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Satellite-based primary forest degradation assessment in the Democratic Republic of the Congo, 2000–2010

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Abstract
Primary forest extent, loss and degradation within the Democratic Republic of the Congo (DRC) were quantified from 2000 to 2010 by combining directly mapped forest cover extent and loss data (CARPE) with indirectly mapped forest degradation data (intact forest landscapes, IFL). Landsat data were used to derive both map inputs, and data from the GLAS (Geoscience Laser Altimetry System) sensor were employed to validate the discrimination of primary intact and primary degraded forests. In the year 2000, primary humid tropical forests occupied 104 455 kha of the country, with 61% of these forests classified as intact. From 2000 to 2010, 1.02% of primary forest cover was lost due to clearing, and almost 2% of intact primary forests were degraded due to alteration and fragmentation. While primary forest clearing increased by a factor of two between 2000–2005 and 2005–2010, the degradation of intact forests slightly decreased. Fragmentation and selective logging were the leading causes of intact forest degradation, accounting for 91% of IFL area change. The 10 year forest degradation rate within designated logging permit areas was 3.8 times higher compared to other primary forest areas. Within protected areas the forest degradation rate was 3.7 times lower than in other primary forest areas. Forest degradation rates were high in the vicinity of major urban areas. Given the observed forest degradation rates, we infer that the degradation of intact forests could increase up to two-fold over the next decade.

Keywords: primary forests, intact forest landscapes, deforestation, forest degradation, remote sensing, Landsat, Democratic Republic of the Congo

1. Introduction

The Democratic Republic of the Congo (DRC) is one of the largest countries in Africa and contains almost 23% of total African forest cover (FAO 2010). DRC contains nearly half of the humid tropical forests of the Congo Basin—the second largest contiguous tropical forest realm after the Amazon (CBFP 2009). Congo Basin forests stand out globally as a region with both high carbon stocks and rich biodiversity (Strassburg *et al* 2009). The total carbon stock of the DRC is about 27 billion tons or 60% of the total carbon stock of the Congo basin countries (CBFP 2009, Gibbs *et al* 2007). The level of plant and animal species diversity and endemism is high throughout the basin especially close to the Albertine Rift (WWF 2006, Olson *et al* 2001). The Congo Basin forest is home to many large forest mammals: great apes, forest elephants, and okapi. Their distribution and survival depends

to a large extent on the unfragmented natural forest areas which are still present within the region (WWF 2006).

While the annual deforestation rate of the Congo Basin is relatively low compared to the Amazon and south-east Asian tropical forests (FAO 2010), the DRC features the highest deforestation area among central African countries (CBFP 2009). During the last two decades, political unrest, corruption, and poor governance have stimulated unregulated resource exploitation, including timber removal, charcoal production, artisanal and commercial mining, and wildlife poaching. These activities within the country threaten the remaining population of great apes and many other large forest mammals (WWF 2006). High population densities (second highest among central Africa countries; CBFP 2009) depend on subsistence agriculture, a primary cause of forest conversion and degradation. Additional forest degradation and resulting biodiversity loss are caused by new and existing infrastructure: transportation routes, mining and logging roads (WWF 2006, Laporte *et al* 2007, Clark *et al* 2009). Forest roads provide access to heretofore intact areas and fragment forest habitat increasing anthropogenic pressure and reducing forests' capacity to host wide-ranging species and to resist natural disasters and climate change effects (Tabarelli *et al* 2004, Laurance *et al* 2006, Thies *et al* 2011). High population growth rates and armed conflicts stimulate human migration inside core forests (Draulans and van Krunkelsven 2002). This process is, in general, uncontrolled and little information about population distribution and forest use exists at the national scale.

The use of medium spatial resolution satellite data provides a means for regular assessment and monitoring of forest change. The medium resolution data collected by the Landsat program have been used to map and monitor DRC forests since the 1970s. The first nation-wide land cover maps were created by the Service Permanent d'Inventaire et d'Amenagement Forestier (SPIAF) with the support of US-AID (United States Agency for International Development) and CIDA (Canadian International Development Agency) in 1970–1990 (Wilkie 1994). Landsat multi-spectral scanner (MSS) data have been used to map forest cover change within selected areas of the DRC (Justice *et al* 1993). It was found, however, that the coarse spatial resolution of MSS data and limited spectral information was inadequate to map small-scale changes resulting from subsistence agriculture (Wilkie 1994). Landsat thematic mapper (TM) and enhanced thematic mapper plus (ETM+) sensors partially overcome these issues by offering higher spatial resolution and short-wave infrared (SWIR) spectral bands important for forest cover loss and infrastructure detection. Landsat data were employed to provide national-scale estimates of forest cover and change within DRC for 1990–1997 (Achard *et al* 2002), 1990–2000 (Duveiller *et al* 2008), 2000–2005 (Hansen *et al* 2008b, Ernst *et al* 2012) time intervals using sampling approaches. While sampling approaches are an effective and fast way to provide forest cover and change estimates, their precision is usually low due to uneven change distribution within the country (Tucker and Townshend 2000). In fact, the standard error of Duveiller *et al* (2008) change

estimate is almost 25% of the total change area. Using a stratified sampling design could increase sample-based change estimate precision (Broich *et al* 2009), however, only Hansen *et al* (2008b) employed stratification based on independently derived low spatial resolution change map.

In contrast to sample-based methods, wall-to-wall mapping approaches have several advantages for forest cover and change estimates within Central Africa. First, it is better suited for change area estimation within regions featuring small-scale and non-random change dynamics. If change is not targeted directly using ancillary information, systematic sampling methods are used and require large sample sizes to reduce overall uncertainty estimates (Broich *et al* 2009). Mapping change directly overcomes this limitation. Second, wall-to-wall maps can be used to analyze the explicit spatial distribution of deforested and degraded areas, analysis of drivers of forest disturbance, and provide the disaggregation of change estimates to sub-national, even local scales (Potapov *et al* 2012). Third, complete forest and change maps are required for national-scale and local land-use planning, for conservation strategies implementation, and for forest use sustainability assessments within logging concessions.

The potential for satellite-based technology to contribute towards national-scale wall-to-wall assessments was restricted until recently due to the combined impacts of high data costs and persistent cloud cover within humid tropical regions. The recent changes in the distribution policy for Landsat data and progress in automated Landsat data processing have enabled wall-to-wall forest mapping and monitoring for large regions such as the DRC (Hansen *et al* 2008a). Freely distributed medium spatial resolution satellite data have been used to provide the first Landsat-based nation-wide forest cover map and to analyze forest cover change from 2000 to 2010 (Potapov *et al* 2012). This work was supported by the USAID-funded CARPE (Central Africa Regional Program for the Environment) project. Forest cover and change maps (hereafter referred to as 'CARPE dataset') can be viewed and downloaded from the CARPE web site (http://congo.iluci.org/carpemapper/).

Mapping forest degradation is a more difficult task compared to forest cover loss in the form of stand-replacement disturbances. A universal definition of forest degradation is absent (Schoene *et al* 2007). For practical reasons degradation is usually defined as a reduction of tree canopy cover and carbon stock, while other aspects of forest ecosystems, like reduction of biodiversity and ecological integrity, are usually omitted (Sasaki and Putz 2009). One way to estimate canopy reduction mapped as 'forest degradation' was presented by Duveiller *et al* (2008). Forest degradation was defined as the expansion of a 'degraded forest' class, defined as 'dense forest perforated by small logging clearings or crop fields' (Duveiller *et al* 2008). However, this approach does not disaggregate pervasive forest cover loss (due to small-scale agriculture expansion) from forest fragmentation and selective logging. The use of medium spatial resolution wall-to-wall change detection products (like CARPE dataset described above) that provide information on small-scale forest cover change makes the step of mapping the forest-agriculture

mosaic as 'degraded forests' redundant. These products, however, don't enable the estimation of another factor of tree canopy reduction—selective logging. Congo Basin timber production relies on low intensity selective logging which has little effect on tree canopy cover change (Brown *et al* 2005). Moderate spatial resolution satellite data are of limited value in quantifying low intensity disturbances (Asner *et al* 2002). However, areas of selective logging are usually manifested by the presence of logging road infrastructure (Margono *et al* 2012). Buffering existing clearings and logging roads could be used to estimate the extent of degraded forests (Mollicone *et al* 2007).

