New insights in tropical forest diversity mapping in Central Africa using low resolution remote sensing

Gond[1] V., Betbeder[1,2], J., Fayolle[1,3], A., Viennois[4], G., Cornu[1] G., Réjou-Méchain[1,4], M., Baghdadi[5] N., Benedet[1], F., Doumenge[1] C., Gourlet-Fleury[1], S.

1 - CIRAD, BSEF, 34398 Montpellier, France. valery.gond@cirad.fr
2 – UMR CNRS 6554 LETG Rennes COSTEL, Université Haute Bretagne, Rennes, France
3 - Gembloux Agro-Bio Tech, Université de Liège, 5030 Gembloux, Belgique
4 – CNRS/IRD UMR AMAP, 34398 Montpellier, France
5 – IRSTEA UMR TETIS, 34093 Montpellier, France

Session 5: Using geospatial technologies to monitor land use, improve delivery of land services, and improve land governance.

Central African forests, when mapped at regional scale using remote sensing, are generally represented as one great homogeneous 'forest' land cover class. However, studies based on ecological and detailed forest inventories have identified spatial patterns of species diversity, functional traits and biomass, outlining the existence of several forest types. These forest types with contrasted structure and floristic composition have been described locally, but have been little or not mapped. A detailed vegetation map, representing the diversity of forest ecosystems at the scale of Central Africa is needed in order to plan and improve the management and conservation of these systems. Such a map has recently been produced, using a multi-temporal satellite approach, and validated with a multi-disciplinary scientific team of foresters and botanists with a strong field expertise.

The study covers the entire forest area of the Congo basin (3.7 million of km²). Photosynthetic activity indices from MODIS (2000 to 2012), Radar data (band L) from PALSAR (from 2007 to 2010) and LiDAR data from GLAS (2003 to 2010) have been used to produce the map.

A temporal synthesis was built in order to obtain seasonal profiles of photosynthetic activity. The different forest classes were identified using unsupervised classifications and visual interpretation. Radar and Lidar data were used for the interpretation of forest classes in swamp areas and forest inventories were used for the interpretation of *terra firme* forests. Nineteen forest companies had conducted inventories on trees with a diameter ≥ 30 cm (at breast height-DBH) on 0.5 ha plots that were all geo-

referenced. In total, 37 898 plots have been measured, covering about 6 million hectares. Information on basal area and the degree of deciduousness of the various forest types were used in order to characterise these forests in terms of structure and functioning.

The *terra firme* forests showed significant spatial variations in terms of deciduousness and structure on both sides of a latitudinal gradient marking the periodical passage of the climatic equator above the Congo forests. In the swamp areas, the spatial organisation of forests was found to be also influenced by the flood period. These results could help quantifying the stocks of biomass according to the identification of different forest types; each with contrasting photosynthetic activities and dynamics.

This study highlights the interest of combining field inventories with multi-sensors satellite measurements in order to characterise forest structures and phenology in undocumented areas (like wetlands), and the importance to work with a team of vegetation specialists having complementary skills. In this poorly documented region of the world (little weather stations, forest monitoring plots or flux towers), forest inventories represent a unique opportunity to document and validate satellite data over large areas.

Key Words: remote sensing, land use mapping, tropical forests, Central Africa, forest inventories

INTRODUCTION

At a time when tropical forests are undergoing profound and rapid changes, characterizing their spatial organisation is of major importance for analysing land-use changes and promoting sustainable management of forest resources (Laurance et al., 2001). In the next decades, African forests are predicted to experience profound climatic changes with increased temperature, alteration of rainfall patterns and possibly longer dry seasons (Zelazowski et al., 2011). In this context, there is an urgent need to have a better understanding of how current climatic conditions influence the vegetation to be able to predict the response to the ongoing climate change. This understanding requires a better knowledge of the spatial distribution of forest types. At the scale of Central Africa, maps of forest types issue from remote sensing analysis have been based on broad environmental classes rather than vegetation characteristics. Central African forest types are usually represented on maps as a heterogeneous continuum. On one hand, regional maps describe the Central African forests within a large broad-leaved evergreen forest distinguishing terra-firme and swamp forest types (Verheggen et al., 2012; Mayaux et al., 2004). On the other hand, local studies and field expertise evidence strong spatial heterogeneity in terms of forest composition and structure (Rejou-Méchain et al., 2008). These maps are neither detailed nor homogeneous enough to help decision-making at Central African management scale. National vegetation maps are useful locally but they not have homogeneous legends and some are missing. A more detailed map evidencing Central African forest types has to be proposed to provide key elements to support forest conservation and management policies in the context of climatic changes. Improvements in remote sensing sensors and quality of the historical archive offer a good opportunity to map and describe Central African forest types. The aim of this study is to present detailed maps of terra-firme forests and swamp forests characterizing land use and land cover of the region, issued from satellite images processing and analysis. At this time we are in a preliminary stage of the study. Images processing and classification were done but not yet the validation analysis using forest logging inventories and national vegetation maps.

