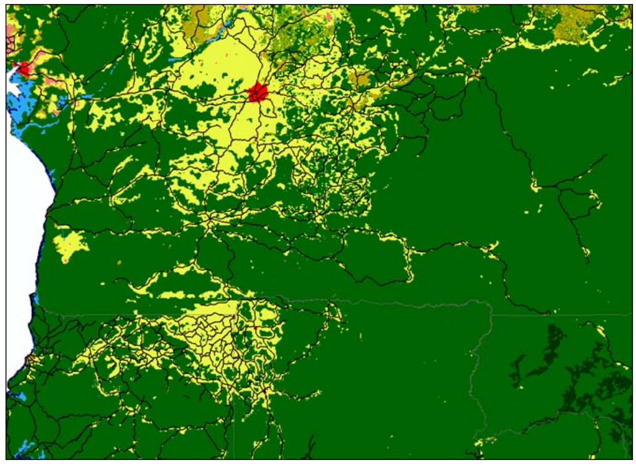

Fig. 11. Road network (OFAC database) is consistent with the spatial distribution of the rural complex class near the Atlantic coast.

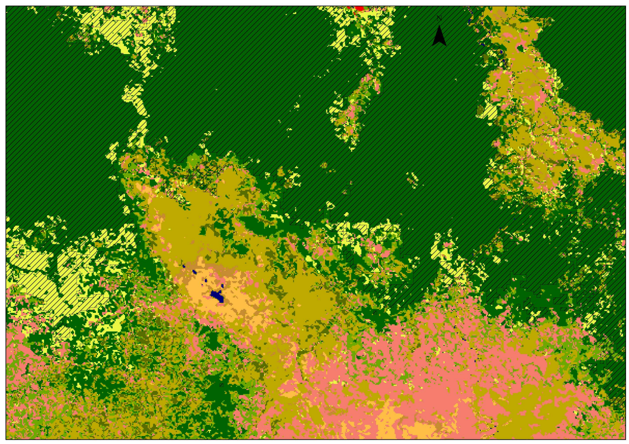

Fig. 12. Illustration of the smooth transition between the seasonal zones. The hatched area is the Eastern Centre (CE) zone. The boundary of this zone does not cause a sharp transition in the vegetation map.

Six vegetation types are considered as forest for both threshold: Class 1 – dense moist forest, Class 2 – submontane forest, Class 3 – mountain forest, Class 4 – edaphic forest, Class 5 – mangrove, Class 8 – closed to open deciduous Woodland. Class 6 – forest/savanna mosaic contains vegetation formations including forest and must therefore be considered in the forest classes, or at least a part of the area of this class. Half of the class area here is included in the total.

Class 9 – savanna woodland/tree savanna and Class 10 – shrubland classes were considered as forest classes for the 10 % threshold for the canopy cover. When the threshold is set to 10 %, 3 306 100 km^2 are therefore considered as forests, representing the majority (81 %) of the region. For the 30 % threshold, only classes 1, 2, 3, 4, 5, 8 and half of 6 are considered as forests. With 30 %, 2 266 000 km^2 are considered as forest, representing 55 % of the territory. Figure 13 suggests that a threshold of 30 % results in a more realistic forest cover representation in Central Africa than the 10 % threshold.

4.5 Carbon stocks in the Congo Basin forests

The C stocks computed with the Congo Basin forest types map are indicated in the Table 8 for forest and savanna vegetation types. There is no estimation for mangroves, as the surface area of this forest type is quite small. No errors estimations were available for the C estimations used in the "stratifying and multiplying" methodology. The resulting values are therefore delivered without error bars. However these results must be taken cautiously due to the scarcity of carbon stock data.

A total C stock of the Basin of 49 360 million metric tons is obtained. The most important stock is contained in the dense moist forest class (65.7 %). Figure 14 presents the spatial distribution of C in the forest types. It highlights the role of dense moist forest as it presents a high value of C stock

Table 8. Carbon stock in the Congo Basin calculated with the C stocks estimation of Nasi et al. (2009) and the Congo Basin vegetation types map.