Fragmentation analysis has been demonstrated by various research groups in assessing forest degradation at the global scale (McCloskey and Spalding 1989, Bryant *et al* 1997, Sanderson *et al* 2002, Kareiva *et al* 2007). However, these analyses were based on existing global maps, which were of extremely poor quality for Central African countries. The alternative approach, called the intact forest landscapes method, based on medium spatial resolution satellite data, has been developed by a group of scientists and environmental non-governmental organizations led by Greenpeace and the World Resources Institute (Potapov *et al* 2008). The essence of the approach is to establish the boundaries of large undeveloped forest areas, or intact forest landscapes (IFL), and to provide timely monitoring of forest conversion and degradation within them. The IFL method has been prototyped for forest degradation assessment and monitoring within European Russia, Central Africa and other regions (Potapov *et al* 2009, Zhuravleva 2011). IFL mapping results within the Tropics for circa 2000, 2005 and 2010 can be viewed and downloaded from a dedicated web site www.intactforests.org/data.monitoring.html.

The objective of the current research is to assess the degradation of primary humid tropical forests within DRC from 2000 to 2010. The year 2000 national-scale primary forest extent from the CARPE dataset (Potapov *et al* 2012) was used as a baseline for our assessment. Primary forests were defined as mature dense natural forests with tree canopy density above 60%. The intact forests were mapped within primary forest area using the IFL method (Potapov *et al* 2008). The combination of IFL and primary forest maps allowed us to analyze intact and non-intact or degraded primary forests (those not meeting IFL criteria) separately. Forest clearing, selective logging and consequent forest landscapes fragmentation were considered to be forms of forest degradation. Forest cover loss data from 2000 to 2010 were taken from CARPE dataset, while IFL change monitoring was performed for the 2000–2010 interval using available cloud-free Landsat image composites. Aggregation of forest cover loss and IFL degradation maps enabled the analysis of primary forest degradation in terms of forest clearing and fragmentation. Forest degradation drivers and threats were analyzed using additional information (protected areas maps and logging permits) provided by the World Resources Institute (WRI 2010). Our results provide a framework for prospective assessments of threatened primary forests from 2010 to 2020.

1.1. Historical background of forest alteration in the DRC

As the African continent is the birthplace of the human race, anthropogenic activity has been a part of ecosystem dynamics in the Congo basin for millennia. The most important factor in shaping the present ecoregion boundaries was wide-scale use of fire for hunting and forest clearing. It is believed that shrinking forest cover and expansion of present day savanna and woodlands ecosystems in the southern part of the basin was driven by prehistoric fire use and that current savanna extent is sustained due to frequent fires (Beerling and Osborne 2006, Bond *et al* 2005). The Bantu migration that started around 1000 BC (Oliver 1966) fueled continued agricultural expansion along the humid tropical forests and savannas interface. However, the population of core humid tropical forest areas remained low until the 20th century.

Intensive forest conversion and fragmentation of natural ecosystems was initiated during the late 19th century in the colonization of the region under the Congo Free State (1884–1908) with intensification of mining operations, logging, and cash-crop agriculture. Industrial timber extraction began in 1924 (Amsallem 2002). At the peak of industrial development in the Belgian Congo in the 1950s, the country was the main exporter of agricultural products and minerals in central Africa. At the same time, agricultural expansion and industrial activity were limited within the central part of the Congo Basin. Agricultural clearing, pasture expansion and mineral resource exploitation were mostly concentrated to the eastern part of the basin, in the Albertine Rift and the lake region (Mararo 1997, Carrere 2010). In the western part of the country, most of the plantations and agriculture were located along the Congo River close to the capital. Timber was a valuable export product, but logging was limited as most of the tropical forests were located far from ports, making transportation time-consuming and expensive (Hance and van Dongen 1958).

Since the 1980s, and especially during the armed conflicts that started in 1996 (First Congo War 1996–1997 and Second Congo War 1998–2003), industrial development declined—timber harvest volumes within the DRC were the lowest among central African nations for 2007 (CBFP 2009, Carrere 2010). Agriculture plantation production continue to decrease, plantations were abandoned, exports halted, and no new plantations initiated (Carrere 2010). However, the population growth and displacement during the period of political unrest caused unregulated expansion of small-scale subsistence agriculture into primary forests. In some regions of the DRC, the war led to the displacement of populations away from road networks and into interior forests (Draulans and van Krunkelsven 2002). Illegal logging, charcoal production, mining, and poaching flourished during this period of political and civil instability. However, without the construction of new infrastructure, new frontiers of agricultural expansion, hunting and logging were limited.

Since the end of the Second Congo War in 2003, and especially since 2005, economic activity is again increasing within the country, although pockets of civil instability remain. In 2009, a review of forest logging permits was

completed by DRC through a multi-stakeholder process and 65 logging permits meeting legality criteria were reinstated; further permits were approved in 2011. A moratorium established in 2005 banned the allocation of new industrial logging permits and is still in effect (WRI 2010). Most of the logging permits are owned by foreign investment companies. Commercial plantation activity has also been restored, with recent attempts to invest in industrial oil palm production by American, European, Canadian and Chinese companies (Carrere 2010). On the other hand, persistent conflicts and the global economic downturn recently increased threats from illegal timber extraction, poaching, artisanal mining and subsistence agriculture expansion (Draulans and van Krunkelsven 2002, Endamana *et al* 2010). One more driver of primary forest degradation is the artisanal logging permit system (Greenpeace 2012). While the moratorium bans the allocation of new industrial logging permits, the DRC government issues artisanal logging permits in 'community' forests for small Congolese businesses. However, with the persistent lack of law enforcement, the process of permit issuing is uncontrolled, and, according to local ecological organizations (Greenpeace 2012), some of the logging permit areas are used for industrial logging.

2. Data

Landsat imagery was used as the main information source for our analysis as it represents the only freely available medium spatial resolution satellite-based dataset over Central Africa. While high spatial resolution data provided by commercial satellite systems may deliver better precision in human influence mapping, their use is limited due to the high data cost and/or restricted distribution. Another important advantage of the Landsat program is its data acquisition strategy that ensures nation-wide observation coverage for the last decade from the ETM+ sensor.

The national-scale forest cover mapping and monitoring CARPE dataset from 2000 to 2010 of Potapov *et al* (2012), as well as the IFL map update for 2000, 2005 and 2010 were generated using time-sequential cloud-free Landsat data composites and time-series metrics. The data processing approach employed the entire archive of Landsat 7 data from 1999 to 2010 (8881 images total, 78 images per scene footprint on average). The data processing algorithm is described in detail by Potapov *et al* (2012). Source images were automatically processed to mask all cloud and cloud shadow affected areas, and radiometrically normalized using standard MODIS-derived surface reflectance products. Composites of high quality observations closest in time to January, 1 of year 2000, 2005, and 2010 were used as a source data for visual image interpretation and IFL map updates.

Because the initial year 2000 IFL mapping (Potapov *et al* 2008) was done before the full Landsat data archive was made available, data from the Global Land Cover Facility (http://glcf.umiacs.umd.edu), specifically the Global Land Survey (GLS 2000) image collection was used (Gutman *et al* 2008) for this reference year. One of the main disadvantages of the GLS dataset is the low observation density, mostly restricted to a single image per each scene footprint. To improve image interpretation quality and to map past forest degradation events, GLS 1990 data were also used to aid visual interpretation.

Data from GLAS (Geoscience Laser Altimetry System) for year 2005 were used as reference to test differences in canopy cover structure between intact and degraded forests. The year 2005 was chosen as the year of inter-comparison as this period coincides with GLAS data acquisitions, which were made from 2003 to 2009. GLAS data were screened for noise and cloud cover, and transformed into estimation of canopy height and the height of median energy (HOME), as described in Goetz *et al* (2010). In total, 226 735 60 m ellipsoidal footprints with GLAS-derived canopy structure metrics for the year 2005 were employed.