MATERIAL AND METHOD

The study area covers the forested regions of Cameroon, Central African Republic, Equatorial Guinea, Gabon, Republic of Congo, and Democratic Republic of Congo within 8°N – 8°S latitude and 8° - 32° E longitude. The climate is tropical humid with a mean annual rainfall of 1400-1800mm. The rainfall seasonality is driven by the inter-tropical convergence zone (ITCZ) that crosses the study area twice a year. Altitude is from the Atlantic coast to the forest altitudinal limit in the eastern rift mountains (up to 1500m). The vegetation is defined such as the Guineo-Congolian forests. The density of the human population is highly heterogeneous, particularly dense around large cities and along the main transportation pathways but very low elsewhere (less than 10 inhabitants per km²; http://www.afripop.org).

Remote sensing data

We used the enhanced vegetation index (EVI) dataset from the National Aeronautics and Space Administration (NASA) Terra-MODIS (Moderate Resolution Imaging Spectro-radiometer) sensor, which is recognized for a good set of absolute calibration; radiometric, atmospheric and geometric corrections; narrow spectral bands to avoid atmospheric absorption windows; a wide field of view; a broad spectral range; a high temporal resolution; and a high spatial resolution (250m). The later two are well suited to cover our huge study area (dataset available at http://reverb.echo.nasa.gov). The EVI is directly related to photosynthetic activity (Myneni et al., 2007). To map terra-firme forest types, EVI was extracted from the 16-day L3 Global 250m product (MOD13Q1 c5) from January 2000 to December 2012 (13 years). During images processing, even when composite images are used to reduce atmospheric and angular artefacts, pixels contaminated by clouds can persist and lead to strong misinterpretations. We used the quality assessment (QA) from the internal MODIS data to control and eliminate low quality pixels (cloud, haze). To eliminate remnant cloud and artefacts in the EVI dataset we computed, for each 16-day period, the average value of the 14 satellite images available (or less depending of the previous QA tests). We thus obtained a mean EVI profile across a synthetic year (23 periods of 16-day images). We reconstructed a 13 year time-series mosaic and then performed a classification on the newly built EVI dataset.

In a previous study (Betbeder et al., 2014), to map swamp forest types, EVI was extracted from the 16-day L3 Global 500m product (MOD13A1 c5) from January 2001 to December 2009 (Betbeder et al., 2014). For this specific swamp forest types the Geoscience Laser Altimeter System (GLAS, GLA01 and GLA14) dataset was obtained from 2003 to 2010. From this data, vegetation structure and topography were extracted.

The phase-array type L-band of the synthetic aperture radar (PALSAR) sensors on board advanced land observing satellite (ALOS) was used to analyse the process of inundation within the swamp forest area (Betbeder et al., 2014). Six images from 2007 to 2010 were obtained with a HH polarization and a spatial resolution of 100m.

Forest inventories and vegetation map

From a previous project (www.coforchange.fr), we got access to commercial forest inventories from 19 timber concessions over a specific area covering south-east Cameroon, south of the Central African Republic, and north of the Republic of Congo A total of 37 898 0.5ha plots were analysed in this area to validate a previous map (Gond et al., 2013). We used a map (Bwangoy et al., 2010) to perform a mask of the inundated landscape which benefited of specific processing to characterize swamp forest types (Betbeder et al., 2014). We built a second mask using the Landsat images compiled by Hansen et al. (2008), to identify forests with a tree cover >= sixty percent. As a result, we discarded north and south savannahs, mountain vegetation, anthropic areas and open water. We used country scale vegetation maps to validate the maps (Letouzey, 1985; Boulvert, 1986; Bégué, 1967).

