Large-scale estimation of forest canopy opening using remote sensing in Central Africa

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Logging activity produces simultaneously open canopy and bare soil. Example of timber impact in a tropical rainforest.
Photograph V. Gond.

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RÉSUMÉ

ESTIMATION À GRANDE ÉCHELLE DE L'OUVERTURE DU COUVERT FORESTIER EN AFRIQUE CENTRALE À L'AIDE DE DONNÉES DE TÉLÉDÉTECTION.

Les activités humaines en forêt humide tropicale sont à l'origine de perturbations et de dégradations du fait de leur mitage du couvert forestier. Des capacités permettant de mesurer l'étendue des dégâts sont indispensables au calcul des émissions de carbone dans le cadre des programmes Redd+ (Réduction des émissions dues à la déforestation et la dégradation des forêts). La télédétection est un outil puissant pour le recueil de ce type d'information (concernant, par exemple, l'exploitation forestière ou minière ou les projets d'infrastructure). Différentes techniques sont mises en œuvre pour identifier et quantifier l'ouverture du couvert forestier. Il s'agit ici de les compléter en comparant l'ouverture passée et actuelle du couvert forestier afin de documenter le renouvellement des écosystèmes suite aux opérations d'exploitation forestière. Cet article présente une approche mettant en œuvre une chaîne de traitement semi-automatisée adaptée à l'imagerie Landsat. En post-traitement, l'information portant sur l'ouverture de la canopée est extraite à l'aide d'algorithmes spécifiques. Un index spatial, calibré sur des données radiométriques à basse résolution, indique les taux d'ouverture passés et actuels. Ce procédé fournit des estimations de la dégradation forestière permettant de décrire les données de télédétection à basse résolution (issues de Modis, par exemple) utilisées pour la cartographie terrestre. Ces estimations sont alors croisées avec des cartes de couverture terrestre afin de distinguer des catégories forestières actuelles. Cet outil a été développé dans le cadre du projet CoForChange, dont l'objectif global est de prévoir l'évolution du couvert forestier et de la distribution des essences dans le Bassin du Congo liée aux changements globaux, et de développer des outils d'aide à la décision. Cet article présente un exemple en grandeur et en temps réels, situé dans la forêt humide aux frontières de la République centrafricaine, de la République du Congo et du Cameroun, analysé année par année à l'aide de trente années d'archives Landsat.

Mots-clés : dégradation forestière, réseau routier, Landsat, Modis, Afrique centrale.

ABSTRACT

LARGE-SCALE ESTIMATION OF FOREST CANOPY OPENING USING REMOTE SENSING IN CENTRAL AFRICA

Human activities in tropical rainforests cause disturbances and degradation by opening up the forest canopy. Capacities for measuring the extent of the damage are essential to the calculation of carbon emissions under REDD+ programmes (Reducing Emissions from Deforestation and Forest Degradation). Remote sensing is a powerful tool to provide this type of information (e.g. on logging, mining or infrastructure projects). Various techniques have been used to identify and quantify canopy opening. A further step is to cross-reference past and present canopy opening in order to document the recovery of ecosystems after logging. The method proposed in this article involves a semi-automatic processing chain adapted for LANDSAT imagery. During post-processing, canopy opening information is extracted by means of specific algorithms. A spatial index, calibrated to a low-resolution radiometer, indicates present and past degrees of opening. This process produces estimations of forest degradation that can describe low-resolution remotely-sensed data (such as MODIS) used in continental mapping. These estimations are then cross-referenced with continental land cover maps to gain insights into present-day forest categories. This tool was developed under the CoForChange project, whose overall objective is to predict changes in forests and in tree species distribution in the Congo Basin as a result of global change, and to develop decision-making tools. The article focuses on a full-scale example in real time, in the rainforest located at the borders of the Central African Republic, the Republic of the Congo and Cameroon, which was analysed on a year-by-year basis with thirty years of LANDSAT image archives.

Keywords: forest degradation, road network, LANDSAT, MODIS, Central Africa.