Class	Total C (million metric tons)	% of the stock
Dense moist forest	32 450	65.7
Submontane forest	436	0.9
Mountain forest	147	0.3
Edaphic forest	1813	3.7
Forest/savanna mosaic	1240	2.5
Rural complex (forest area)	3452	7
Closed to Open Deciduous Woodland	2669	5.4
Savanna woodland/Tree savanna	5781	11.7
Shrubland and shrubland with sparse trees	1083	2.2
Grassland	294	0.6
Total Congo Basin	49 360	100
30 % Tree cover REDD threshold	42 200	85

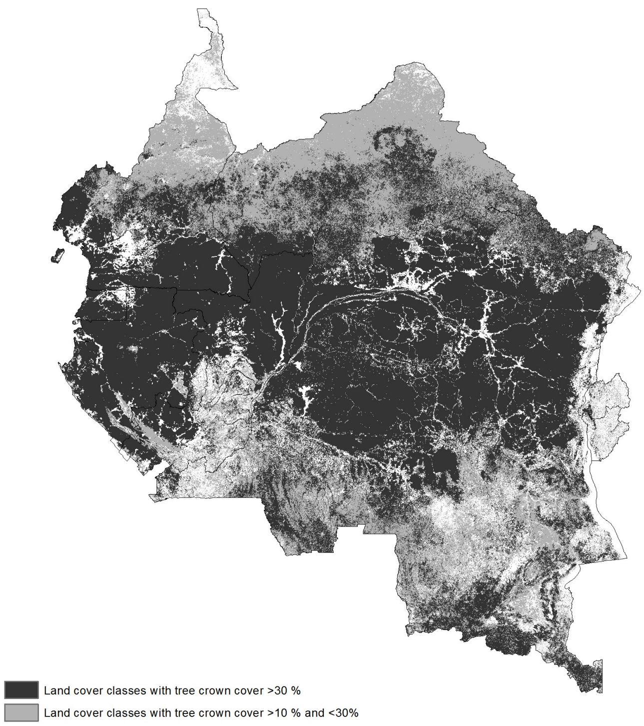

Fig. 13. Spatial representation of the area of the region considered as forest according to the 10 % (light and dark grey) or 30 % (dark gray) tree crown cover threshold forest definition in the framework of the REDD. Land cover classes with a tree crown cover > 30 % are classes 1, 2, 3, 4, 5, 6 and 8. Land cover classes with a tree crown cover > 10 % are classes 1, 2, 3, 4, 5, 6, 8, 9 and 10.

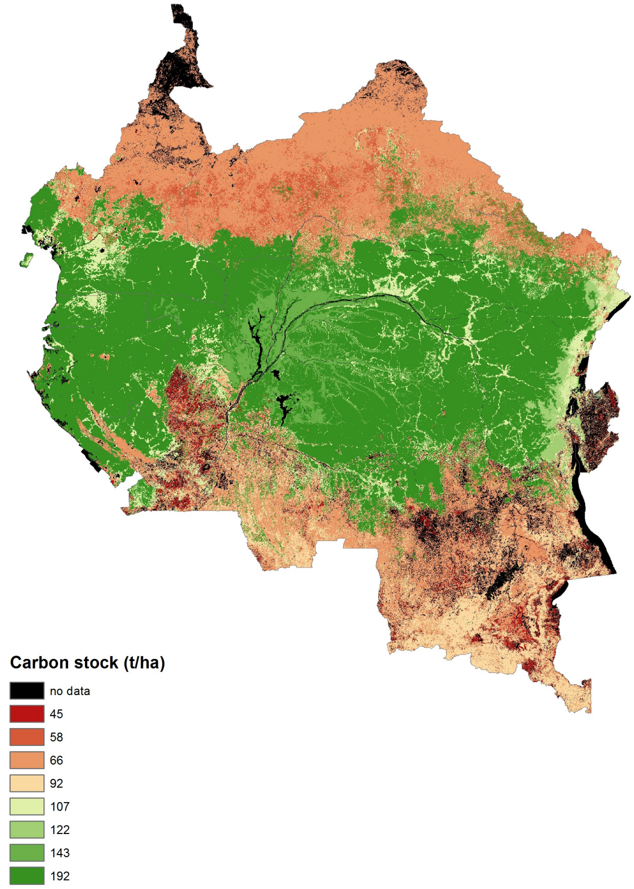

Fig. 14. Spatial representation of the carbon stock in t ha^{-1} by vegetation types; the region is stratified with the Congo basin vegetation types map and the C stocks values are coming from Nasi et al. (2009).

and an important spatial extent (41.2 %). On the contrary, the savanna woodland/tree savanna covers 21.4 % of the spatial extent of the Basin but only represents 11.7 % of the Carbon stock, underlying the importance of an accurate discrimination of vegetation types.