3. Methods

The forest degradation assessment was performed within primary humid tropical forests of the year 2000. Primary forests were defined as mature humid tropical forests with tree canopy cover above 60% (Potapov *et al* 2012). Primary forests were mapped using Landsat image composites and spectral metrics employing visually interpreted training data and a supervised decision tree classifier (Potapov *et al* 2012). The IFL method (Potapov *et al* 2008) allowed us to disaggregate the year 2000 primary forests into intact primary forests (within IFLs) and non-intact or degraded primary forests (outside IFLs). The IFL definition and mapping method are outlined below (section 3.1). Degraded primary forest defined as a natural forest which has been fragmented or subjected to forest utilization including wood and or non-wood forest product harvesting that alters the canopy cover, and overall forest structure (ITTO 2002, Margono *et al* 2012).

Forest degradation was defined as remotely detectable anthropogenic alteration and fragmentation of primary forests. Some forest disturbance events, namely gross forest cover loss due to subsistence agriculture clearing, road construction, and settlement expansion could be directly mapped using Landsat data. Gross forest cover loss for 2000–2010 was mapped by Potapov *et al* (2012) using multi-temporal Landsat spectral metrics and a supervised change detection algorithm. Gross forest cover loss was assessed within both intact and degraded primary forests.

Forest degradation events, like selective logging and landscape fragmentation, could not be directly mapped using Landsat data in the DRC. To address small-scale and scattered forest degradation, the IFL method was employed. This method enabled the mapping of areas affected by selective logging by buffering logging roads, and to map small primary forest fragments separated from the core intact forests by transportation routes and agricultural areas. Areas affected by fragmentation and selective logging could not be distinguished using the IFL method, and were analyzed together. The fragmentation and selective logging assessments were performed only within intact primary forests, and resulted in the reclassification of intact primary forests to degraded primary forests.

Forest degradation was assessed for two 5 year time intervals (2000–2005 and 2005–2010) to estimate temporal trends. The roles of each forest degradation factor (clearing and fragmentation) have been analyzed separately. Both primary forest clearing and intact primary forest degradation were defined as unidirectional change events, and no primary forest expansion (through land abandonment and natural restoration) was considered. For primary forests, our change mapping approach was similar to the one applied for Brazil within the PRODES (Programa de Cálculo do Desflorestamento da Amazônia) project (Câmara *et al* 2006). We considered the year 2000 primary forest extent as a baseline, and no primary forest gain was considered during the analysis timeframe. For the IFL mapping, all disturbances that have occurred within the past 30 years are excluded from the intact area according to the IFL mapping methodology (Potapov *et al* 2008). This age since disturbance criterion does not allow considering intactness gain during the decadal analysis timeframe.

3.1. IFL mapping and monitoring

An intact forest landscape (IFL) is defined as an unbroken expanse of natural ecosystems that exhibit no remotely detectable signs of human activity or habitat fragmentation and is large enough to maintain all native biodiversity, including viable populations of wide-ranging species (Potapov *et al* 2008). Along with forests, an IFL may include a small fraction of other natural ecosystems (lakes, swamps, rocks, etc). The IFL mapping approach is based on 'inverse logic', i.e. on mapping the opposite of intactness: altered and fragmented forest areas. Medium resolution satellite data were used to map areas affected by alteration or conversion (clearing, logging, infrastructure development, etc). To assess fragmentation, all infrastructure and settlements were buffered by 1 km, and the remaining areas were checked to fit the IFL size and width criteria. For the national-scale IFL analyses, the following criteria were used: (1) minimum area of 50 thousand ha (kha); (2) minimum IFL patch width of 10 km; and (3) minimum corridor/appendage width of 2 km. The criteria were chosen to insure that IFL patch core areas are large enough to provide refuge for wide-ranging animal species.

Decadal IFL monitoring was performed separately for two 5 year intervals: 2000–2005 and 2005–2010, to correspond with the CARPE dataset. The IFL map for year 2000 is a subset of the global IFL mapping results (Potapov *et al* 2008). For the current analysis, the IFL map was updated using additional data, namely cloud-free Landsat image composites and regional expert information. The IFL boundaries were updated for years 2005 and 2010 using Landsat data visual interpretation and the same set of criteria as for initial IFL mapping. For the visual interpretation we used start and end-point image composites (e.g. circa 2000 and circa 2005) along with SWIR band difference images which facilitate forest change detection. All areas cleared or fragmented within the analyzed period were excluded from the IFL map (figure 1). The area and width of the remaining IFL patches were analyzed to exclude patches that no longer fit our fragmentation criteria.

3.2. Forest degradation drivers and threats assessment

The gross forest cover loss and intact forest degradation rates were used for comparison. 10 year and 5 year change rates were calculated by dividing the forest loss (or intact forest degradation) area within specified time interval by the primary (or primary intact) forest area for the beginning of the time interval.

The forest degradation data have been analyzed for the entire country, by administrative units (provinces), logging permits, and protected areas using boundary layers from the Interactive Forest Atlas of the DRC (WRI 2010). The logging permits database used in this analysis was updated by the WRI in 2012 to include new logging titles deemed convertible to legal logging concessions in January 2011. In addition, we analyzed forest degradation within buffer zones of 5 km around protected areas.

To analyze primary forest loss and degradation due to urban population growth, an analysis of forest cover change and degradation rates was performed within a 100 km radius of the major 55 urban areas of the DRC (Potapov *et al* 2012). Urban areas were selected based on population density derived from the LandScan 2005 Global Population Database (Dobson *et al* 2000).

