

Forest cover and carbon stock change dynamics in the Democratic Republic of Congo: Case of the wood-fuel supply basin of Kinshasa

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Photo 1.

At the bottom of the Lufimi River valley, on the Bateke plateau, a farmer shows the limits of the field that he created by slashing and burning the gallery forest.

On the other side of the valley, one can see his old fields, where the regular passage of bushfires favors the development of herbaceous savannah to the detriment of forest vegetation.

Photo R. Peltier.

RÉSUMÉ

DYNAMIQUES DE CHANGEMENT DE LA COUVERTURE FORESTIÈRE ET DU STOCK DE CARBONE EN RÉPUBLIQUE DÉMOCRATIQUE DU CONGO : LE CAS DE L'APPROVISIONNEMENT EN BOIS-ÉNERGIE DU BASSIN DE KINSHASA

Afin de contribuer à la mise au point de méthodes de gestion durable des écosystèmes forestiers en Afrique centrale, la question de recherche suivante a été posée : l'analyse de l'évolution de la couverture végétale permet-elle de comprendre et de documenter l'organisation spatiale et les mécanismes de la dégradation des forêts tropicales ? Pour cela, en République démocratique du Congo, le projet Makala a cartographié les arbres et les ressources forestières du bassin d'approvisionnement en bois-énergie de Kinshasa et a essayé de prédire son évolution future. La carte a été réalisée à quatre périodes (1984, 2001, 2006 et 2012) avec une mosaïque de quatre images Landsat. L'estimation de la biomasse aérienne a été faite en 2012, par l'inventaire forestier de 317 parcelles (4 337 arbres de 44 espèces) dans les quatre types de couverture végétale, sur le plateau Batéké. Entre 2000 et 2012, le volume moyen de bois-énergie a chuté de plus de 50 % et les stocks de carbone de 75 % en 28 ans. La réduction drastique du couvert forestier, la baisse significative des périodes de jachère, l'augmentation des surfaces de savane, le déclin des stocks de biomasse et de carbone, constituent des signaux particulièrement forts. Mais ces premières estimations sont dérivées des données d'un petit échantillon, extrapolées au bassin d'approvisionnement. Il serait très utile d'augmenter l'échantillonnage, pour approcher des valeurs plus justes et concrètes. L'expérience du projet Makala montre clairement que l'analyse de l'évolution de la couverture végétale permet de comprendre et de documenter l'organisation spatiale et les mécanismes de la dégradation des forêts. Mais seules une politique consciente et une gestion durable des terres des communautés, combinées avec une réintroduction des arbres dans les terres agricoles, peuvent initier un processus de restauration durable.

Mots-clés : bois-énergie, stock de carbone, couvert forestier, dégradation forestière, inventaire forestier, restauration forestière, télédétection, Kinshasa, République démocratique du Congo.

ABSTRACT

DYNAMICS OF FOREST COVER AND CARBON STOCK CHANGE IN THE DEMOCRATIC REPUBLIC OF CONGO: CASE OF WOOD-FUEL SUPPLY BASIN FOR KINSHASA

To contribute to the development of methods for the sustainable management of forest ecosystems in Central Africa, the following research question was addressed: can analyses of land cover change help to understand and document the spatial organization and mechanisms of forest degradation? To answer this question in the Democratic Republic of Congo, the Makala project mapped the tree and forest resources of Kinshasa's wood-fuel supply basin and attempted to predict how they would evolve in the future. Maps were made for four periods (1984, 2001, 2006 and 2012) using a mosaic of four LANDSAT images. The above-ground biomass was estimated in 2012 using forest inventories in 317 plots distributed across the four types of plant cover found on the Bateke plateau (4,337 trees and 44 species were recorded). This inventory data combined with the satellite data allowed us to make the first comprehensive assessment of above-ground biomass in the study area. Between 2000 and 2012, the average volume of wood-fuel fell by more than 50%. Over the entire period studied (1984 to 2012), carbon stocks fell by 75%. In the wood-fuel supply area for Kinshasa, the drastic loss of forest cover, shortened fallow periods, savannah encroachment and the decline of biomass and carbon stocks are clear signals of degradation. However, these initial estimations were derived from a small sample that was extrapolated to the entire supply area. It would be very useful to increase sampling in order to obtain more accurate and realistic figures. The experience of the Makala project clearly shows that the analysis of land cover change helps to understand and document the spatial organization and mechanisms of forest degradation. However, only with a sound wood-fuel resource policy and sustainable community land management, combined with very dynamic tree reintroduction on agricultural land, will it be possible to initiate a sustainable process of restoration.