Some limitations are inherent to this approach, such as that a same vegetation type should actually present variability for the biomass. Saatchi et al. (2011) and Baccini et al. (2008) have recently released maps presenting spatial variability. The C stocks computed here were compared with the results of these two studies and found consistent. The map of Saatchi et al. (2011) was based on in situ inventory plots, satellite, lidar imagery and allometric equations to determine the C contained in world tropical forests. Table 9 illustrates the C stock estimated by Saatchi et al. (2011) for a canopy cover of 30 % for the countries that contain the highest pool of Carbon in the Congo Basin. The same estimation is presented for the Congo Basin vegetation types map by aggregating for the countries the C stock of the vegetation types classes that present a 30 % canopy cover according to the

Table 9. **(A)** Estimates of forest carbon stocks in the 4 largest national pools in Central Africa (Saatchi, 2011) and **(B)** Estimates of forest carbon stocks from Congo Basin vegetation types map for a 30 % canopy cover threshold.

	(A) Saatchi et al. (2011)			**(B)** Congo Basin vegetation types map		
Country	Area (Mha)	Total C (Gt C)	C density ($Mg\,C\,ha^{-1}$)	Area (Mha)	Total C (Gt C)	C density ($Mg\,C\,ha^{-1}$)
Democratic Republic of Congo	164	22	134	145.4	23.9	164.3
Cameroon	27	4	151	22.7	3.9	170.6
Republic of Congo	23	4	162	22.1	3.9	178.3
Gabon	21	4	165	22.38	4.29	191.52

previous section. Forest areas vary between the two studies but the total C in Gt is very similar for DRC (23.9 Gt for the Congo basin vegetation types map versus 22 Gt for Saatchi et al. (2011), Cameroon (3.9 vs. 4 Gt), Republic of Congo (3.9 versus 4 Gt) and Gabon (4.3 vs. 4 Gt). The map of Baccini et al. (2008) delivered aboveground biomass estimation for Africa. Estimating C stock or biomass is equivalent. C stock in woody plants (Cw) is linked to the biomass (Bw) expressed in dry matter by unit of area by a simple relation: $Cw = k$ Bw with $k \approx 0.47$ (Nasi et al., 2009). A visual comparison of the spatial structure of the biomass versus the spatial structure of the Carbon stocks was made. The limits of the dense forest domain in Baccini et al. (2008) are similar to the ones of the Congo Basin vegetation types map. The highest values of biomass are also reached in this dense forest domain. However, the West Atlantic coast seems affected by the cloud cover in Baccini et al. (2008), presenting low values of biomass in zones where dense moist forest is expected. In the non-forest area, the dry forest patches are identified in both maps with a higher biomass or carbon content than the vegetation around. For DRC, Baccini et al. (2008) obtained a value of 23 Gt C when accounting for above- and below-ground carbon, this is very close to the estimation of Table 8 of 23.9 Gt C.

The similarities with the two previous published maps gives confidence in the estimation made here even if the spatial variability of the biomass is not taken into account inside each specific land cover class.

5 Discussion

From the visual comparison it appears that, thanks to the 300 m spatial resolution of the MERIS data and by the choice of 8 yr of SPOT VGT data for mapping cloudy areas, the map is spatially consistent and that details such as forest gallery and deforestation patterns on the Atlantic coast are better identified than ever before. The accuracy of the map is supported by the validation result.

Dense tropical forests, including dense moist forest, edaphic forest, submontane and mountain forest occupy the major area of the Congo Basin region and are important among other functions in term of C stock, habitat and biodiversity. The comparison between the areas of dense tropical forest derived from the Congo Basin vegetation types map shows good matching with GLC 2000 and GlobCover 2009 (Table 10). These dense forests classes also present high accuracy in the validation.

The discrimination of rural complex pattern in the Atlantic coast has a repercussion on the statistics of the dense moist forest and rural complex classes for Cameroon, Equatorial Guinea and Gabon (Table 11). For Cameroon, nearly half of less rural complex is detected in GLC 2000 than in the Congo Basin vegetation types map. More rural complex is detected by GlobCover in Cameroon and Gabon but a visual comparison suggests that this is not representative of reality (no spatial pattern characteristic of the rural complex which is often following roads networks).

The MERIS dataset is the same as the one used in the GlobCover processing chain but the results are better for this specific region than from a global automatic map thanks to (i) a seasonal stratification of Central Africa that follows more precisely the dense moist forest limits, (ii) the use of SPOT VGT to overcome the clouds limitations, (iii) the manual interaction and use of temporal information in the labeling process, (iv) the consultation of experts. The 300 m is a good spatial resolution to map Central African vegetation types. This spatial resolution allows a better discrimination between forest and savanna. The fragmentation of the habitats can also be better studied. There is no guarantee of a better discrimination of vegetation types with higher resolution images as these kinds of images often present problems of spatial consistency.