RESUMEN

ESTIMACIÓN A GRAN ESCALA DE LA APERTURA DEL DOSEL EN ÁFRICA CENTRAL A TRAVÉS DE LA TELEDETECCIÓN

Las actividades humanas en las selvas tropicales causan perturbaciones y degradaciones al abrir claros en la cubierta de copas. Es necesario disponer de medios que permitan medir la magnitud de los daños para calcular las emisiones de carbono en el marco de los programas REDD+ (Reducción de Emisiones debidas a la Deforestación y a la Degradación forestal). La teledetección es una potente herramienta para proporcionar este tipo de información (relativa, por ejemplo, al aprovechamiento forestal, explotaciones mineras o proyectos de infraestructuras). Se han venido empleando distintas técnicas para identificar y cuantificar la apertura del dosel. Aquí tratamos de completarlas mediante la comparación de la apertura pasada y actual del dosel para documentar la recuperación de los ecosistemas después de un aprovechamiento forestal. Este artículo presenta un enfoque basado en una cadena de procesamiento semiautomático adaptado a las imágenes LANDSAT. Durante el post-procesamiento, se extrae la información relativa a la apertura del dosel arbóreo mediante algoritmos específicos. Un índice espacial, calibrado basándose en datos radiométricos de baja resolución, indica los grados actuales y pasados de abertura. Este procedimiento proporciona estimaciones de la degradación forestal que permiten describir los datos de teledetección de baja resolución (procedentes de MODIS, por ejemplo) utilizados en la cartografía terrestre. Dichas estimaciones se cruzan posteriormente con mapas de ocupación del suelo para distinguir las categorías forestales actuales. Esta herramienta se ha desarrollado en el marco del proyecto CoForChange, cuyo objetivo global es prever la evolución del dosel arbóreo y de la distribución de especies en la cuenca del Congo como consecuencia del cambio global, así como desarrollar herramientas de ayuda a la decisión. Este artículo presenta un ejemplo a gran escala y en tiempo real, ubicado en la selva que se extiende entre la República Centroafricana, la República del Congo y Camerún, analizado año a año con la ayuda de trenta años de archivos LANDSAT.

Palabras clave: degradación forestal, red de carreteras, LANDSAT, MODIS, África Central.

Introduction

Humans are cutting down tropical forests for agriculture, timber and wood fuel. These activities cause disturbances and degradation by opening the canopy. This article focuses on selective logging, an activity that entails building roads to open the forest cover and provide access to timber resources. As these resources are sparsely located within the forest, roads proliferate in a hierarchical network (from main roads to trails). As IPCC (2007) recommends estimating carbon emission mitigation within the REDD+[1] program, it seems important to characterize in time and place the canopy opening associated with logging. Knowledge on the subject is limited (ACHARD *et al.*, 2007; ASNER *et al.*, 2005) but several studies highlight the ecological consequences of road building in tropical forests (BRIANT *et al.*, 2010; LAURANCE *et al.*, 2009; BROADBENT *et al.*, 2008). Then several software developments are proposed to estimate the logging opening in large areas (SOUZA *et al.*, 2003) and the vegetation capacity to recover (BROADBENT *et al.*, 2006; DE WASSEIGE & DEFOURNY, 2004). LAPORTE *et al.* (2007) showed that it is possible to digitize manually the road networks of a large region using remotely-sensed data, then ASNER (2009) developed a software able to process data in a semi-automated way – but its access is restricted –, finally PITHON *et al.* (2013) also developed a semi-automated software – but it can only be applied to specific data. Today, the forestry community still needs an operational tool capable of informing on the logging impact and capacity of the forest to recover. This tool must be able to extract small objects and aggregate them in time and space.

The purpose of the study was to measure bare soils (opened canopy) associated with logging roads and revegetation after logging. The present hypothesis is that the revegetation speed depends on soil substratum and road types. So, it was used a multi-temporal process to estimate bare soils in the forest. This tool can map a logging road network over a large area on a yearly basis. This approach helps to stack yearly maps and analyse the logging road impact and revegetation capacity of the forest over time.

Firstly, a methodological approach based on LANDSAT imagery was developed to estimate degradation at a lower resolution compatible with MODIS pixel size, and secondly preliminary results obtained in the south of the Central African Republic (CAR) and in the Northern Republic of Congo were analysed to highlight its capacity to measure forest revegetation in different geological substrata.

[1] Reducing Emissions from Deforestation and Forest Degradation (REDD) is an effort to create a financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development. REDD-plus goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks (The United Nations Collaborative Programme).