Keywords: wood-fuel, carbon stocks, forest cover, forest degradation, forest inventory, forest restoration, remote sensing, Kinshasa, Democratic Republic of Congo.

RESUMEN

DINÁMICAS DE CAMBIOS EN LA CUBIERTA FORESTAL Y LAS RESERVAS DE CARBONO EN LA REPÚBLICA DEMOCRÁTICA DEL CONGO: CASO DEL SUMINISTRO DE LEÑA DEL ÁREA DE KINSHASA

Para contribuir a la puesta a punto de métodos de manejo sostenible de los ecosistemas forestales en África Central, se formuló la siguiente pregunta de investigación: ¿se pueden comprender y documentar la organización espacial y los mecanismos de degradación de los bosques tropicales analizando la evolución de la cubierta vegetal? Para intentar dar una respuesta, en la República Democrática del Congo el proyecto Makala cartografió árboles y recursos forestales del área de suministro de leña de Kinshasa e intentó predecir su evolución. El mapa se elaboró en cuatro períodos (1984, 2001, 2006 y 2012) a partir de un mosaico de cuatro imágenes Landsat. La biomasa aérea se estimó en 2012 mediante el inventario forestal de 317 parcelas (4 337 árboles de 44 especies) en los cuatro tipos de cobertura vegetal en la meseta Bateké. Entre 2000 y 2012, el volumen promedio de leña cayó más del 50% y las reservas de carbono disminuyeron un 75% en 28 años. La drástica reducción de la cubierta forestal, el acortamiento significativo de los períodos de barbecho, el aumento de las áreas de sabana y la disminución de las reservas de biomasa y carbono son indicios muy claros. No obstante, estas primeras estimaciones se obtuvieron de datos de una pequeña muestra que se extrapoló a toda el área de suministro. Sería muy útil aumentar el muestreo para lograr valores más exactos y concretos. La experiencia del proyecto Makala muestra claramente que el análisis de la evolución de la cobertura vegetal permite comprender y documentar la organización espacial y los mecanismos de degradación de los bosques. Sin embargo, sólo se podrá acometer un proceso de restauración duradero combinando voluntad política y manejo sostenible de tierras de las comunidades con la reintroducción de árboles en las tierras agrícolas.

Palabras clave: leña, reserva de carbono, cubierta forestal, degradación forestal, inventario forestal, restauración forestal, teledetección, Kinshasa, República Democrática del Congo.

Introduction

Wood-fuel, used in both raw and processed forms (firewood and charcoal), is a major source of energy in Africa, especially for domestic use. Until the 1970s, the abundance of wood resources in Central Africa, their regeneration capacity, and low population densities hid forest degradation and wood-fuel resource depletion. A lack of easily accessible alternative energy, rapid population growth, and the uncontrolled development of large cities over the past few decades have resulted in a growing imbalance between supply and demand that is threatening the sustainability of forest ecosystems. The share of wood-fuel in energy consumption appears to have been widely underestimated because the wood-fuel market is complex and informal, rendering it difficult to quantify and therefore evaluate.