A forest degradation threats assessment was performed for the primary intact forests for the year 2010 to highlight areas under imminent threat of exploitation. Two main factors of forest degradation were accounted for: agriculture and infrastructure expansion from the established settlements and transportation routes, and legal industrial timber harvesting. To predict the possible reduction of intact forest areas for the 2010–2020 time interval, a buffering approach was implemented using the IFL 2010 map as a starting point. Our prediction model was based on the following assumptions: (i) the speed of agriculture expansion within intact forests during this coming decade will be similar to the one observed for the 2000–2010 interval; (ii) the forest degradation frontier will expand in all directions with the same speed; and (iii) the maximum speed of the penetration fragmented/converted areas into IFL patches will be less or equal to 1 km yr^{-1}, similar to what has been observed for the 2000–2010 interval (Potapov *et al* 2012). We predicted the expansion of the degraded forest area from every compact patch of forest degradation detected from 2000 to 2010. For each patch, the maximum distance between the year 2000 and year 2010 IFL boundaries was measured, and employed to map maximal possible expansion of degraded area by the year 2020 using the buffering approach. To predict the threat of industrial logging, we assume that industrial timber harvesting will be limited to the extent of established logging permits, and that no new logging titles will be approved during the next decade. We analyzed logging companies' activity within current logging permits. Using these data we predicted which permits have the highest probability of being exploited in the nearest future. From the existing logging permits containing intact forests for 2010, we selected those that fulfil at least one criterion: (i) intact forest degradation 2000–2010 within the permit was higher than the average among all permits in
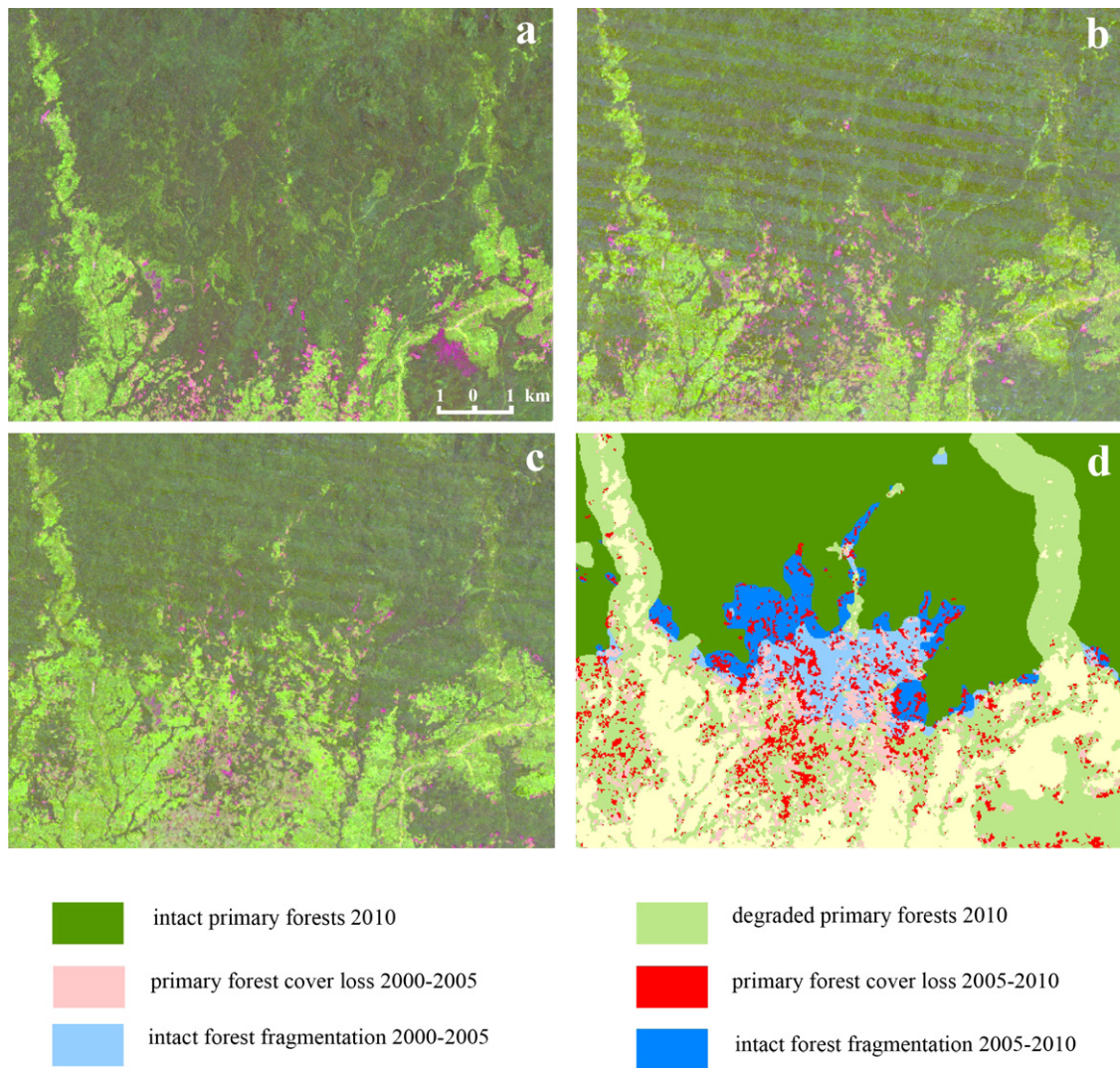
Figure 1. Composite images and forest degradation monitoring results. Landsat image composites (Orientale Province, subset centered at 03° 0′ 29″ north 24° 48′ 55″ east): (a) circa year 2000; (b) circa year 2005; (c) circa year 2010; (d) primary forest cover and forest degradation, 2000–2010.

the DRC, and (ii) the permits belong to companies which have higher 10 year rate of forest degradation than the average among all companies in the DRC. After predicting the expansion of degraded areas for the 2010–2020 time interval, the IFL layer was updated and remaining IFL patches checked to fit our size criteria. The modeling approach was used to highlight areas with a high probability of intact forest degradation within the coming decade.

### 3.3. Structural comparison of intact and degraded forest classes

The canopy height and HOME estimations derived from GLAS data have been shown to relate to tree canopy structure, biomass (Baccini *et al* 2008), and forest degradation due to selective logging (Margono *et al* 2012). GLAS-derived data for 2005 were used within the DRC to quantify structural differences between primary intact, primary degraded and other forests. The CARPE and IFL maps for 2005 were used

as the basis for the analysis. To avoid problems that may arise within recently deforested patches, all forest cover change areas from 2000 to 2005 were excluded from the analysis. Because the GLAS laser illuminates an approximately 60 m ellipsoidal footprint, the forest cover type from the 60 m pixel nearest to the footprint center was used for comparison. The mean and standard deviation of canopy height and HOME parameters were calculated for each forest type, and the statistical significance of the inter-class differences evaluated using a 95% *t*-test confidence interval.

4. Results

4.1. IFL and primary forests for year 2000

Within-country IFL area for the year 2000 was 64 676 kha. The national IFL extent stands out as the second largest within the tropical forest biome, after Brazil (Potapov *et al* 2008). According to the CARPE forest cover map of the
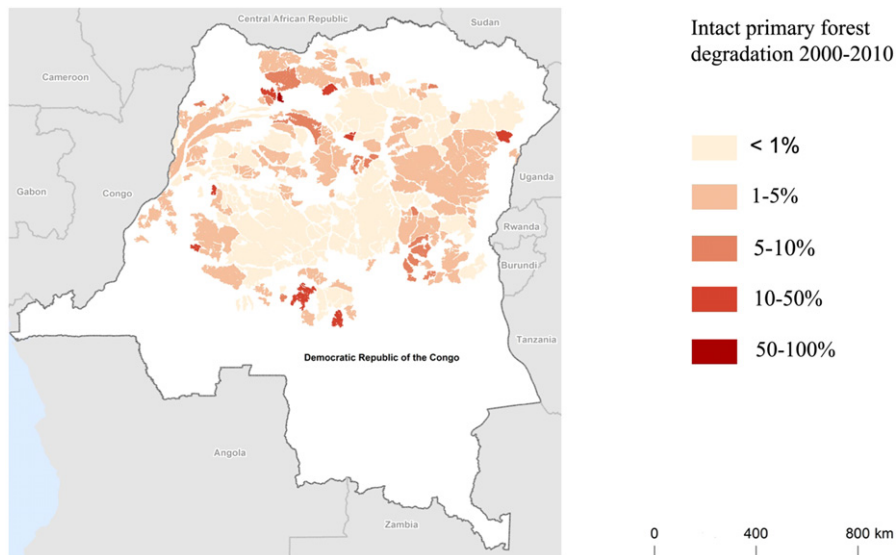
Figure 2. Intact primary forest degradation 2000–2010 by IFL patch.

year 2000 IFLs in the DRC almost exclusively consist of primary humid tropical forests (99.2% of the year 2000 IFL area). The remaining 0.8% was classified as secondary forests, water bodies, and non-forest lands (primarily rocky outcrops). Intact forests are located in the central and northern parts of the country within the Congo River basin, mostly within Congolian lowland and swamp forests, with a small fraction in the Albertine Rift montane forests.

For the year 2000, primary humid tropical forests occupied 104 455 kha of the country (Potapov *et al* 2012). From this area, 61% were found within IFLs and classified as primary intact forests. The remaining 39% of primary forests have been fragmented or affected by selective logging, and were labeled degraded primary forests.

4.2. Primary forest degradation 2000–2010

From CARPE dataset, the total area of primary forest loss was 1067 kha, and the loss area nearly doubled (from 367 to 701 kha) between the two analyzed 5 year intervals. The forest loss represents 1.02% of total primary forests of year 2000 (12% occurred within intact primary forests and 88% within degraded primary forests). Primary intact forest extent was reduced by 0.2%, and primary degraded forests by 2.3%.

The change in area of intact primary forest is used as a fragmentation indicator. From 2000 to 2010 the area of intact primary forest decreased by 1214 kha which represents nearly 2.0% of the year 2000 area. Intact forest fragmentation decreased slightly over the two epochs, with 624 kha lost during the first 5 years, and 590 kha during the second half of the decade. The degradation rate was spatially heterogeneous as illustrated by a per-patch IFL change analysis (figure 2). From 187 IFL patches mapped in 2000, 160 had lost less than 5% of their area during the decade, 19 had lost 5–10%, 8 lost 10–40% and one IFL patch was excluded due to patch area reduction below the IFL minimal area threshold.

To illustrate the spatial variability in forest degradation, we provide a disaggregation of primary forest area and change per province (table 1, figure 3). As of 2000, eight DRC provinces contained primary intact forests and three none. From these three provinces, two (Bas-Congo and Kinshasa) likely lost their primary forest cover due to historic clearing, and one (Katanga) is located mostly outside the humid tropical forest biome. The primary forest cover was predominantly intact within the northern and eastern parts of the country, while in more populated provinces (Bandundu and Kasai-Occidental), more than 50% of primary forests were fragmented or degraded.