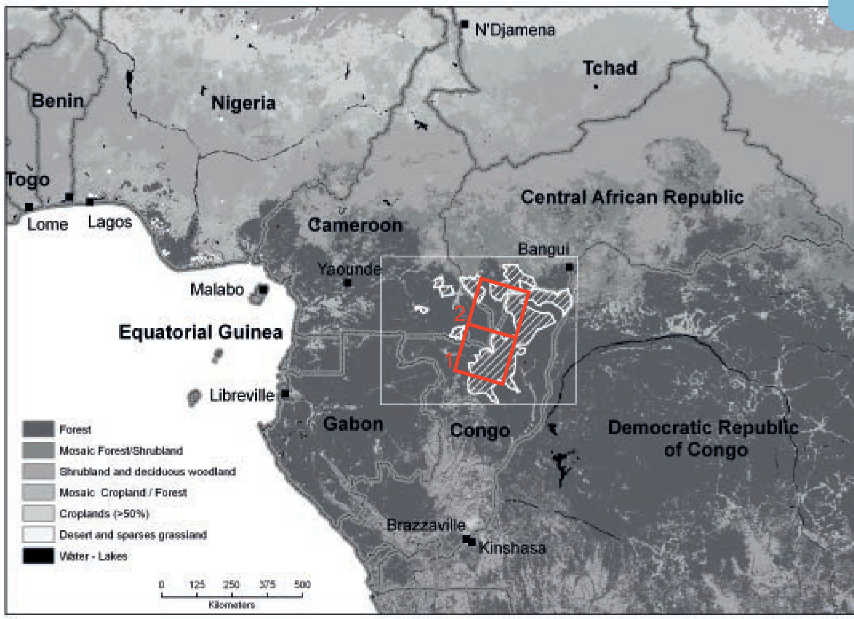

Figure 1.
Location of the study site. Background is the land cover map from MAYAUX *et al.* (2004). White square is the CoForChange study area, white stripes are forest concessions involved in the project, and red squares are the two LANDSAT footprints used in the study.

Material and Methods

Study area

The study was carried out within the CoForChange project (www.coforchange.eu) located in Southeastern Cameroon, Southern CAR and Northern Republic of Congo (figure 1). The climate in the area is humid tropical, with a mean annual rainfall of 1,400-1,700 mm and a 0-4-month (‹100 mm/m) dry season (www.worldclim.org). Altitude ranges from 30 to 800 m above sea level. The vegetation belongs to the mixed, moist, semi-deciduous rainforest. The human population density is very low. Most of the forests have been granted to private logging companies and have been impacted by selective logging since the 1950's (RUIZ PÉREZ *et al.*, 2005). Within this area two test zones corresponding to two LANDSAT imagery footprints were selected (figure 1, red squares). Zone 1 is located in Congo and centred at 2.5°N/16°E (LANDSAT path/row 182-59) on quartzite substratum. Zone 2 is located across the three borders, and centred at 3.5°N/15.2°E (LANDSAT path/row 182-58) on sandstone substratum.

Remotely-sensed imagery

LANDSAT images were used because they have adequate spatial (30 m pixel size) and spectral resolutions. Five LANDSAT were used with wavelength bands: blue [B: 0.45-0.515 µm], green [G: 0.525-0.605 µm], red [R: 0.63-0.69 µm], near infrared [NIR: 0.75-0.90 µm] and shortwave