Data analysis

To identify forest types we used an unsupervised ISODATA classification (iterative self-organizing data analysis techniques). The ISODATA classification is a K-mean algorithm which allows selecting clusters by splitting and merging the initial pixels datasets. The main advantage of this technique is the stabilization of the number of classes when the gravitational centre of the classes could not be split any more. After several tests we adopted a 10 class's classification obtained with 50 iterations. It was the better trade-off between a too small number of classes (not representative of the spatial diversity) and a too high number of classes (impossible to interpret). We used an unsupervised classification because of the lack of training data for the whole area. This classification was performed by using ENVI 4.3 software (Research Systems Inc.). A multi-disciplinary team of foresters and botanists with a strong field expertise in was gathered to interpret and validate the classification. The next step will be an objective validation on terra-firme using forest inventories from logging concessions like previously done (Gond et al., 2013) but extended to the entire Congo basin forests.

Within the swamp forest types, each class was documented with 200 GLAS footprint. The maximum height of each swamp forest type was determined by waveform analysis using the distance between the beginning of the signal and the centroid of the ground return.

A k-mean unsupervised classification was performed on the temporal series of PALSAR data to represent different periods of flooding.

RESULTS

We identified and mapped 10 terra-firme forest types in Central Africa based on EVI seasonal profiles (fig 1). Classes are spatially organised along a west-east and a north-south gradient highlighting an obvious oceanic influence, from bright colours (yellow, light-green and cyan) on the coastal region to dark colours in the hinterland (dark-green, purple and pink). Another pattern seems to be related with ITCZ influence, evidenced by a gradient from dark-purple in the north to dark-blue in the south. Northern classes (cyan, dark-green, dark-purple) are under northern hemisphere climatic influence. Southern classes (yellow, dark-blue, purple and pink) are under southern hemisphere climatic influence. Within these gradients, classes like dark-purple (north-west) and orange (east) are strongly related to human activities (Table 1). These two classes tend to be linear, or located on the forest edges. In Cameroon, the area around Yaoundé and Yokadouma is clearly impacted by agricultural activities and shows a degraded forest class associated with the dark-purple halo. The same phenomenon is visible in DR Congo in the region of Kisangani where the road network (masked by the Hansen et al., 2008 data) is surrounded by a degraded forest class in orange. Each class has a particular temporal profile of photosynthetic activity. This profile is a signature of forest functioning and of the influence of environmental drivers such as water and light availability. All profiles are bimodal in time corresponding to the two dry seasons (December-February and July-August) and the two rainy seasons (March-June and September-November). Table 1 specify classes under climatic influences (coastal, north and south regimes).