Of all primary forest loss, nearly half (49%) was found in the Northern part of the country (Equateur and Orientale provinces). However, the decadal rate of primary forest loss was highest within the densely populated Kinshasa and Bas-Congo provinces which lost 9.6% and 4.6% of their primary forests, respectively. Between the 2000–2005 and 2005–2010 time intervals, primary forest loss increased in all provinces, but the highest increase (more than by factor of two) was detected in Kinshasa, Nord-Kivu, Kasai-Occidental and Bandundu provinces.

The vast majority of intact forest degradation (74%) was detected in the northern part of the DRC within Equateur, Orientale and Nord-Kivu provinces. Nord-Kivu had the highest rate of intact forest degradation, losing 5.3% of its primary intact area during the decade. The rate of intact forest degradation differed by region between two 5 year intervals. It decreased in Nord-Kivu (almost by factor of five) and Kasai-Occidental (by factor of four); increased in Equateur province by factor of four; and remained relatively stable for the rest of the country.

4.3. Forest degradation factors

Two major degradation factors, forest clearing and fragmentation (including areas affected by selective logging), were
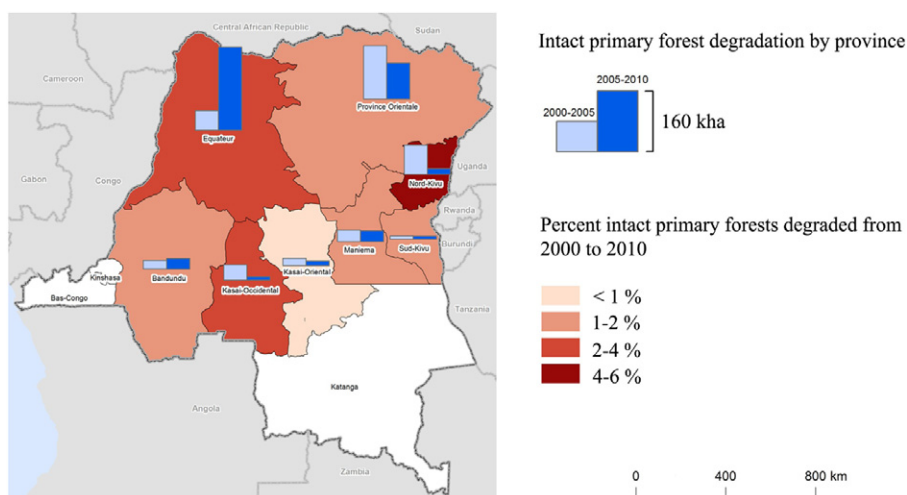
Figure 3. Intact primary forest degradation 2000–2010 in the DRC (by province).

Table 1. Primary forests cover and change by DRC province.

Province name	Total primary forests 2000 (kha)	Intact primary forests 2000 (%)	Total primary forest loss 2000–2005 (kha)	Total primary forest loss 2005–2010 (kha)	Intact primary forest degradation[a] 2000–2005 (kha)	Intact primary forest degradation[a] 2005–2010 (kha)
Country total	104 455	61.4	367	701	624	590
Bandundu	10 018	48.2	33.8	67.6	42	35
Bas-Congo	79	0.0	1.3	2.3	0	0
Equateur	31 227	57.7	90.1	162.2	330	78
Kasai-Occidental	6 802	45.4	52.8	110.4	14	62
Kasai-Oriental	7 881	67.6	36.6	62.5	18	29
Katanga	621	0.0	3.5	5.3	0	0
Kinshasa	15	0.0	0.4	1.0	0	0
Maniema	7 721	63.6	30.1	54.0	44	46
Nord-Kivu	3 595	72.5	10.0	26.4	22	116
Province Orientale	33 234	70.3	91.7	180.4	142	211
Sud-Kivu	3 262	62.0	16.3	28.5	12	13

[a] Including forest cover loss and fragmentation within intact primary forests.

assessed separately using a combination of forest loss and IFL change detection methods. Of the area of primary intact forest degradation, 9% was due to clearing and the remaining (91%) due to fragmentation and selective logging.

Visual analysis of the Landsat image composites within the IFL change areas shows that fragmentation is caused both from agricultural expansion and infrastructure development, primarily of logging roads. Logging road construction is expected to occur within officially designated logging permits. The impact of selective logging and agricultural expansion within areas of designated logging permits was analyzed using a logging titles spatial database. The expansion of forest degradation should be limited by the implementation of a national nature conservation strategy, especially within officially designated protected areas. The forest degradation analysis within protected areas illustrates the effectiveness of governmental regulations.

4.3.1. Forest degradation within logging permits. There are 80 logging permits operated by 26 companies provisionally

approved for subsequent concession contract establishment in the DRC, including 65 permits approved by 2009 (WRI 2010), and 15 permits approved in 2011. Logging titles cover an area of 14 838 kha.

In 2000, industrial logging permits included 12 706 kha of primary forest (12.2% of total primary forest area), 62% of which were classified as intact (12.4% of the total intact forest area). In total, primary forests represented 86% of the permit's area with primary intact forest covering 53%. Industrial logging permits with the largest proportion of intact forests are mostly concentrated along the Congo River in three provinces: Equateur, Orientale and Bandundu.

The rate of intact primary forest degradation within permits (5.3%) was significantly higher than outside of them (1.4%). The primary intact forest degradation area within logging permits declined between the first and second half of the decade, from 246 to 177 kha. Of the total primary forest loss, 13% (139 kha) was found within logging permits. The area of primary forest loss increased by 51% inside permits (compared to 48% outside of them) in the most recent 5 years.
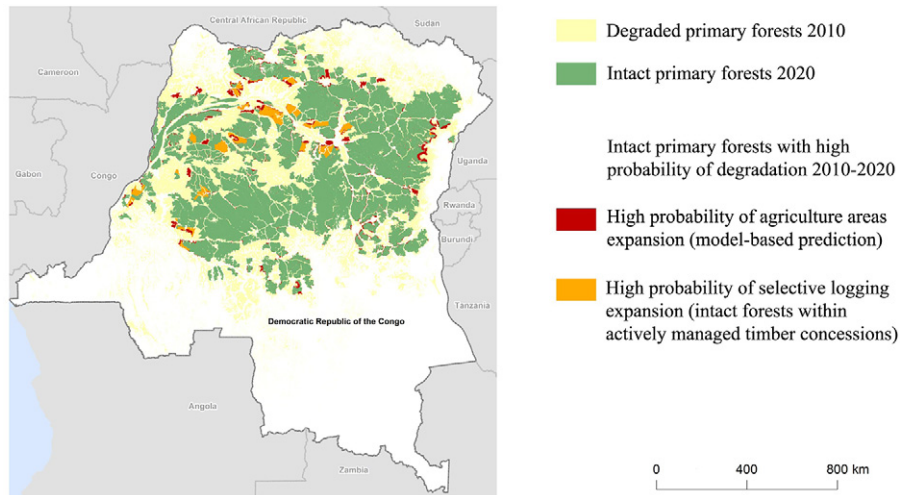
Figure 4. Intact primary forests with high probability of degradation 2010–2020.

4.3.2. Forest degradation within protected areas. Primary forests are included within 33 protected areas in the country: 5 national parks, 12 nature reserves, 2 hunting reserves and 14 hunting domains (last two categories were analyzed together). Total area of protected primary forests for year 2000 was 13 982 kha, of this 11 004 kha were intact forests. Of all intact primary forests, 7.6% and 7.1%, respectively, were located within national parks and nature reserves, and 2.4% within hunting reserves. More than 55% of primary forests within nature reserves and national parks, and about 16% of primary forests within hunting reserves were intact in 2000.

During the last decade, 41 kha of primary forests in protected areas have been cleared (including 6 kha within intact primary forests). Additionally, about 48 kha of intact primary forests were fragmented and resulted in 54 kha of intact forest area being degraded inside protected areas. The decadal rates of forest loss and degradation within protected areas were significantly lower than within the rest of country. The primary forest loss rate (0.3%) was 3.4 times lower then national average (1.02% was lost within primary forests in the DRC), and the intact primary forest degradation (0.5%) was 3.7 times lower. National parks have the lowest rate of primary forest loss and intact primary forest degradation (0.06 and 0.08%, respectively), while hunting reserves feature the highest rate of change for protected areas (0.6 and 1.7%, respectively).