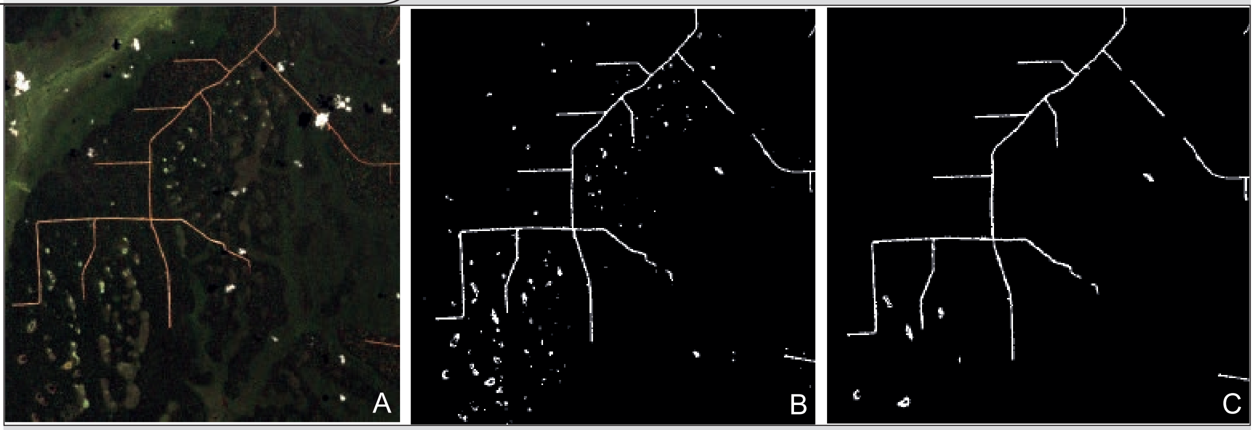

Figure 2.
Extract from LANDSAT ETM+ image (A) of the road network using bare soil identification (B) and final restitution using the morphological filter (C) that removes most inclusions of savannahs and water bodies. At the end of the process the road network is accurately extracted even if false objects remain (for instance large savannahs).

infrared [SWIR: 1.55-1.75 µm]. Images cover large areas (180x180 km) and are long term archives (since 1984). GloVis interface (glovis.usgs.gov) enabled us to download all data. the valuable data were limited to 20% cloud cover. This option limited the use of many LANDSAT images in the study area. LANDSAT 5 and 7 images for years 1990 and from 2000 to 2003 were used in zone 1. LANDSAT 5 and 7 images for years 1986, 1987, 1990, 1994 and from 2001 to 2003 were used in zone 2. It was decided not to use images after 2003 because of the SLC-off problem of LANDSAT 7.

Methodological development

The processing workflow was prototyped with the box image processing software (ArcGIS, ENVI and SAGA). The process was then recoded into a semi-automated application developed in C++ by ORFEO (wiki.orfeo-toolbox.org), an image processing library created by CNES and a few shell scripts.

It was applied standard data pre-processing with calibration to standardize the reflectance of each image (from digital number to top of atmosphere reflectance). Specific indices to enhance the spectral contrast between forest and bare soil were calculated. Two indices were necessary, the normalized difference vegetation index (NDVI = NIR-R/NIR+R) and the green-red index (GR = G-R/G+R), to increase the contrast between photosynthetic active surface and bare soil surface. A local contrast process using a spatial filter improves this contrast (GOND *et al.*, 2004). Bare soils were identified using spectral channels and indices (a pixel is considered as bare soil when R›0.006 and GR›0.019 and NDVI+GR›0.052). A cloud and water mask was applied to all data to avoid confusion with bare soils (a pixel is considered as cloud or water when B›0.12 and SWIR‹0.04).

A morphological filter from the ORFEO toolbox (SHAPE functions) was applied to eliminate isolated pixels and extract the road network (an object is considered as bare soil/road when SHAPE_Size›50 pixels or SHAPE_Elongation›3 pixels; figure 2). Then a Boolean model (0 or 1) was created considering forest (0) and bare soil (1). This process avoids missing values along road networks and masks isolated pixels. Finally, a yearly synthesis was used to develop a year-to-year database for comparisons and analyses over time. A mosaic was assembled from the latest image (December) to the earliest (January) for each considered year. This method ensures filling up the gaps caused by artefact masks. To obtain a canopy opening index at a MODIS cell size of 500 m (MCS), the ratio of bare soil pixels to other pixels was calculated (figure 3). For each MCS in each year an indication on the bare soil percentage surface was obtained. This new index was called the canopy opening index.