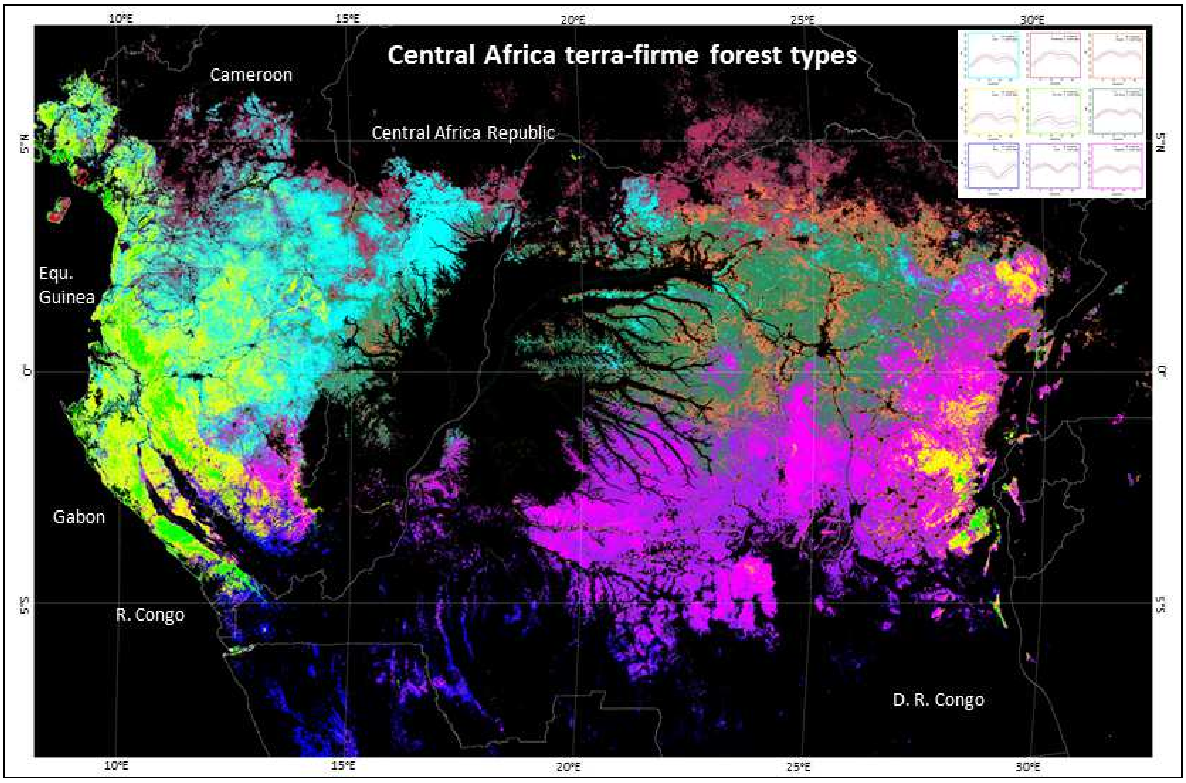

Fig. 1: Central Africa terra-firme forest types in 10 classes. Class 1 is not given a caption because it is specifically located on volcanoes (Mont Cameroon).

Table 1: Terra-firme forest classification statistics with corresponding class colours, preliminary description, pixel class number equivalent surface and percentage.

Colour	Description	nb pixels	km²	%
Red	Evergreen cloud forests	22 610	1 413	0%
Light green	Mid-altitude (Mount Cristal) evergreen forests under the influence of coastal climate	899 736	56 234	3%
Dark-blue	Deciduous and gallery forests under the influence of southern climate	1 014 356	63 397	3%
Yellow	Evergreen forests under the influence of coastal climate	3 499 002	218 688	12%
Cyan	Semi-deciduous forests and old-growth secondary forests under the influence of northern climate	5 005 165	312 823	17%
Pink	Semi-deciduous forests under the influence of southern climate	4 461 902	278 869	15%
Dark-purple	Secondary and degraded deciduous forests under the influence of northern climate	2 973 438	185 840	10%
Dark-green	Mixed evergreen and semi-deciduous forests	5 513 491	344 593	19%
Purple	Semi-deciduous forest under the influence of southern climate	3 671 464	229 467	13%
Orange	Secondary and degraded deciduous forests under the influence of southern climate	2 256 306	141 019	8%
Total		29 317 470	1 832 342	100%

Using the EVI, PALSAR and GLAS datasets we mapped 4 swamp forest types in Central Africa (fig. 2). The four classes are spatially organised along the main rivers and large lakes, depending of the floods duration. For example, the duration of the floods is shorter within the darker green classes. Validation was performed using aerial photographs to recognize the main swamp forest types. GLAS data informed us about the height of the trees (Betbeder et al., 2014).

