ABSTRACT

Title of Dissertation: FOREST COVER DYNAMICS OF SHIFTING CULTIVATION IN THE DEMOCRATIC REPUBLIC OF CONGO

Giuseppe Molinario, Doctor of Philosophy, 2019

Dissertation Directed By: Professor Matthew C. Hansen, Department of Geographical Sciences

This dissertation is focused on contextualizing spatio-temporally forest cover loss in the DRC for the period 2000-2015 as it relates to the shifting cultivation dynamic and the rural complex mosaic. Impacts of forest loss on forest ecosystems, carbon release and biodiversity habitat differ depending on where and when it occurs relative to the rural complex. This was done by mapping the rural complex and disaggregating forest cover loss due to cyclical, livelihood shifting cultivation within three areas: 1) the baseline established rural complex (ERC) for 2000 and new 2000-2015 primary forest loss occurring as either 2) rural complex expansion (RCE) or 3) isolated forest perforations (IFP) further into core forest. Finally the influence of large-scale commercial land uses on forest cover loss is also assessed, from a spatial perspective.

Between 2000 and 2010 the rural complex grew by 10% from 12% to 13% of the DRC's land area, at an average yearly rate of 1%, while perforated forest grew by 74%, from 0.8% to 1.5% of DRC's land area in 2010 at an average yearly rate of 0.7%. Core forest decreased by -3.8% at an average yearly rate of -0.4% per year, from 38% to 36.6% of the 2010 land area. Of particular concern is the nearly doubling of perforated forest, representing greater spatial intrusion of forest clearing within core forest areas.

The land cover and land use (LCLU) components of the ERC were estimated by photo-interpreting high resolution imagery selected using a simple random sampling scheme. In the ERC 76% of land was already actively used for shifting cultivation. Therefore, together with remnant patches of primary forest (11%), an estimated 87% of the ERC was available for future shifting cultivation. Assuming a 4.6% clearing rate, this allowed estimating a ~18 year reuse rate of land in the ERC. Only 2% of the ERC area was occupied by large-scale commercial land use. This led to positing that commercial land uses might be more prevalent further away from settlements into core forest, where lower population density leads to less competition for natural resources.

This hypothesis was tested by extending the probabilistic sampling analysis to new primary forest cover loss occurring *outside* of the ERC during the period 2000-2015. The map of the rural complex developed in Chapter 2 was validated, confirming larger proportions of primary forest and smaller proportions of shifting cultivation further away from the ERC and into core forest areas. LCLU proportions were established for both the RCE and IFP areas. Finally a concentric buffer distance analysis around sample points was used to quantify large-scale commercial land uses at the landscape scale, such as logging, mining and plantations that might be influencing shifting cultivation-driven forest cover loss.

In the RCE the proportion of commercial land use was 0.4%, whereas it was 0.5% in IFPs; less than the proportion of commercial land use found in the ERC (2%). At the same time, results of the concentric buffer distance analysis show that 12% of sample points in the RCE and 9% of sample points in the IFP had commercial land uses within 5km. Commercial land uses are possibly more prevalent closer to the ERC because while there is more competition for land, there are also roads and communities that allow for the transportation of goods and provide labor.

These results support the conclusion that large scale LCLU change dynamics in the DRC, such as commercial operations for export, are currently dwarfed by the reliance of rural populations on shifting cultivation. The vast majority of forest cover loss in the DRC remains due to smallholder farming not associated with commercial land uses. However, large-scale agroindustry or resource extraction activities lead to increased forest loss as their worker populations and communities rely on shifting cultivation for food, materials and energy. The spatial analysis of the rural complex allows us to peer into the future of forests in the DRC, as where isolated perforations lead, the rural complex soon follows and as the rural complex expands, so do commercial land uses.