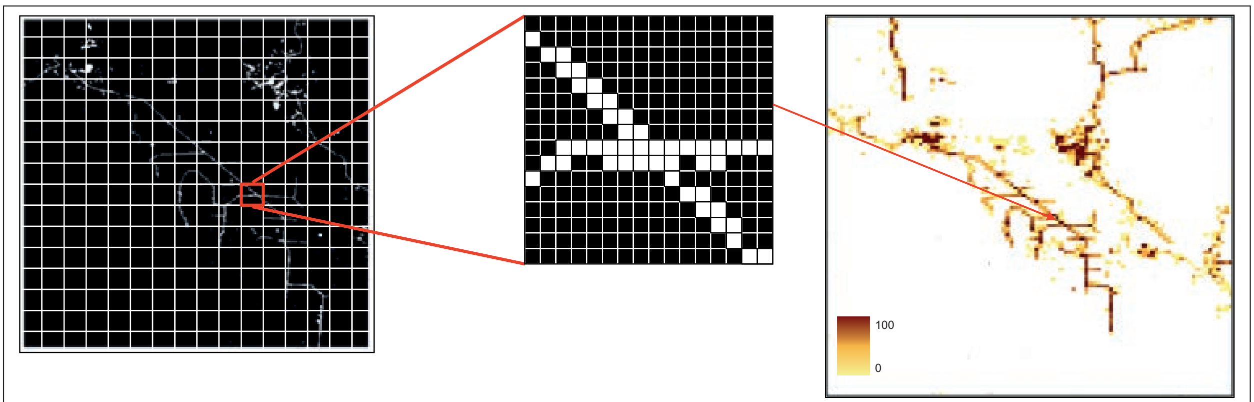

Figure 3.
Canopy opening index building using bare soil identification with LANDSAT imagery (left). A spatial aggregation at a MODIS cell size of 500 m (centre) is used to resize information and estimate the bare soil ratio from 0 to 100% (right). The up-scaling methodology shown here provides estimations of canopy opening at a resolution comparable to large-scale mapping (typically from SPOT-VEGETATION or MODIS data). It helps also remove cloud and artefact contamination using a temporal filter. This powerful tool evaluates degradation by, and recovery from logging activities of tropical forests.

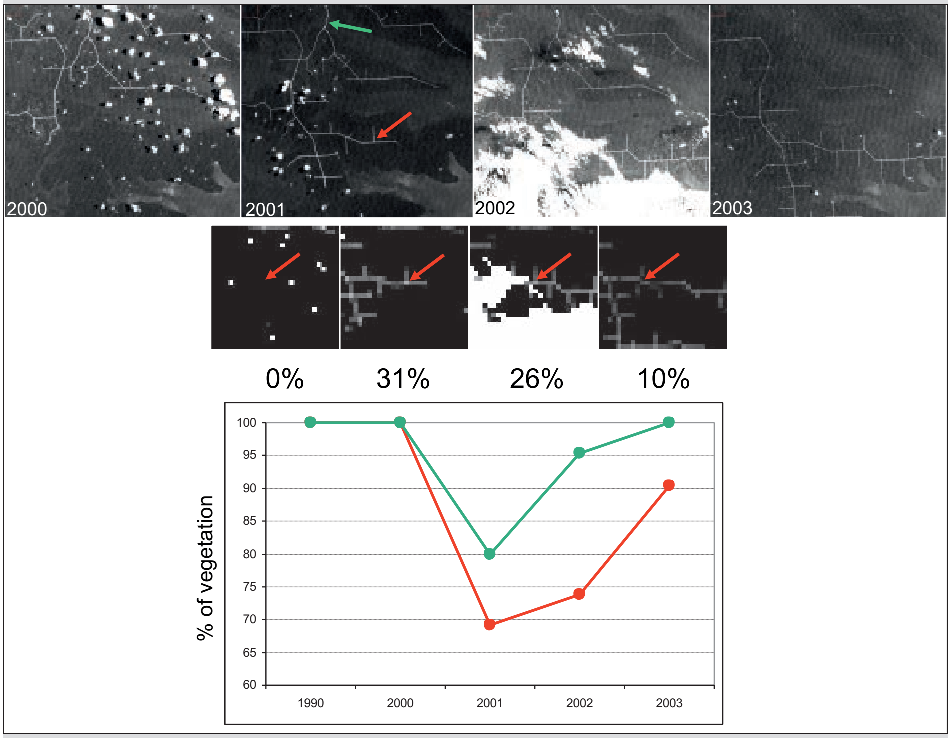

Figure 4.
Temporal analysis of the canopy opening index. Upper part: LANDSAT extract shows the road network from 2000 to 2003. Middle part: location of the corresponding MODIS cell size. Lower part: the temporal profiles of two MODIS cell size highlight the potential to track down revegetation after logging. This example is located in zone 1 with quartzite substratum. This approach serves to estimate area of revegetation. For example 26% of a MODIS cell size (500mx500m is 25ha) is equivalent to 6.5ha of canopy openness in 2002.