Primary forest loss within protected areas increased between the first and second half of the decade by 48%. The highest increase was observed in hunting reserves (by 50%), while it decreased within National Parks from 2 kha (2000–2005) to 1 kha (2005–2010). Intact primary forest degradation decreased in all categories of protected areas by 42%. Within 5 km buffer zones around protected areas, the intact primary forest degradation rate was higher than within these areas by factor of 5.

### 4.4. Forest degradation in the vicinity of urban areas

The high rate of population growth and urbanization in the DRC is thought to be a reason for intensive primary forest degradation in the vicinity of urban areas. We analyzed 100 km buffer zones around each of the 55 major urban areas. In total, 42% of all primary forests, and 36% of intact primary forests were located within the buffer zones. The buffer zones were the site of 65% of total forest cover loss within primary forests and of 69% of all intact forest degradation. The rate of primary forest cover loss within these areas was 36% higher than the average for the country, and the rate of intact primary forest degradation was 49% higher. The primary forest cover loss area increase between 2000–2005 and 2005–2010 time intervals was twice higher compared to the national average.

4.5. Primary intact forests threat assessment

Our prediction model showed the maximum extent of intact primary forests that could be degraded during 2010–2020 if agricultural and infrastructure expansion speed was held constant. The model predicted that the intact primary forest area in the DRC could be reduced by 2435 kha during the next 10 years, or by 4% of year 2010 primary intact forest area (figure 4). The majority of the predicted changes would be due to rapid agricultural expansion in Nord-Kivu and Orientale provinces, and with logging infrastructure expansion within the logging permits in Equateur and Orientale province. Of all 2010 IFL patches, 13 small patches will have their area reduced below the IFL area threshold. The predicted intact forest degradation rate is twice higher than the observed decadal degradation rate for 2000–2010 time interval. It should be noted that our forecast model represents the maximum possible area of forest degradation and does not account for local difference in future forest degradation trends.

In addition to primary intact forests that are in the vicinity of recent degradation hotspots, intact areas within actively managed logging permits are under threat of fragmentation and alteration by industrial logging. Of 68 permits that include intact primary forests, 32 were highlighted as having the highest probability of rapid forest degradation (using set of criteria described in section 3.2). Intact forests within these active logging concessions represent 4% of the total IFL area.
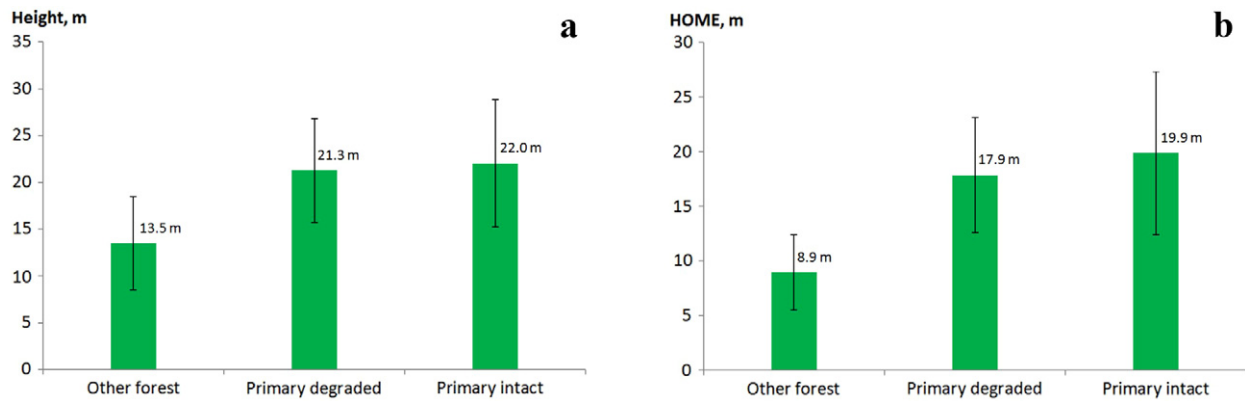
Figure 5. Mean and standard deviation of GLAS-derived within primary intact, primary degraded and non-primary ('other') forests: (a) vegetation height. (b) HOME metrics for year 2005.

4.6. Tree canopy structure metrics

Mean GLAS-derived vegetation height quantifies a difference of 0.7 m between primary intact and primary degraded forests, and a difference of 7.8 m between primary degraded and other forests (including secondary humid tropical forests and woodlands, according to the CARPE dataset). While the mean vegetation height difference between primary intact and primary degraded forest is small, it is statistically significant with *t*-test *p*-values of ≪0.000 for the 95% confidence interval. The difference of the mean HOME estimate for primary intact and primary degraded forests equals 2.0 m and is also statistically significant with *t*-test *p*-values of ≪0.000 for the 95% confidence interval (figure 5).

5. Discussion

5.1. Primary and intact forest extent in the DRC

Given the long history of anthropogenic influence and the expansion of illegal logging and poaching in recent decades, it is generally assumed that the extent of intact forest areas in the Congo basin is limited. Comparison of the IFL map for year 2000 with existing global intactness datasets (McCloskey and Spalding 1989, Bryant *et al* 1997, Sanderson *et al* 2002) showed that all former approaches, which were based on outdated and imprecise road maps in the core Central African forests, showed high forest degradation levels. In fact, medium resolution satellite imagery, analyzed from 1990 to 2010, did not reveal high road densities within the central Congo basin. According to the LandScan dataset, the mean population density in DRC within IFL for year 2000 is 3.4 persons per square km, which totals more than 2 million people. Because our mapping algorithm does not permit inclusion of any permanent settlements or agriculture areas within IFLs, such population density seems significantly overestimated. Another argument against the designation of remaining IFLs as 'intact' is the wide-scale poaching within the country leading to 'defaunization' of primary forest patches (Redford 1992). Wildlife hunting is a significant problem in central Africa, and poaching may

occur in remote areas away from roads and settlements. It was shown, however, that large animals are hunted mostly in the vicinity of roads, and within fragmented and/or secondary forests (Barnes *et al* 1995, Barnes 2002). While poaching and consequent local animal extirpation is one of the major threats to forest ecosystems in Congo Basin, hunting was not analyzed in our remote-sensing based assessment due to data limitations. Large intact forest areas selected using the IFL approach have several features that make them important for priority conservation. First, with their natural (unaltered) plant species composition and large patch areas sustaining relatively inaccessible core zones, intact forests provide a refuge for animal populations, ensuring their resilience to natural disturbances and climate fluctuations. Second, limited access due to a lack of infrastructure discourages and limits hunting. Third, these areas play an important role in carbon sequestration due to the preservation of natural forest structure and dynamics. The DRC plays an important role in primary forest conservation in Central Africa, having 41% of its total forest cover within IFLs and accounting for two-thirds of total Congo Basin IFL area.

5.2. Results accuracy and data availability

The presented analysis was based on the integration of two independent and well established methods and products: supervised Landsat-based forest cover and change mapping (Hansen *et al* 2008a, Potapov *et al* 2012), and fragmentation analysis using the IFL approach (Potapov *et al* 2008, 2009). Thus, the primary forest degradation dataset uncertainty should be derived from the source datasets (CARPE dataset and IFL dataset) uncertainty. The CARPE dataset was created using supervised expert-driven classification, similarly to other Landsat-based national-scale change estimation projects (Achard *et al* 2002, Duveiller *et al* 2008, Hansen *et al* 2008b, 2008a). To map the primary forests and change areas, an iterative supervised classification approach was used, with cross-verification by international and local experts (Potapov *et al* 2012). Presented forest cover and change estimates are close to UNFAO estimates (FAO 2010). However, the spatial accuracy of change detection was not validated due

to the lack of high spatial resolution data or field plots. The main limitation for the 2000–2010 product validation was the absence of reference field and/or high spatial resolution satellite imagery for the year 2000 epoch. Establishing a regular and recurring validation data collection strategy is required for future monitoring of the DRC (Potapov *et al* 2012).