FOREST COVER DYNAMICS OF SHIFTING CULTIVATION IN THE DEMOCRATIC REPUBLIC OF CONGO

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Preface

Material from Chapters 2 and 3 was published in two jointly authored articles of which Giuseppe Molinario is the primary author. Material from Chapter 4 was submitted for publication in an article for which Giuseppe Molinario is the primary author. All external contributions are identified with citations, references, and/or footnotes. All other methods, analyses, and results were developed and/or executed by Giuseppe Molinario, as is all the text of this dissertation.

Dedication

I dedicate this dissertation to my dad.

Acknowledgements

I'd like to thank my committee for their support and guidance. In particular thanks to Matt Hansen, for his mentorship and friendship over the years and the opportunity to learn about cutting-edge, global-scale, satellite remote sensing. Thanks for sharing your treasure-trove of Congolese anecdotes and experiences.

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Thanks to Dr. Olivi, who I will never be able to repay, and Eileen Zigone for her kind and gentle support.

Last but not least, thanks to my friends and family for caring and supporting me endlessly through these years. If I completed this dissertation, it's only thanks to you.

List of Abbreviations

ERC: Established rural complex

RCE: Rural complex expansion

IFP: Isolated forest perforation

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Chapter 1: Introduction

1.1 Background of the Research

Mapping forest cover change in the Democratic Republic of Congo (DRC) is essential as the forest provides livelihoods for local populations, biodiversity habitat and both regional and global ecosystem services while experiencing at the same time the highest annual rate of forest cover loss among Central African countries (Justice *et al* 2001, Duveiller *et al* 2008, Maniatis 2008, Hansen *et al* 2008, Potapov *et al* 2012, DeWasseige *et al* 2012, Mayaux *et al* 2013).

The vast majority of forest cover loss in the DRC is attributed to shifting cultivation (Mayaux *et al* 2004, Defourny *et al* 2011, Potapov *et al* 2012, Tyukavina *et al* 2018). Shifting cultivation, also known as swidden agriculture or slash and burn, is an agricultural practice in which small clearings are carved out of the forest to create new fertile fields. This farming practice results in the rural complex; a characteristic land cover mosaic enveloping roads, rivers and settlements, and composed of clearings, active and fallow fields, primary and secondary forest and other artisanal and commercial land uses (Mayaux *et al* 1999).

The population in the DRC is predominantly rural and relies for their livelihood on traditional small-holder shifting cultivation, small livestock, hunting, and gathering of Non Timber Forest Products (NTFP). Clearing size is generally small, ranging from 0.25ha in areas such as the Ituri forest (Wilkie *et al* 1998) to 1.4ha nationally (Potapov *et al* 2012), in line with average global estimates of 1ha (Aweto 2013).

However, shifting cultivation is not the only cause of forest cover loss in the DRC, as a number of proximate causes and underlying socio-economic drivers create a mosaic of land cover and land uses that can be hard to separate (Rudel and Roper 1996, Mather *et al* 1998, Geist and Lambin 2002). In the DRC, these proximate causes include the harvest of woody biomass and production of charcoal for energy, agricultural plantations and both artisanal and large-scale logging and mining (Geist and Lambin 2002, DeWasseige *et al* 2012, Ickowitz *et al* 2015).

Forest cover loss in the DRC has been mapped for over a decade using satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (Mayaux *et al* 1999, Defries *et al* 2000, Achard *et al* 2002, Hansen *et al* 2010, Ernst *et al* 2013). The term "rural complex" was initially coined by Philippe Mayaux, and mapped as a homogenous area distinct from primary forest (Mayaux *et al* 1999). However, only recently advancements in greater spatial and temporal resolution, powered by the mass-processing of Landsat imagery, allowed for more granular land cover classification accuracy of the constituent components of the rural complex, such as secondary forests and fallows (Potapov *et al* 2012, Hansen *et al* 2013). This enables the quantification of the periodicity of fallows, a key indicator of land use intensity in rural complex landscapes, and the distinction of forest cover loss observed based on whether it occurs *inside* the rural complex or *outside* of it; either expanding it or occurring in greater isolation.