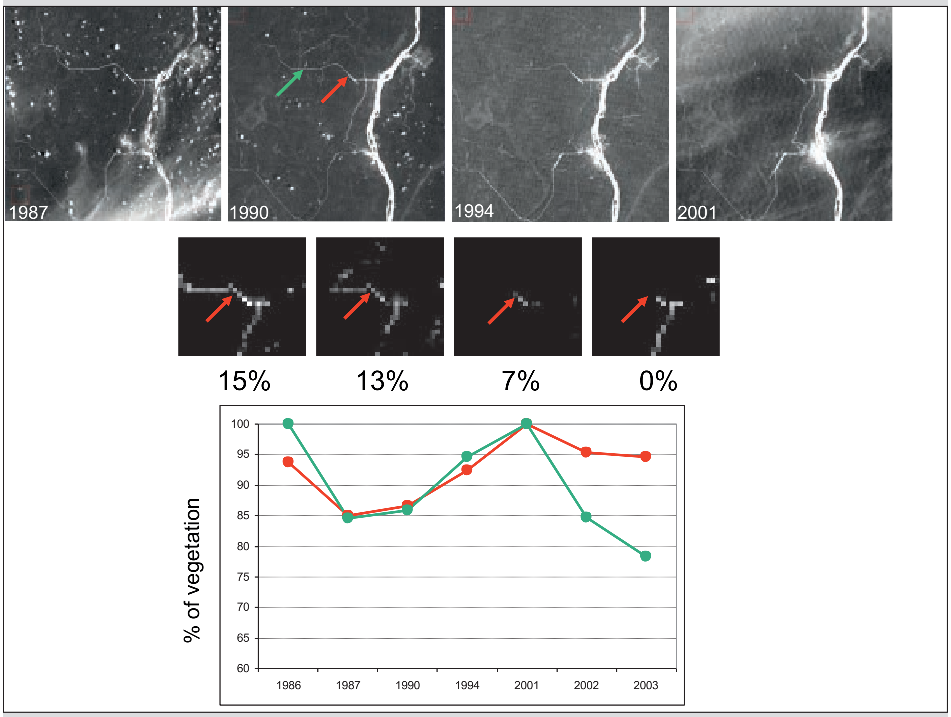

Figure 5.
Temporal analysis of the canopy opening index. Upper part: LANDSAT extract shows the road network from 1987 to 2001. Middle part: location of the corresponding MODIS cell size. Lower part: the temporal profiles of two MODIS cell size highlight the potential to track down revegetation after logging. This example is located in zone 2 with sandstone substratum. Note in this example the forest recovery after logging in 1987 was followed by a second opening with different intensity. Cell by cell monitoring is thus informative in terms of large-scale degradation estimation.

Results

The canopy opening index was analysed for zone 1 (figure 4) and zone 2 (figure 5) during their respective monitoring periods. These figures are organized into three parts. The upper parts show LANDSAT imagery extractions of road network evolutions over periods of time. The middle parts correspond to a canopy opening index from 0 to 100% for each MCS in the same surface as in the upper parts. The lower parts show the temporal evolution of selected MCSs (red and green curves) during monitoring time.

Figure 6 (same arrangement as in figures 4 and 5) shows the revegetation speed of a main road (green on the right) and a secondary road (red on the left) in a specific year (2001).

Discussion

The semi-automated processing chain was carried out to estimate the canopy opening index. This study analyses revegetation of the logged rainforest in the studied area in relation with the substratum and hierarchical position in the road network. Three examples show the possibility of the system.

In zone 1 (quartzite substratum) the interpretation of the two profiles of figure 4 would indicate a high logging impact from 2001 to 2002. The selected MCS (in red) is located at the crossroads between a main road and a secondary road. Traffic seemed dense during this period. Later on (2003) the road network extended to the east and this MCS shows revegetation and thus a decrease in the logging activity in the area. The second selected MCS (in green) is located at the end of a secondary road. Traffic was less important and revegetation was faster. In 2003, this road was not detectable. This shows that revegetation was fast on quartzite substratum, even more so at the end of the road network (two years).