Background and research question

In Central Africa, human impacts on tropical natural forests are mostly linked to slash-and-burn cultivation (Molinario *et al.*, 2015) and wood-fuel extraction (Megevand, 2014). This is especially true around Kinshasa, the capital of the Democratic Republic of the Congo (DRC). The population of Kinshasa is estimated at 10 million inhabitants, 90% of whom rely largely on charcoal for cooking. The city's annual needs were assessed at 4.8 million cubic meters of wood equivalent, in the form of firewood or charcoal, with a value of US\$143 (Schure *et al.*, 2011; Schure, 2014). The conglomeration is surrounded by wooded savannah interspersed with gallery forests which are becoming degraded (photo 1). Shifting agriculture, practiced most often in forests, covers most of the demand for food, notably cassava and maize, and charcoal (Peltier *et al.*, 2014a). Pressure on natural forests is increasing and leading to reductions in the length of the fallow periods required to restore soil fertility (Floret and Pontanier 2000; Katembera-Ciza *et al.*, 2015). As a result, the biodiversity and biomass of fallows are steadily diminishing, soils are being leached, and invasive herbaceous plants and shrubs, such as *Chromolaena odorata*, *Pteridium aquilinum* and *Imperata cylindrica*, are beginning to replace forests (Peltier *et al.*, 2014b). Savannah fires penetrate into the most degraded fields bordering the savannah, which may lead to the savannization of the environment and a reduction in the arable land traditionally cultivated by shifting cultivation. Many authors have long considered the impact of small farmers on the degradation of natural formations to be overestimated. In their view, tropical forests are very resilient (Anglo-French Forestry Commission, 1973) and a significant portion of deforestation should be attributed to large agribusiness companies (Fischetti, 2015). However, in the particular case of the gallery forests on the Bateke plateau, small farmers are behind most of the destruction turning the forests into savannahs (Marquant, 2011).

To contribute to the development of methods for the sustainable management of these forest ecosystems, the following research question was posed: "can the analysis of land cover change allow the spatial organization and

mechanisms of forest degradation to be understood and documented?"

Lack of information about forest cover and changes in wood-fuel resources

Existing data on the forest cover, land-use and carbon stock changes in Kinshasa's wood-fuel supply basin are scarce and unreliable. To identify potential options for local decision makers, and the threats and risks posed by the uncontrolled use of wood-fuel resources, a holistic analysis of the entire supply area is required. Such an analysis needs to be based on an understanding of the spatial organization of the landscape to locate and evaluate forest resources.

The objectives of this study were to map the forest stock of the wood-fuel supply basin of the city of Kinshasa to predict its evolution and to propose solutions to end its degradation. The analysis of past and actual land cover used satellite image techniques. The purpose was to understand and document the spatial organization of the study area, mechanisms of forest degradation, and mechanisms for the recovery of forest stands (Gond *et al.*, 2015).

Given the spatial scale and time periods considered, satellite imagery appeared to be a useful tool of analysis (Duveiller *et al.*, 2008). This tool can be used to analyze data sets over several years (Oszwald *et al.*, 2011) and over very large areas (Vancutsem *et al.*, 2009). However, intensive field work must be conducted alongside these satellite measurements to estimate the biomass in space and time.

The study area covered the entire supply basin, an area of 9,000 km² (figure 1). This area includes part of the Bateke plateau (savannah interspersed with gallery forests) and the Bas-Congo region that originally was densely forested (Boulogne *et al.*, 2013) (photo 2).