Some land uses are very difficult to distinguish from the rural complex mosaic of shifting cultivation using remote sensing alone, for example the extraction of wood fuel and charcoal production, which are thought to contribute significantly to forest disturbance and degradation especially in peri-urban areas (Allen 2003, Grau *et al* 2008, DeWasseige *et al* 2012, Douglas 2012). Peri-urban environmental degradation will be a major factor in the environmental and economic development path of the DRC, as population increase and urbanization will have consequent impacts on the forest ecosystem that provides most if not all fuel, food and resource needs for the population of cities (Allen 2003, Simon 2008, Douglas 2012, Tyukavina *et al* 2018).

Hunting and gathering of NTFP are impossible to observe at large extents from satellite remote sensing, as these have a very small forest cover loss footprint, mostly associated with overnight camps. However, they have a considerable impact on the ecological integrity of the forest by increasing human access and disturbance of the interior forest and are constituent components of livelihoods in the rural complex (Nagendra *et al* 2004).

The DRC has one of the lowest per capita Gross National Income (GNI) in the world, estimated in 2016 at $460, compared to the Sub-Saharan average of $1,516 (World Bank 2018). An estimated 63.6% of the population is living in poverty (World Bank 2018) making the country rank 176th out of 187 countries in the Human Development Index (UNDP 2017). In 2016, the DRC's Gross Domestic Product (GDP) growth fell drastically to 2.4%, its lowest point since 2001 (World Bank 2017).

Further, a surge in violent conflict in 2017 has worsened an already critical humanitarian situation, adding to decades of brutal conflict and bringing the number of Internally Displaced People (IDPs) to 4.3 million (UNOCHA 2018).

Revisited projections of future global poverty highlight a paradox; where the DRC, one of the countries with the most abundant natural resources in the world will remain one of the poorest (Kharas and Rogerson 2017). This bleak outlook in fact occurs despite the country's vast reserves of mineral deposits, potential for commercial plantations and forests that are economically valuable not only for logging but also for conservation in payment for ecosystem services (PES) schemes like Reduced Emission from Degradation and Deforestation (REDD+) (DeWasseige 2015).

Socio-economic drivers of forest cover loss in the DRC include changing economic opportunities, infrastructure development leading to access to markets, changing population dynamics, migration, conflict, political, religious, gender, tribal and cultural traditions, among others (Geist and Lambin 2002, Lambin *et al* 2001, 2003, Ickowitz 2006, DeWasseige *et al* 2014, Pollini 2014). Many drivers are associated with economic development but are also of major environmental concern, like infrastructure development for example, which can increase the viability of unplanned forest exploitation in previously inaccessible intact forest areas (Geist and Lambin 2002, Walker 1987, Wilkie *et al* 2000).

The gender dynamic is particularly important in the dynamic of shifting cultivation, as it is the men who traditionally open new fields in the forest, whereas women do more of the farming itself (Ickowitz *et al* 2015, Pollini 2014). Clearing of new forest in many places therefore remains also a cultural norm, for men to claim new land and fulfill their role. Most women get access to use land only through their husbands or the village chief and land tenure is secured when traditional leaders allocate user rights among families and clan lines (Pollini 2014).

Conflict has prevented the safe operation of industries and transportation of goods and led to forest degradation by pushing farmers away from roads, and further into the core forest, in the attempt to avoid contact with militias (Nackoney *et al* 2014, Butsic *et al* 2015). Conflict has also led to increasing demographic pressure through migration and displacement (Butsic *et al* 2015). For example, during the Rwandan genocide, when hundreds of thousands of IDPs took refuge across the border in the eastern DRC, where they settled seeking shelter and sustenance. The burgeoning population density greatly increased forest loss and degradation, as shifting cultivation, hunting and gathering of NTFP and fuelwood extraction provided livelihoods for refugees (Butsic *et al* 2015).