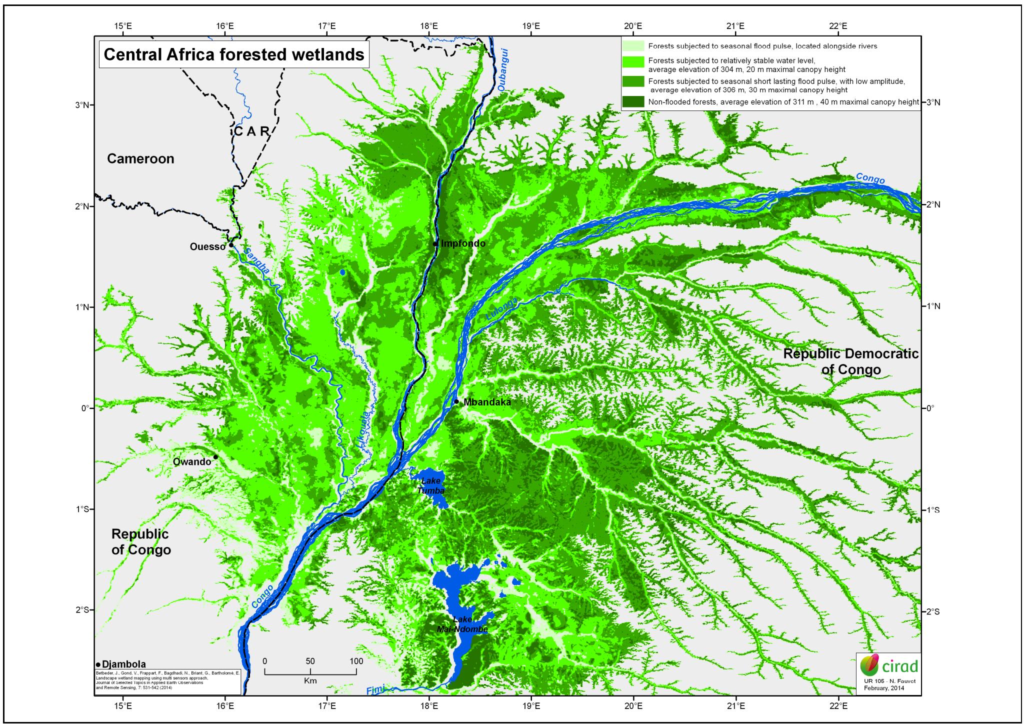

Fig. 2: Central Africa swamp forest types (Betbeder et al., 2014).

DISCUSSION

In this study we identified a wide spectrum of terra firme and swamp forest types spatially organised at the region scale. This study can be considered as a first step in the detailed characterization of Central African forest types. Our results helped translate previous heterogeneous information into a coherent map evidencing forest type's spatial distribution. On terra-firme, two large gradients were detected: a west to east gradient and a north to south gradient. These gradients reveal forest types heterogeneity at the regional scale, possibly under the control of geological substrates (Gourlet-Fleury et al., 2011, Fayolle et al. 2012) and climatic conditions (Philippon et al., 2014). This step goes beyond the large broad-leaved evergreen forest map (Verheggen et al., 2012). Our map promotes a better vision of the central African forest type's diversity. This new insight should support better adapted future forest management and conservation policies.

This map also shows the diversity of forest types in order to develop a better understanding of the regional atmosphere/biosphere interface. Photosynthetic activity of tropical forest types is highly seasonal (Bradley et al., 2011). The temporal curves reported in the legend underline the photosynthetic activity variations in relation with tree phenology (Gond et al., 2013). These temporal phenomena are linked with environmental drivers such as water and light availability (Gond et al., 2013). In the context of climate change, it is important to propose a new vision of the second tropical forest block where the spatial heterogeneity should imply adapted logging and conservation management. In the heart of the region, the inundated plain plays a specific environmental role in relation with duration of the flood where any modification could have dramatic consequences for the ecological equilibrium of the region. In this case, threats are linked with the project to transfer water from the Congo Basin into the Lake Chad (Misser, 2003).

CONCLUSION

In Central Africa where climatic variability is important with annual heterogeneous rainfall regime from west to east combined with climatic inversion between north and south hemisphere, any modification in dry season length and intensity could have dramatic consequences on vegetation. Tropical forests do not necessarily function similarly across the globe, so it is important to work at continental scale to improve our understanding of forest functioning. The documentation and the study of this huge area are fundamental for understanding continental natural resources, carbon stocks at the tropical atmosphere/biosphere interface. In the context of climate change and increasing anthropogenic pressure, forest type' characteristics have to be kept in mind with regard to future management and conservation policies.

ACKNOWLEDGEMENT

The authors thank NASA, ESA and IRD for providing the remote sensing data. This study is part of the ERA-Net BiodivERsA 2012 Congo Basin forests: tipping points for biodiversity conservation and resilience of forested social and ecological systems (CoForTips) project funded by the National Research Agency (ANR).

Data accessibility. We wish to thank the timber companies Alpicam, BPL, Danzer, DLH, IFB, Likouala Timber, Rougier, SEFCA, SCAD, SCAF and Vicwood for authorizing access to the inventory data.