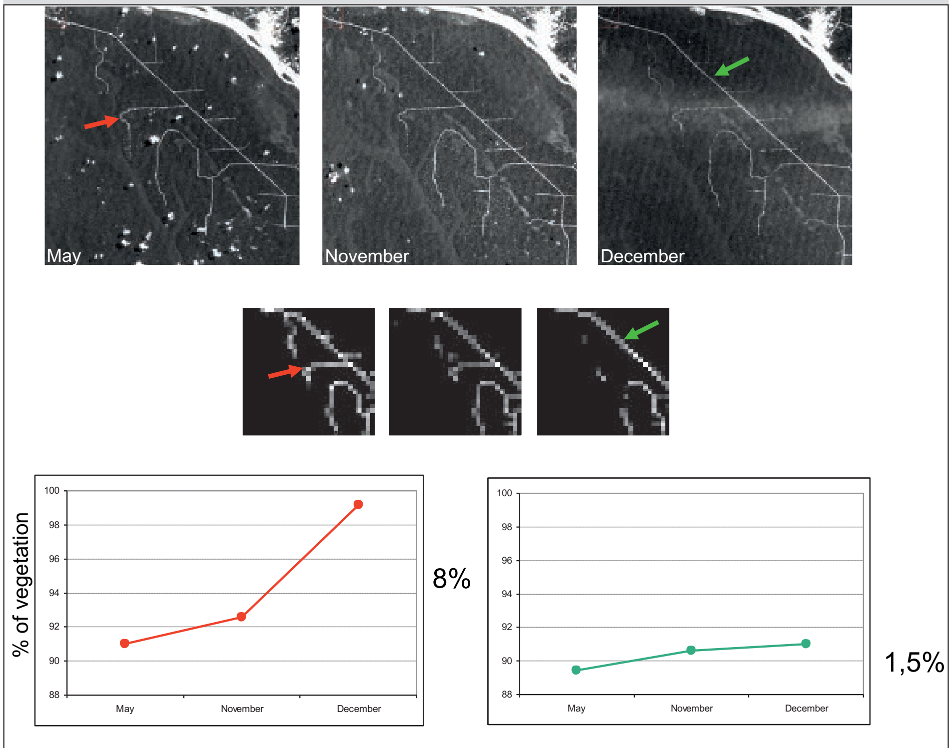

Figure 6.
Temporal analysis of the canopy opening index. Upper part: LANDSAT extract shows the road network in 2001 from May to December. Middle part: location of the corresponding MODIS cell size. Lower parts: the temporal profiles of two MODIS cell size highlight the potential to track down revegetation after logging. This example shows revegetation differences between main and secondary roads. The level of detail of the canopy opening index is accurate enough to highlight road network use and local population practices. This would be of great interest when applied to monitoring activities of remote areas.

Timber prepared for export. Log yard expose large bare surface areas and the vegetation strives hard to recover because of light intensity, local drought and soil compactness.
Photograph C. Féau.

In zone 2 (sandstone substratum) logging was less important and the road network was probably used for other activities (proximity of villages). After logging in 1987, revegetation was slow and the canopy opening index took seven years to disappear. This shows that revegetation was slower in sandstone substratum. The MSC location within the road network also needs considering. In some cases, a one-year analysis shows fast changes in revegetation. When nearing timber resources, roads become increasingly narrower and less affected by traffic. Figure 6 shows that the secondary road (in red) closed much faster than the main road (in green) after logging. This clearly shows that road network management is essential to conserving the future of stands. These examples highlight the multiple parameters that drive revegetation of the logged rainforest. The substratum, proximity of multiple-use roads, and location on the road network are determinant for the recovery of logged rainforests in the region.

The study was carried out in real situation. A main limitation was the persistence of the cloud cover. This problem associated with the SLC-off problem of post-2003 LANDSAT imagery eliminates 93% of LANDSAT archived data. The solved SLC-off problem (landsat.usgs.gov) bodes well for the use of the full potential of LANDSAT archives.

Nevertheless, within REDD+ context, the richness of LANDSAT archives throughout the tropical world has been crucial to monitoring the canopy opening index in the last three decades. A combination with Spot images may complete this approach. The study of the road network locates the areas of logging activity. Applying the approach of GUITET *et al.* (2012) will enable us to evaluate more precisely the canopy opening index and thus monitor logging activities. This approach could be implemented in Libreville satellite reception station. Then, the association of long-time archives with high-resolution satellite images will provide a powerful tool to manage tropical rainforests.

The process described here is built upon widely-used frequently updates open toolboxes. Thanks to a modular approach, the processing chain can be improved or adapted easily. The main advantages of the scaled-up approach are: time and space comparisons (across years and pan-tropical rainforests); spatial homogeneity for a whole area (within or between several tropical rainforests); a low resolution link (to integrate or validate broad-scale tropical rainforest mapping).

Photograph 3.
Track used to transport wood from logging area to sawmill. The road network is primarily built for timber trucks. Depending on their location and post logging controls, these roads can be re-used for other purposes such as population movements or illegal logging activities.
Photograph D. Louppe.

Acknowledgements
The authors wish to thanks the CoForChange project (contract No 2008-29489-55915-16) for its financial and scientific support.

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