Shifting cultivation, hunting and gathering of NTFP can spill out of the established rural complex because of any one of the above factors, which apply pressure on rural populations and lead them to choose which forest patch to clear, field to crop and path to take. On top of that, commercial investments in large-scale plantations, logging and mining operations will compete for land.

Remote forests are much less susceptible to anthropogenic degradation (Mollicone *et al* 2007) as population, and therefore deforestation rates, drop with increased distance to roads (Broadbent *et al* 2008, Potapov *et al* 2008, Southworth *et al* 2011, Potapov *et al* 2017). Roads, including logging roads, facilitate contagious development, but also contagious environmental degradation if they are not planned and their impacts not fully integrated with their social and environmental costs (Ibisch *et al* 2016, Damania and Wheeler 2015). Forest intactness is therefore a good indicator of the conservation value of a forest landscape (Luyssaert et al 2008, Balmford et al 2002, Potapov et al 2017). Forest fragmentation, and the erosion of core forests has important implications for the forest ecosystem, from increased edge effects to loss of biodiversity habitat (Skole and Tucker 1993, Broadbent *et al* 2008). In the DRC, like in many countries, forest degradation from transforming unmanaged intact forests into managed non-intact forests is as important a source of Greenhouse Gas Emissions (GHGs) as from deforestation (Maniatis and Mollicone 2010) adding an estimated 6%-132% of emissions from forest lands (Bucki *et al* 2012).

Understanding the land cover and land use change (LCLUC) dynamics in the DRC is increasingly important in light of new sustainable development pathways such as payment for ecosystem services (PES). The United Nations Framework Convention on Climate Change (UNFCCC) Reduced Emissions from Deforestation and Degradation (REDD+) funding mechanism is a PES scheme which gives developing countries a financial incentive to conserve forests in order to reduce greenhouse gas emissions from forest clearance. To participate, however, countries need to provide monitoring, reporting and verification (MRV) systems that ensure the accuracy of the reported avoided deforestation. Therefore land managers need to accurately separate and map the extent and growth of the rural complex footprint, and isolated forest perforations, in order to correctly map the "permanent agricultural area" of communities, and because forest loss has different impacts on the forest ecosystem depending on where it occurs. Furthermore, mapping isolated forest perforations allows us to peer into the future of the forests of the DRC, as the rural complex eventually incorporates and replaces them, with a more permanent anthropogenic footprint.

In this context, land use planning is of utmost importance in balancing economic development, sustainable resource use and conservation. However, the capacity to sustainably manage natural resources is limited in the DRC; as war, poverty and collapsed government and infrastructure have created a fundamental deficit of institutional and human capacity which has crippled the country. International aid programs like USAID's Central Africa Regional Program for the Environment (CARPE) have been strengthening the institutional capacity for land use planning and laying the foundations for the scientific investigation of LCLUC and its integration in decision-making processes. This is particularly important given the reliance of the population on the forest ecosystem and the estimates of massive population increase (Tyukavina *et al* 2018). Well-informed strategic land use planning will continue to be a crucial tool for sustainable development in the DRC.