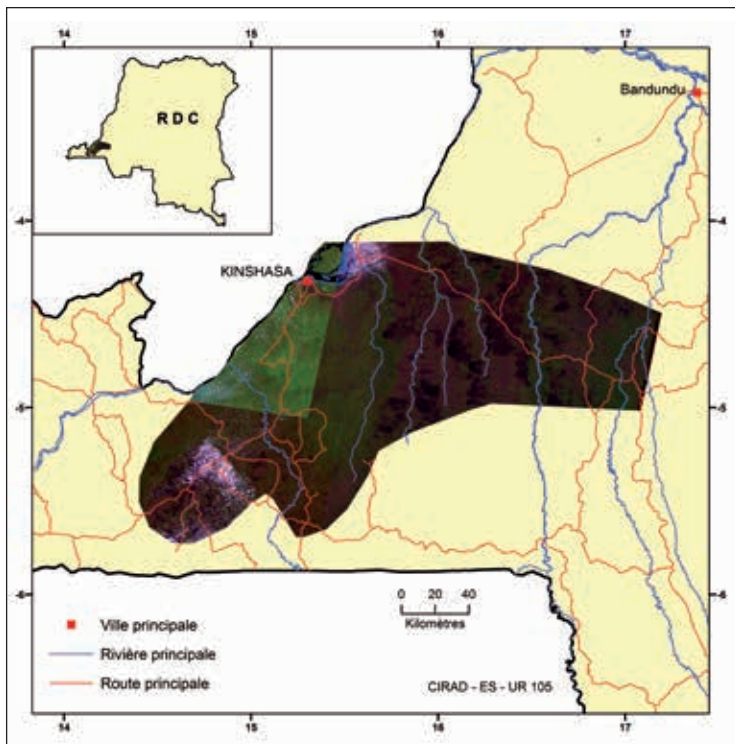
Methods

Satellite imagery processing

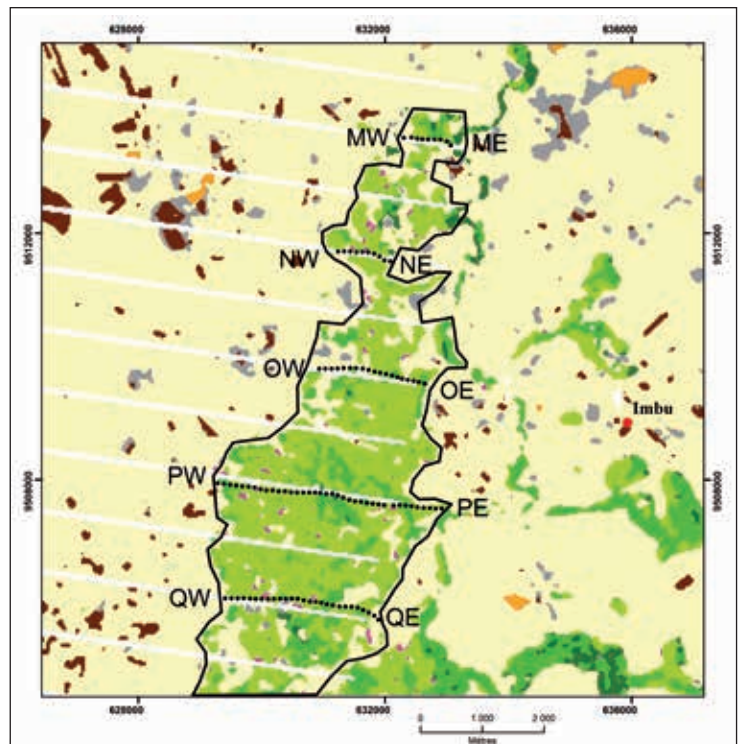
Maps of the land cover of the wood-fuel supply basin were made for four periods (1984, 2001, 2006 and 2012) using a mosaic of four LANDSAT images (figure 1). Two remote sensing sensors were used, Landsat-5 TM for 1984 and Landsat-7 ETM+ for 2001, 2006 and 2012. Mid-infrared [1.55-1.75 microns], near infrared [0.78 to 0.9 microns] and red [0.63 to 0.69 microns] spectral bands were used. For each image, radiometric corrections were applied from digital number (DN) to apparent reflectance. At the same time, an atmospheric correction was performed based on standard atmospheric transparency data using the 5S model (Keromard, 2000). A cloud mask was performed for each image in order to avoid disruption of the classification model. We cumulated the footprints of the stripes on the Landsat-7 ETM+ (2006 and 2012) images to obtain a stripe mask. The surfaces from these two masks were subsequently systematically removed from all of the calculations.

**Photo 2.**

The tall trees of the original forest only remain in some sacred forests (a). Elsewhere, particularly in Bas-Congo, savanna, interspersed with fields and punctuated with rare palm trees, have replaced this forest (b).
Photos R. Peltier.

**Figure 1.**

Location of the wood-fuel supply basin around the city of Kinshasa (DRC).

**Figure 2.**

Location of inventory plots (black spots on the map), in the four types of vegetation, along five transects of the Lufimi Valley.