Funding statement. This study is part of the ErA Net BiodivERsA 2008 CoForChange project, funded by the National Research Agency (ANR) and the Natural Environment Research Council (NERC), see http://www.coforchange.fr.

REFERENCES

Bégué, L., 1967, Chronique phytogéographique. Les forêts du nord de la République du Congo (Brazzaville). *Bois et Forêts des Tropiques*, **111** : 63-76.

Betbeder, J., Gond, V., Frappart, F., Bagdhadi, N., Briant, G., Bartholomé, E., 2014, Landscape wetland mapping using multi sensors approach, *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **7**: 531-542.

Boulvert, Y., 1986, Carte phytogéographique de la République Centrafricaine à 1:1,000,000. Notice explicative 104, Editions de l'ORSTOM, Paris.

Bradley, A., Gerard, F., Barbier, N., Weedom, G., Anderson, L., Hutingford, C., Aragao, L., Zelazowski, P., Arai, E., 2011, Relationship between phenology, radiation and precipitation in the Amazon region, *Global Change Biology*, **17**: 2245-2260.

Bwangoy, J-R., Hansen, M., Roy, D., De Grandi, G., Justice, J., 2010, Wetland mapping in the Congo Basin using optical and radar remotely sensed data and derived topographical indices, *Remote Sensing of Environment*, **114** : 73-86.

Fayolle et al., 2012, Geological substrates shape tree species and trait distribution in African moist forests, *PLos ONE*, **7**: e42381.

Gond, V., Fayolle, A., Pennec, A., Cornu, G., Mayaux, P., Camberlin, P., Doumenge, C., Fauvet, N., Gourlet-Fleury, S., 2013, Vegetation structure and greenness in Central Africa from MODIS multi-temporal data, *Philosophical Transaction of the Royal Society (serie B)*, **368**: 20120309 http://dx.doi.org/10.1098/rstb.2012.0309

Gourlet-Fleury, S. et al., 2011, Environmental filtering of dense-wooded species controls above-ground biomass stored in African moist forests, *Journal of Ecology*, **99**: 981-990.

Hansen, M., Roy, D., Lindquist, E., Adusei, B., Justice, C., Altstatt, A., 2008, A method fo integrating MODIS and Landsat data for systematic monitoring of forest cover and change in the Congo Basin, *Remote Sensing of Environment*, **112**: 2495-2513.

Laurance, W., Williamson, G., Delamonica, P., Oliveira, A., Lovejoy, T., Gascon, C., Pohl, L., 2001, Effects of a strong drought on Amazonian forest fragmentation and edges, *Journal of Tropical Ecology*, **17**: 771-785.

Letouzey, R., 1985, Notice de la carte phytogéographique du Cameroun au 1 :500,000. Institut de la Carte Internationale de la Végétation, Toulouse et Institut de la Recherche Agronomique de Yaoundé.

Mayaux, P., Bartholomé, E., Fritz, S., Belward, A., 2004, A new land cover map of Africa for the year 2000. *Journal of Biogeography*, **31**: 861-877.

Misser, F., 2003, RD Congo economy, in Africa south of the Sahara 2003, 22nd edition, 1360 pages, London, UK.

Myneni et al., 2007, Large seasonal swings in leaf area of Amazon rainforests, *Proceedings of the National Academy of Sciences of USA*, **104**: 4820-4823.

Philippon, N., Martiny, N., Camberlin, P., Hoffman, M., Gond, V., 2014, Timing and patterns of the ENSO signal in Africa over the last 30 years: insights from Normalized Difference Vegetation Index data, *Journal of Climate*, **27**: 2509-2532.

Verheggen, A., Mayaux, P., de Wasseige, C., Defourny, P., 2012, Mapping Congo basin vegetation types from 300m and 1 km multi-sensor time series for carbon stocks and forest areas estimation, *Biogeosciences*, **9** : 5061-5079.

Zelazowski, P., Malhi, Y., Huntingford, C. Sitch, S., Fisher, J., 2011, Changes in the potential distribution of humid tropical forests on a warmer planet, *Philosophical Transactions of the Royal Society A*, **369**: 137-160.