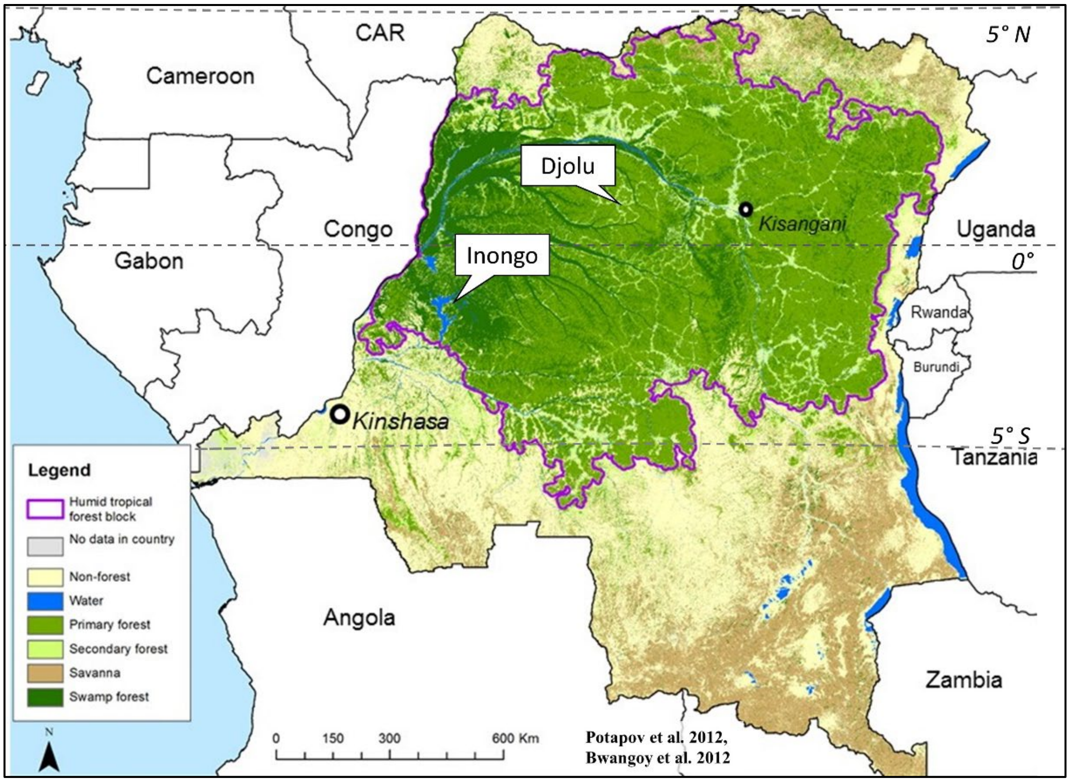


Figure 1.1: FACET DRC map. The white markers show the locations of Inongo and Djolu, where field data were collected in 2011/2012.