Fields surveys

Conducted in August 2012, 283 field surveys allowed us to realize a typology of land and build a training zones database (GPS, photo, description of vegetation structure). These training areas were used in the supervised classification model (maximum likelihood algorithm) to map land cover of the 2012 image. A median spatial filter (3 x 3 pixels) was applied to limit the “salt-and-pepper” effect of the classification. Four vegetation classes were mapped on the 2012 image (savannah, young fallow, old fallow and forest). The statistical validation was determined by the confusion matrix and Kappa index (Oszwald *et al.*, 2011). The classification of the 2012 image had an overall accuracy of 82% (table I) and a Kappa coefficient of 0.89, which was quite satisfactory. We then used older satellite data to map the years 2006, 2001 and 1984, using the spectral and visual correspondences of the four vegetation types identified in 2012.



Biomass measurements

The inventory work was carried out in the Lufimi River Valley on the Bateke plateau (Gigaud, 2012). The height and diameter at breast height (dbh) of a total of 4,337 trees on 317 plots (20 m radius) were measured along transects (figure 2) (photo 3). The total surface areas inventoried were quite large given the difficulty of the terrain: forest 0.37 ha (0.18%), old fallow 0.78 ha (0.08%) young fallow 1.57 ha (0.06%) and savannah 1.34 ha (0.08%).

Volume tables were established from trees 5-15 years old felled in 14 plots distributed over four vegetation classes defined by remote sensing (Péroches, 2012). Field work consisted of measuring 5 main tree species (*Albizia adianthifolia*,

Photo 3.
 Inventories on an old fallow, along the Lufimi River valley.
 Photos R. Peltier.

Table I.
Confusion matrix of the 2012 classification.

| Land cover | Water | Forest | Old fallow | Young fallow | Savannah | Burnt savannah | Crops | Recent burnt area | Bare soil | Samples | Producer accuracy | Omission error |
|-------------------|-------|--------|------------|--------------|----------|----------------|-------|-------------------|-----------|---------|-------------------|------------------|
| Water | 307 | | | | | | | | | 307 | 100% | 0% |
| Forest | | 66 | 30 | | | | | | | 96 | 69% | 31% |
| Old fallow | | 9 | 135 | 18 | 139 | 4 | | | | 305 | 44% | 56% |
| Young fallow | | | 4 | 301 | 39 | | 5 | | | 349 | 86% | 14% |
| Savannah | | | | | 1,009 | | 1 | | | 1,010 | 100% | 0% |
| Burnt savannah | | | | | | 94 | | 188 | | 282 | 33% | 67% |
| Crops | | | | | | | 1 | | | 1 | 100% | 0% |
| Recent burnt area | | | | | | | | 15 | | 15 | 100% | 0% |
| Bare soil | | | | | | | | | 101 | 101 | 100% | 0% |
| Samples | 307 | 75 | 169 | 319 | 1,187 | 98 | 7 | 203 | 101 | 2,466 | | |
| User accuracy | 100% | 88% | 80% | 94% | 85% | 96% | 14% | 7% | 100% | | | |
| Commission error | 0% | 12% | 20% | 6% | 15% | 4% | 86% | 93% | 0% | | 82% | Overall accuracy |

Hymenocardia ulmoides, *Markhamia tomentosa*, *Oncoba welwitschii*, *Pentaclethra eetveldeana*) and a group of 6 secondary species (*Dracaena mannii*, *Macaranga monendra*, *Millettia eetveldeana*, *Millettia laurentii*, *Sapium cornutum*, *Vitex congolensis*). The height and dbh of 30 trees of each species were measured. The trees were then cut into billons. The length and circumference of each of these wood billons were measured at the large and small ends (minimum 13 cm). Tree volume was calculated using the Smalian equation (Picard, 2015).

Using the Global Wood Density Database (Zanne *et al.*, 2009), the mean wood density obtained was 0.546 t/ha.

Results

A 30% decrease of carbon stocks

Four maps of vegetation types were produced for 1984, 2001, 2006 and 2012. Biomass and carbon estimation values were assigned to each class. An estimation of carbon stock was then calculated for each period and each vegetation type (figure 3). A net decrease of carbon stock clearly appears. Mainly forest and old fallow decreased drastically. Estimations for above ground biomass were: forest 75 t/ha, old fallow 33 t/ha, young fallow 6 t/ha and savannah 3 t/ha. Carbon stock was: forest 38 t/ha, old fallow 17 t/ha, young fallow 3 t/ha and savannah 1.5 t/ha. The carbon stock (tons) dynamic within the wood-fuel supply basin of Kinshasa consequently shows a 30% loss over the 28-year period (-1% per year on average).