The low intensity of selective logging did not allow us to map forest degradation directly, except for the extension of logging roads. However, we were able to predict areas that have a high probability of selective logging using the IFL approach. The IFL method had been shown to be an effective method for large-scale forest degradation assessment (Potapov *et al* 2009). The simplicity of the IFL mapping criteria and large minimal size of the IFL patch ensures that only areas without significant recent anthropogenic influence are mapped as 'intact'. The structural analysis of tree canopy cover within primary intact and degraded forests using GLAS data quantifies a structural difference between primary intact and primary degraded forests, with degraded forests having slightly lower maximum canopy height and significantly lower mean HOME values. The observed difference is most probably a consequence of selective logging practices, including the extraction of large commercially valuable trees, consequent disturbance of portions of the tree canopy during felling and removal, with a large portion of the canopy remaining intact (Brown *et al* 2005). Similar results for degraded forests affected by selective logging were obtained by Margono *et al* (2012) for Sumatra, Indonesia.

While several projects have been performed to estimate forest cover and change within the DRC, few have made their results, along with baseline satellite imagery, available for independent assessment and cross-validation. Both products used in our analysis are available online. For the IFL product, a continuous external review process has been organized on a dedicated web site (www.intactforests.org). The CAPRE map is also freely available (http://congo.iluci.org/carpemapper). Both the CARPE and IFL maps are being used as the basis for the National Forest Monitoring system of the DRC (www.rdc-snsf.org). We believe that the unrestricted distribution of satellite-derived products is a fast and effective way for cross-validation and quality assessment.

5.3. Forest degradation factors and intact forests conservation strategy

Our analysis of forest degradation factors (forest loss and fragmentation) performed independently for two 5 year time intervals showed that while forest cover loss nearly doubled, intact forest fragmentation remained stable and even decreased slightly. Visual image analysis and literature review suggested that the major driver of forest loss and fragmentation was agricultural expansion and other means of forest clearing (e.g. charcoal production) fueled by population growth. As population continued to increase, so did subsistence agriculture area expansion. However, agricultural expansion was mostly located around settlements and existing infrastructure objects, affecting mainly degraded

forests. The observed rate of forest loss within degraded primary forests was 12 times higher compared to intact areas. The highest forest degradation rates were observed in the eastern part of the country along the Congo River, close to the Great Lakes region, and in the vicinity of mining towns in the southern forest/savanna border. Nord-Kivu province was a noteworthy hope spot, where agricultural expansion was probably related to internally displaced populations.

Industrial logging, one of the most important factors of forest fragmentation in other central African countries (e.g. Gabon and the Republic of Congo) remained limited within the DRC due to political and economic instability. Limited industrial logging expansion is thought to be the primary reason why intact forest degradation in the DRC is the less compared to other countries of the Congo basin (Zhuravleva 2011). Fragmentation by logging roads was detected mostly in the eastern part of the country, especially within areas having approved logging permits, where it slowed during the second half of the decade. Several factors could be responsible for the observed degradation reduction including the global economic downturn of 2008. Because forest fragmentation in the DRC is mostly connected with agriculture expansion, and not with selective logging, intact forest fragmentation reduction within the DRC was smaller compared to other Central African countries where IFL degradation decreased from 3.5% in 2000–2005 to 2% in 2005–2010 (Zhuravleva 2011). The future of intact forests within the DRC timber concessions depends on the successful implementation of government policies.

Considering current agriculture and road network expansion speed, we predicted that intact forest degradation could increase up to two-fold during the next decade. This scenario is plausible taking into account the high rates of population growth. However, due to the intensification of selective logging within current logging permits, the rate of intact forest degradation could increase even higher. Protected areas establishment could be one way to preserve intact primary forests. Our analysis shows that both intact primary forest degradation and forest loss within protected areas were significantly lower than the national average. National parks were the most effective in protecting primary forests from degradation. The rate of intact primary forest degradation within a 5 km buffer around protected areas was significantly higher than inside the protected areas, illustrating the ongoing threats from neighboring developed areas.

The derived primary forest cover map, change detection results, and forest degradation prediction model results could be used as a baseline for forest conservation planning within the country. New road construction opening access to heretofore intact forest areas should be considered the greatest threat to intact forest areas. While intact primary forest protection should be considered as a goal, it is expected that there will be a further degradation of the remaining primary forest. In this case, a zoning strategy could be implemented to minimize infrastructure impact on core intact forest areas, while leaving peripheral parts for sustainable use (Thies *et al* 2011, Sidle *et al* 2012). Zoning strategies have been successfully implemented in some of the central African

countries, e.g. in Cameroon (WRI 2007). The 'permanent forest zone' in Cameroon prohibits forest conversion to agriculture or plantations. This zone is further separated into strictly protected areas and logging concessions, where limited timber extraction is permitted. In the DRC zoning have been successfully implemented on a sub-national level, specifically within Congo Basin Forest Partnership (CBFP) landscapes (Sidle *et al* 2012). National-scale forest zoning in DRC is supported by a National Steering Committee for Forest Zoning since 2009. Another important tool would be limiting access and supporting vegetation restoration on abandoned logging roads to prevent expansion of hunting range and agricultural clearing. Land-use zoning and management planning is especially important within degraded primary forest to prevent further land degradation and permanent deforestation.

References

Achard F, Eva H D, Stibig H J, Mayaux P, Gallego J, Richards T and Malingreau J P 2002 Determination of deforestation rates of the world's humid tropical forests *Science* **297** 999–1002

Amsallem I 2002 *Status and Trends in Forest Management in Central Africa* (*Forest Management Working Paper* vol 3) (Rome: FAO, Forest Resources Development Service, Forest Resources Division)

Asner G P, Keller M, Pereira R and Zweede J C 2002 Remote sensing of selective logging in Amazonia assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis *Remote Sens. Environ.* **80** 483–96

Baccini A, Laporte N, Goetz S J, Sun M and Dong H 2008 A first map of tropical Africa's above-ground biomass derived from satellite imagery *Environ. Res. Lett.* **3** 045011

Barnes R F W 2002 The bushmeat boom and bust in West and Central Africa *Oryx* **36** 236–42

Barnes R F W, Bloom A and Alers M P T 1995 A review of the status of forest elephants it Loxodonta africana in Central Africa *Biol. Conserv.* **71** 125–32

Beerling D J and Osborne C P 2006 The origin of the savanna biome *Glob. Change Biol.* **12** 2023–31

Bond W J, Woodward F I and Midgley G F 2005 The global distribution of ecosystems in a world without fire *New Phytol.* **165** 525–38

Broich M, Stehman S V, Hansen M C, Potapov P and Shimabukuro Y E 2009 A comparison of sampling designs for estimating deforestation from Landsat imagery: a case study of the Brazilian Legal Amazon *Remote Sens. Environ.* **113** 2448–54

Brown S, Pearson T, Moore N, Parveen A, Ambagis S and Shoch D 2005 *Impact of Selective Logging on the Carbon Stocks of Tropical Forests: Republic of Congo as a Case Study* (Arlington: Winrock International)

Bryant D, Nielsen D and Tangley L 1997 *The Last Frontier Forests: Ecosystems and Economies on the Edge* (Washington, DC: World Resources Institute)

Câmara G, Valeriano D M and Soares J V 2006 *Metodologia para o Cálculo da Taxa Anual de Desmatamento na Amazônia Legal* (São José dos Campos: INPE)

Carrere R 2010 *Oil Palm in Africa: Past, Present and Future Scenarios* (*World Rainforest Movement Series on Tree Plantations* vol 15) (Montevideo: World Rainforest Movement)

CBFP (Congo Basin Forest Partnership) 2009 *The Forests of the Congo Basin—State of the Forest 2008* ed C de Wasseige, D Devers, P de Marcken, A R Eba'a, R Nasi and

Ph Mayaux (Luxembourg: Publications Office of the European Union)

Clark C J, Poulsen J R, Malonga R and Elkan P W Jr 2009 Logging concessions can extend the conservation estate for Central African tropical forests *Conserv. Biol.* **23** 1281–93