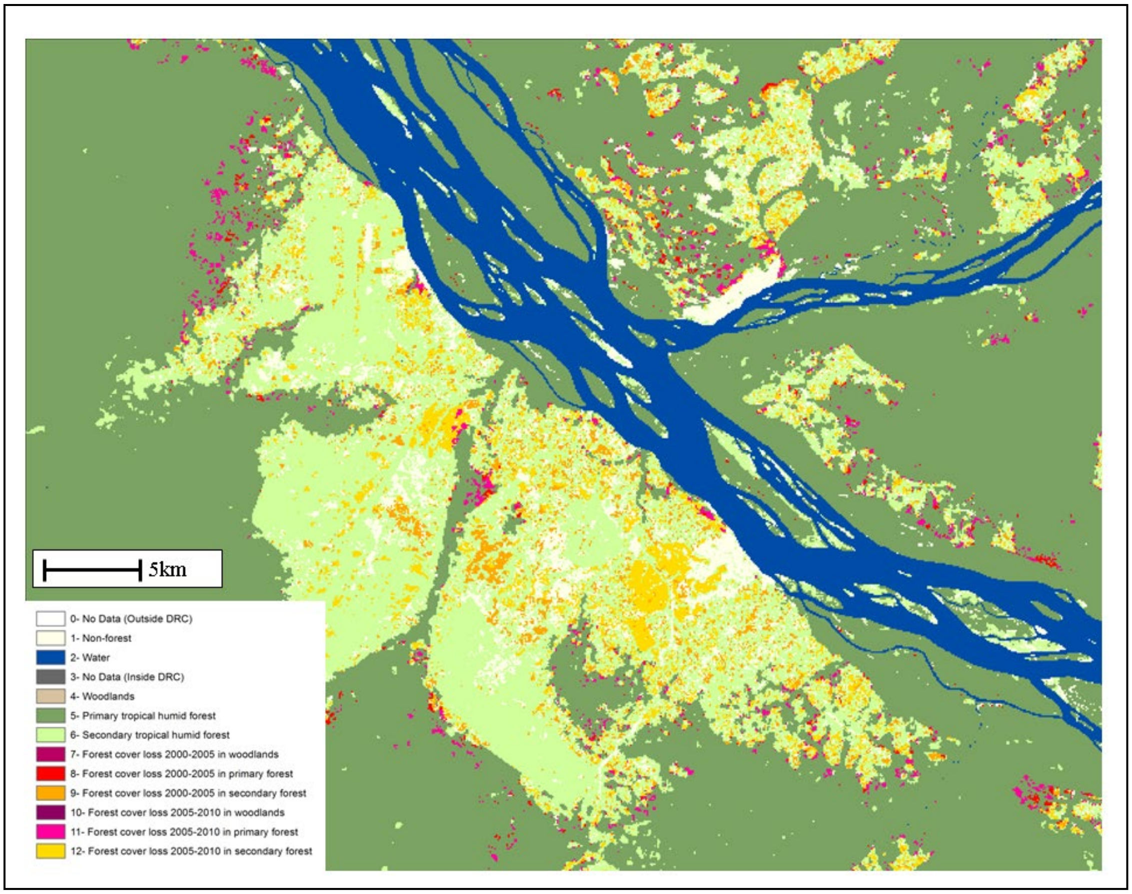


Figure 1.2: The footprint of the rural complex is visible in FACET (Potapov et al 2012) as a homogenous and patterned mosaic of land cover separate from core primary forest.

1.2 Previous Efforts in Mapping the Rural Complex

In 1997 Philip Mayaux (Joint Research Center), Pierre DeFourny (UCL) and Carlos Evrard coined the term "Secondary forest and rural complex" after developing AVHRR satellite remote sensing based maps in which a halo of secondary forest was found along settled roads and rivers, carved out of the primary humid tropical forest block of the DRC (Mayaux *et al* 1999). Previous legends called the rural complex area simply "degraded forest" which did not capture the complexity of land cover and land use within it due to the agricultural land cover mosaic (Laporte *et al* 1995). The TREES map produced relied on AVHRR observations and represented the first step into investigating in more detail the rural complex and shifting cultivation dynamic in the DRC. In their paper, Mayaux et al. compared the TREES map with previous IGBP Discover maps as well as earlier vegetation maps of Africa from White (1983). The rural complex was clearly visible in the TREES map (Figure 1.7).

Subsequently the work done for the TREES project evolved into the global mapping of land cover in the Global Land Cover map for 2000 (GLC2000). GLC 2000 is a SPOT-based (*Satellite Pour l'Observation de la Terre*) global land cover map, downgraded to 1km resolution to achieve higher consistency across regions. In the GLC2000 map, the separation of the rural complex from surrounding primary forest was clearer than in previous map products (Mayaux *et al* 2004) (Figure 1.5).

Both TREES and GLC2000 are classified map products, meaning that they have a land cover classification legend that allows the separation of land cover into discrete classes. On one hand, this allows for the clear distinction of classes on the map, but on the other, it introduces a number of decisions made by the authors on how to best derive the separations of those classes. The opposite approach in satellite remote sensing mapping is the production of maps that contain continuous values, as for example the percent tree cover products first produced with AVHRR (Defries *et al* 2000) and then the MOD44B product from MODIS (Hansen *et al* 2003). In these maps the rural complex is visible as a homogenous area, yet it clearly contains a heterogeneity of tree cover by percentage (Figure 1.3 & Figure 1.4).