Local trends

The study revealed some local trends. The example of Mampu, where 8,000 hectares of *Acacia auriculiformis* were planted between 1987 and 1993 (Bisiaux *et al.*, 2009), is presented in figure 4. The 1984 map shows the situation before the plantations were set up. By 2001, the plantations were mature. On the 2001 map, forest covers an important surface area but logging and cultivation have already modified the plantations (photo 4). Strips are visible corresponding to squares allocated to charcoal production and cultivation. The area of old tree regrowth is large. In 2006, the situation is totally different. Logging is intense and mainly supported by old regrowth. In 2012, the phenomenon has become worse with the quasi disappearance of forest and old regrowth. Carbon stock has dropped dramatically.

In the Bas-Congo region, the dynamics of change were different (figure 5). Carbon stock was high in 1984 relative to the small surface covered by forest. By 2001, the forest had almost disappeared, and by 2006 it had totally disappeared. The situation was even worse in 2012 when even young fallow had severely decreased (Nsimundele, 2010).

Discussion and conclusion

This article has described how the Makala project developed dynamic maps of surface states from satellite imagery, and how these maps were documented with field data to

estimate stock biomass and therefore carbon. The analysis of the maps highlighted the evolutionary trends of the stock at the level of the supply area and of village territories. This picture helps identify the dangers and threats to wood energy resources in the context of rapid population growth in Central Africa. These data are very important to guide public policies on domestic energy and the development of agriculture, forestry and agroforestry (Gautier *et al.*, 2011).

Despite the low inventory levels, this study clearly confirms what was suggested in the satellite study by Megevand (2014), namely a sharp deterioration of forest formations on the outskirts of Kinshasa over the past few decades. It clearly shows that the analysis of land cover change helps to understand and document the spatial organization and mechanisms of forest degradation.

Given the sharp decline in wood energy and carbon stocks in the supply basin of Kinshasa demonstrated by this study, the Ministries of Energy, Agriculture and the Environment should develop strategies to stabilize or reduce the consumption of wood energy, develop more intensive cropping systems with less reliance on the burning of forests, and encourage people to sustainably manage their environment (Neufeldt *et al.*, 2015). To test some solutions, the Makala project has proposed a strategy based on: i) land security (Vermeulen *et al.*, 2011) and management of village lands (Dubiez *et al.*, 2013); ii) the development of Assisted Natural Regeneration (ANR), a technique which can be used by slash-and-burn farmers in the ecological and social context of the DRC that does not upset the farmers' habitual routines, involve payment incentives, or require supplementary material (Peltier *et al.*, 2015); and iii) plantations of acacias and

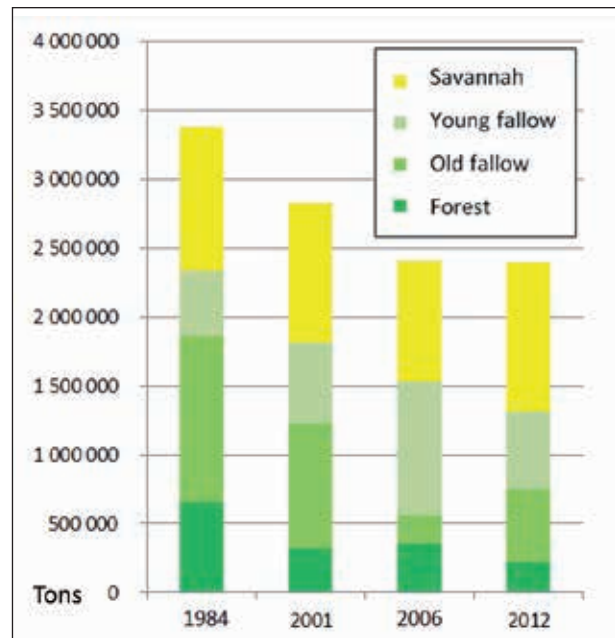


Figure 3. Carbon stock evolution from 1984 to 2012 for the four types of vegetation in the wood-fuel supply basin of Kinshasa.