According to the validation, vegetation classes that are characterized by Nasi et al. (2009) with the highest C stocks in ton per hectares are the classes that present very good accuracy. In terms of Carbon stocks, in addition to the dense forests, the dry forests as well as the mosaic forest/savanna

Table 10. Dense tropical forest areas from the vegetation types map, GLC 2000 and GlobCover 2009.

	Area (10^6 ha)	%
Congo Basin vegetation types map (dense moist forest, submontane forest, mountain forest, edaphic forest)	186.5	45.4
GLC 2000 (Closed evergreen lowland forest, submontane forest, montane forest, swamp forest)	182.7	44.6
GlobCover 2009 (Closed to open broad-leaved evergreen or semi-deciduous forest, Closed to open broad-leaved forest regularly flooded, fresh water)	193.1	47.1

Table 11. Dense moist forest and rural complex areas from the vegetation types map, GLC 2000 and GlobCover 2009 in countries near the Atlantic coast.

	Cameroon (10^6 ha)	Equatorial Guinea (10^6 ha)	Gabon (10^6 ha)
Dense moist forest			
vegetation types map	18.66	2. 10	22. 28
GLC 2000	18.14	2.03	22.69
GlobCover 2009	19.73	2.03	20.42
Rural complex			
vegetation types map	3 .93	5.13	1 .39
GLC 2000	2.15	4.25	1.39
GlobCover 2009	4.70	3.02	2.32

are considered as forest, representing a total of 85 % of the C stock of the Basin.

The stratifying and multiplying methodology used here is a quite simplified method to estimate carbon stocks, (not accounting for different forest conditions that could lead to lower carbon stocks, such as logged, burnt or secondary forest; Gibbs et al., 2007), but it presents the advantages to be based on a validated map at a fine spatial resolution. The comparison with other C (Saatchi et al., 2011) and biomass (Baccini et al., 2008) maps in the region showed consistency with these two products. The vegetation types map presents the advantages of having an improved consistency on the Atlantic coast. While waiting for better estimations with methods using radar or LIDAR data, the estimation made here may therefore provide materials in the context of the REDD and other climatic negotiations.

Concerning the REDD forest definition, a first investigation suggests that a threshold of 30 % results in a more realistic forest cover representation in Central Africa than the 10 % threshold. The choice of the threshold is found crucial as the forest area varies largely from one threshold to another and should be further investigated. While bringing relevant information to support the countries' decisions of a forest definition in the context of the REDD process, these estimations do not present a lot of flexibility. A possible improvement would be to present scenario in addition to the 10 % and the 30 %, probably with the help of higher resolution data.

Central Africa is a difficult and large region to map, due to the very important cloud cover and the little field information available. Other types of data, typically SAR data, could be used to map the edaphic forests. Some land cover classes show room for improvement, such as the savanna woodland/tree savanna class that could be split in two categories, savanna woodland and tree savanna. This could be achieved with an increased use of the temporal information of the vegetation indices in these areas, by directly using it in classification and not only for labelling.

6 Conclusion and perspectives

A new vegetation types map of Central Africa with times series of 300 m and 1 km has been completed. The map and digital data are freely available for non-commercial uses from http://www.uclouvain.be/eli-maps or via the OFAC regional office (http://www.observatoire-comifac.net/).

By taking into account the seasonal and cloud coverage specificity of the region for the choice of the period of the compositing or the sensor used, an improvement from global automatic maps is observed. The full advantages of the 300 m spatial resolution of MERIS and the temporal archive of SPOT VGT have been used. The manual editing is time-consuming but makes a difference compared to an automatic land cover mapping method. Although this vegetation map wanted to be as exhaustive as possible, there is still a limitation due to the extractible information from optical remote sensing. SAR data could be used to map the edaphic forests. Use of time series in the classification step could also increase the discrimination between savanna classes. The perspective of a longer dataset of MERIS data will allow in the future achieving the mapping of the Atlantic coast at a 300 m spatial resolution.

A validation of the product provides a satisfactory overall accuracy of 71.5 % and even 78.9 % when the two savanna classes are aggregated. This product not only provides a precise mapping of vegetation types in Central Africa, but could moreover be used to compute statistics of the vegetation types, useful for the monitoring of these ecosystems. Forest definition for different tree cover thresholds was illustrated based on the vegetation types map, showing that a 30 % threshold is more realistic in the context of Central Africa.

The combination of the map with C estimates by land cover classes allows us to compute a Carbon stocks estimation of 49 390 million metrics tons for the Congo Basin. This estimation is found consistent with recent literature.

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