An enormous advancement in spatial, temporal and classification resolution occurred in 2012, when Potapov et al. (2012) published the *Forêts d'Afrique Centrale Evaluées par Télédétection* (FACET) map for 2000-2005-2010. The methodology for

FACET relied on the development of metrics based on decision tree algorithms in a supervised classification scheme building on metrics developed more than a decade earlier in vegetation continuous fields products from AVHRR (Hansen and DeFries 2004). Some of these methods relied heavily on the use of the Normalized Difference Vegetation Index (NDVI) (Tucker 1979). This map used Landsat imagery to show at 60m resolution the separation of primary and secondary forest, as well as primary and secondary forest loss (Figure 1.6). On top of that, this forest-cover-specific map identified non-forest and woodlands, and allowed for the subsequent mapping of swamp forest (Bwangoy *et al* 2010). As a result of this unprecedented spatial resolution in a wall-to-wall map for the DRC, forest cover loss observations and the distinction between primary and secondary forest and their respective cover losses in time, it was possible to develop the granular rural complex maps presented in Chapter 2 that enabled this entire dissertation research.

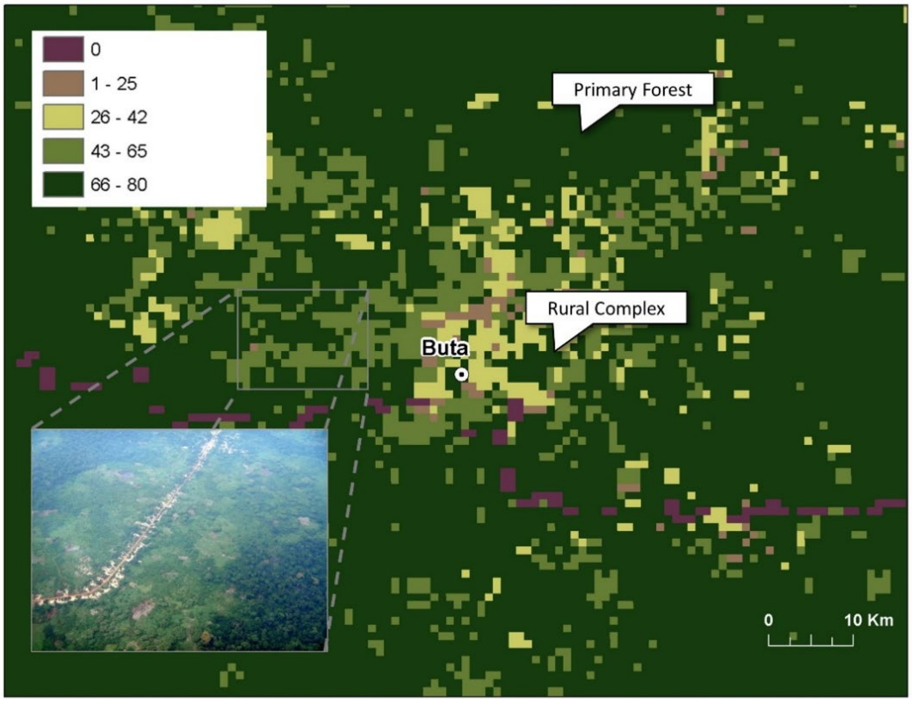


Figure 1.3: AVHRR percent tree cover map for the year 2000 at 1km resolution (Defries *et al* 2000). Zoom for the town of Buta (2°48'30.0"N, 24°44'49.1"E).