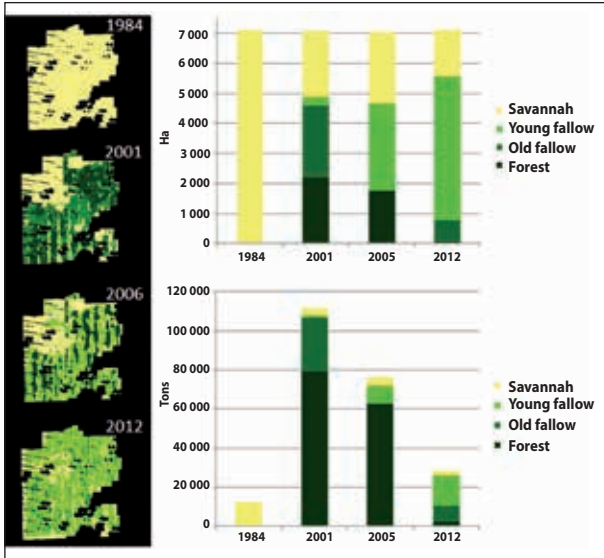


Figure 4. Vegetation maps of Mampu from 1984 to 2012 (left), surface area (in hectares) for each vegetation type (top right) and carbon stock (in metric tons) for each vegetation type (bottom right).

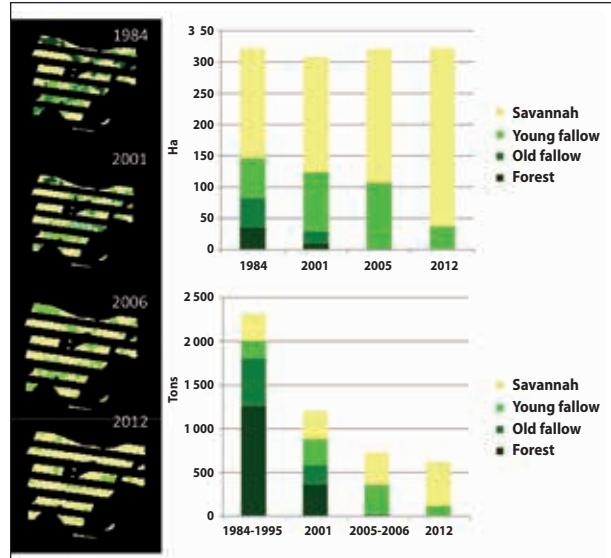


Figure 5. Vegetation maps of Kinduala (Bas-Congo) from 1984 to 2012 (left), surface area (in hectares) for each vegetation type (top right) and carbon stock (in metric tons) for each vegetation type (bottom right).



Photo 4. Mampu, on the savannahs of the Bateke plateau. A plantation of *Acacia auriculiformis* aged about twenty years (a). Acacia wood waiting carbonization following the exploitation of a plot (b). Harvest of cassava that was grown after the slashing and burning of an acacia parcel (c). Photos R. Peltier.

other species of leguminous trees when tree vegetation has become too rare in fallows (Bisiaux *et al.*, 2013) (photo 5).

While the Makala project has pointed the way forward, a wood-fuel supply scheme now needs to be developed for the city of Kinshasa similar to those that have been developed in many cities of the Sahel since the 1990s (Ribot, 2003;

Rives *et al.*, 2012). This would involve setting up a management system for the remaining forests, disseminating large-scale agroforestry throughout the supply basin and implementing an energy saving and substitution policy (gas, electricity) as has been proposed by the World Bank for Niger (Cirad *et al.*, 2015). Indeed, if the biomass and biodiversity of



Photo 5.

To restore degraded areas, the Makala project proposed a strategy based on: Land security and management of village lands (a); Development of Assisted Natural Regeneration (b); Plantations of acacias when the tree vegetation has become too rare in the fallows (c). Photos R. Peltier.

the tree formations of the Kinshasa region are to be rebuilt while ensuring coverage of the energy needs of a rapidly growing population, it is absolutely necessary that some of this energy comes from other sources. Hydroelectric dams under construction or renovation (Inga) on the falls of the Congo River, the most powerful in the world, should help.

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