Dobson J E, Bright E A, Coleman P R, Durfee R C and Worley B A 2000 LandScan: a global population database for estimating populations at risk *Photogramm. Eng. Remote Sens.* **66** 849–57

Draulans D and van Krunkelsven E 2002 The impact of war on forest areas in the Democratic Republic of Congo *Oryx* **36** 35–40

Duveiller G, Defourny P, Desclée B and Mayaux P 2008 Deforestation in Central Africa: estimates at regional, national and landscape levels by advanced processing of systematically-distributed Landsat extracts *Remote Sens. Environ.* **112** 1969–81

Endamana D, Boedhihartono A K, Bokoto B, Defo L, Eyebe A, Ndikumagenge C, Nzooh Z, Ruiz-Perez M and Sayer J A 2010 A framework for assessing conservation and development in a Congo Basin Forest Landscape *Trop. Conserv. Sci.* **3** 262–81

Ernst C, Verheggen A, Mayaux P, Hansen M and Defourny P 2012 Central African forest cover and cover change mapping *The Forests of the Congo Basin—State of the Forest 2010* ed C de Wasseige, P de Marcken, N Bayol, F Hiol, Ph Mayaux, B Desclée, R Nasi, A Billand, P Defourny and A R Eba'a (Luxembourg: Publications Office of the European Union) pp 23–42

FAO (Food and Agricultural Organization) 2010 *Global Forest Resources Assessment 2010* (Rome: UNFAO)

Gibbs H, Brown S, Niles J and Foley J 2007 Monitoring and estimating tropical forest carbon stocks: making REDD a reality *Environ. Res. Lett.* **2** 045023

Goetz S J, Sun M, Baccini A and Beck P S A 2010 Synergistic use of space-borne LiDAR and optical imagery for assessing forest disturbance: an Alaska case study *J. Geophys. Res.—Biogeosci.* **115** G00E07

Greenpeace 2012 *'Artisanal Logging' = Industrial Logging in Disguise* (Kinshasa: Greenpeace Africa)

Gutman G, Byrnes R, Masek J, Covington S, Justice C, Franks S and Headley R 2008 Towards monitoring land-cover and land-use changes at a global scale: the global land survey 2005 *Photogramm. Eng. Remote Sens.* **74** 6–10

Hance W A and van Dongen I S 1958 Matadi: focus of Belgian African transport *Ann. Assoc. Am. Geogr.* **48** 41–72

Hansen M C, Roy D P, Lindquist E, Adusei B, Justice C O and Altstatt A 2008a A method for integrating MODIS and Landsat data for systematic monitoring of forest cover and change and preliminary results for Central Africa *Remote Sens. Environ.* **112** 2495–513

Hansen M C *et al* 2008b Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data *Proc. Natl Acad. Sci. USA* **105** 9439–44

ITTO (International Tropical Timber Organization) 2002 *ITTO Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests* (*ITTO Policy Development Series* vol 13) (Yokohama: International Tropical Timber Organization)

Justice C O, Horning N and Laporte N 1993 *Central Africa: Global Climate Change and Development—Synopsis. Remote Sensing and GIS Contributions to a Climate Change Program in Central Africa* (Washington DC: Biodiversity Support Program)

Kareiva P, Watts S, McDonald R and Boucher T 2007 Domesticated nature: shaping landscapes and ecosystems for human welfare *Science* **316** 1866–9

Mararo B 1997 Land, power, and ethnic conflict in Masisi (Congo-Kinshasa), 1940s-1994 *Int. J. Afr. Hist. Stud.* **30** 503–38

Margono B A, Turubanova S, Zhuravleva I, Potapov P, Tyukavina A, Baccini A, Goetz S and Hansen M C 2012 Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010 *Environ. Res. Lett.* **7** 034010

McCloskey J M and Spalding H 1989 A reconnaissance level inventory of the amount of wilderness remaining in the world *Ambio* **18** 221–7

Mollicone D *et al* 2007 An incentive mechanism for reducing emissions from conversion of intact and non-intact forests *Clim. Change* **83** 477–93

Laporte N T, Stabach J A, Grosch R, Lin T S and Goetz S J 2007 Expansion of industrial logging in Central Africa *Science* **316** 1451

Laurance W F, Croes B M, Tchignoumba L, Lahm S A, Alonso A, Lee M E, Campbell P and Ondzeano C 2006 Impacts of roads and hunting on Central African Rainforest Mammals *Conserv. Biol.* **20** 1251–61

Oliver R 1966 The problem of the Bantu expansion *J. Afr. Hist.* **7** 361–76

Olson D M *et al* 2001 Terrestrial ecoregions of the world: a new map of life on earth *Bioscience* **51** 933–8

Potapov P V, Laestadius L, Yaroshenko A and Turubanova S 2009 *Case Studies on Measuring and Assessing Forest Degradation. Global Mapping and Monitoring the Extent of Forest Alteration: the Intact Forest Ladscape method* (*FAO Working Paper* vol 166) (Rome: FAO, Forest Resources Assessment Programme)

Potapov P V, Turubanova S A, Hansen M C, Adusei B, Broich M, Altstatt A, Mane L and Justice C O 2012 Quantifying forest cover loss in Democratic Republic of the Congo, 2000–2010, with Landsat ETM+ data *Remote Sens. Environ.* **122** 106–16

Potapov P V *et al* 2008 Mapping the world's intact forest landscapes by remote sensing *Ecol. Soc.* **13** 51

Redford K H 1992 The empty forest *Bioscience* **42** 412–22

Sanderson E W, Malanding J, Levi M A, Redford K H, Wannebo A V and Woolmer G 2002 The human footprint and the last of the wild *Bioscience* **52** 891–904

Sasaki N and Putz F E 2009 Critical need for new definitions of forest and 'forest degradation' in global climate change agreements *Conserv. Lett.* **2** 226–32

Schoene D, Killmann W, von Lüpke H and LoycheWilkie M 2007 *Definitional Issues Related to Reducing Emissions from Deforestation in Developing Countries* (*FAO Forests and Climate Change Working Paper* vol 5) (Rome: UNFAO)

Sidle J G, Dupain J, Beck J, Nackoney J, de Wasseige C, Biang J D M, Leprohon R and Malele S 2012 Forest zoning experience in Central Africa *The Forests of the Congo Basin—State of the Forest 2010* ed C de Wasseige, P de Marcken, N Bayol, F Hiol, Ph Mayaux, B Desclée, R Nasi, A Billand, P Defourny and A R Eba'a (Luxembourg: Publications Office of the European Union) pp 207–31

Strassburg B B N *et al* 2009 Global congruence of carbon storage and biodiversity in terrestrial ecosystems *Conserv. Lett.* **3** 98–105

Tabarelli M, Cardoso Da Silva J and Gascon C 2004 Forest fragmentation, synergisms and the impoverishment of neotropical forests *Biodivers. Conserv.* **13** 1419–25

Thies C, Rosoman G, Cotter J and Meaden S 2011 *Intact Forest Landscapes: Why It is Critical to Protect Them From Industrial Exploration* (Amsterdam: Greenpeace)

Tucker C J and Townshend J R G 2000 Strategies for monitoring tropical deforestation using satellite data *Int. J. Remote Sens.* **21** 1461–71

Wilkie D S 1994 Remote sensing imagery for resource inventories in Central Africa: the importance of detailed field dalta *Hum. Ecol.* **22** 379–403

WRI (World Resources Institute) 2007 *Interactive Forestry Atlas of Cameroon—Version 2.0* (Washington, DC: World Resources Institute)

WRI (World Resources Institute) 2010 *Atlas Forestier Interactif de la Republique Democratique du Congo—Version 1.0* (Washington, DC: World Resources Institute)

WWF (World Wildlife Fund) 2006 *A Vision for Biodiversity Conservation in Central Africa: Biological Priorities for Conservation in the Guinean—Congolian Forest and Freshwater Region* (Washington DC: WWF-US/Central African Regional Program Office)

Zhuravleva I V 2011 Intact forest landscapes in the tropics: mapping and monitoring in 2000–2010 *Abstracts of Fifth Int. Conf. Earth from the Space: The Most Effective Solutions* (Moscow: Scanex)