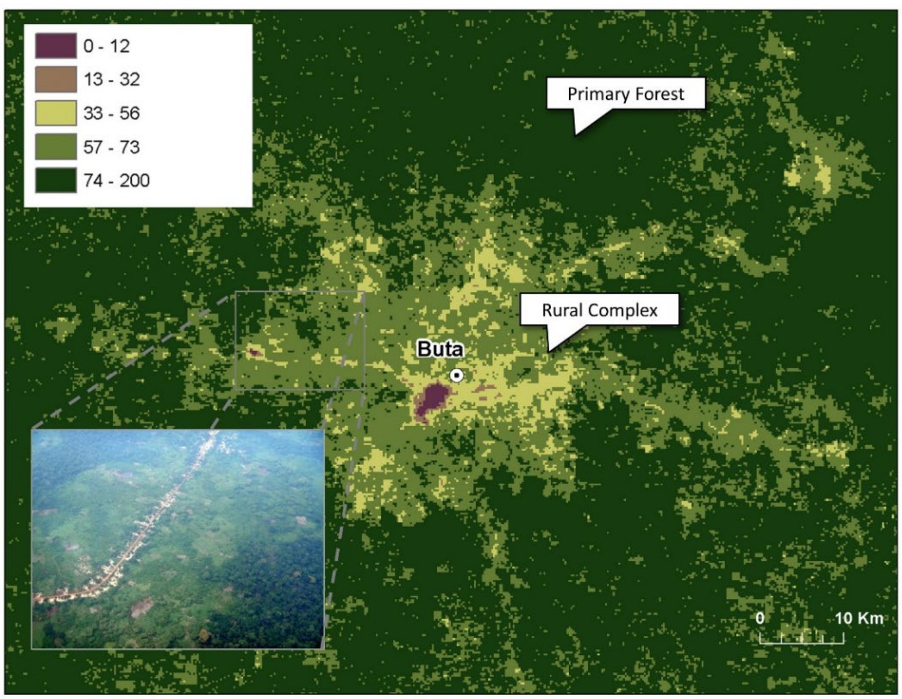


Figure 1.4: MODIS MOD44B percent tree cover product for the year 2010 at 250m resolution (Hansen *et al* 2003, DiMiceli *et al* 2017). Zoom for the town of Buta (2°48'30.0"N, 24°44'49.1"E).

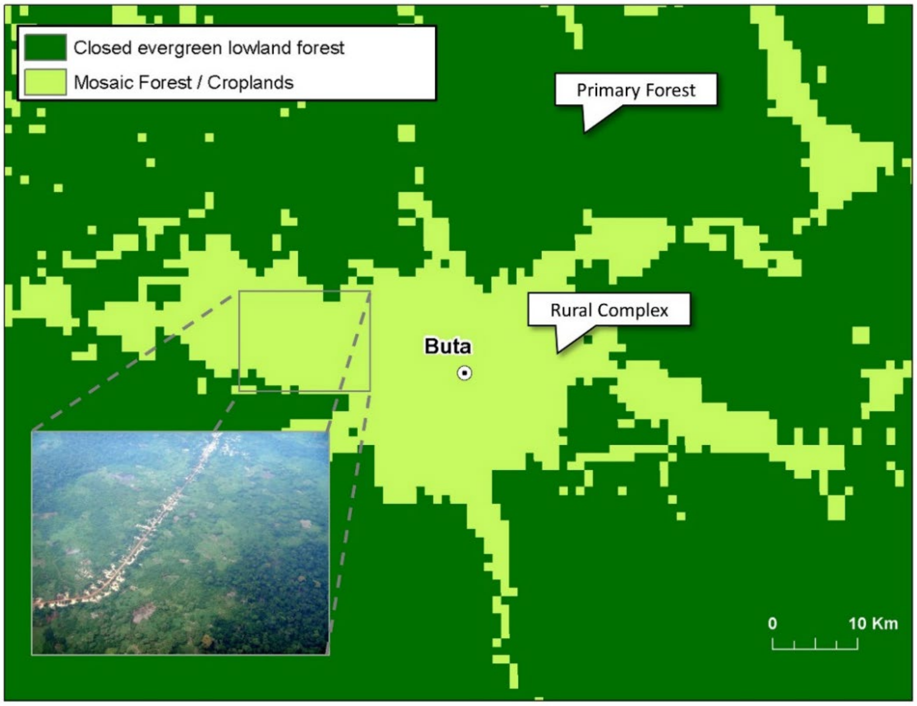


Figure 1.5: GLC 2000 map showing clearly the distinction between primary forest and the rural complex (Mayaux *et al* 2004). Zoom for the town of Buta (2°48'30.0"N, 24°44'49.1"E).

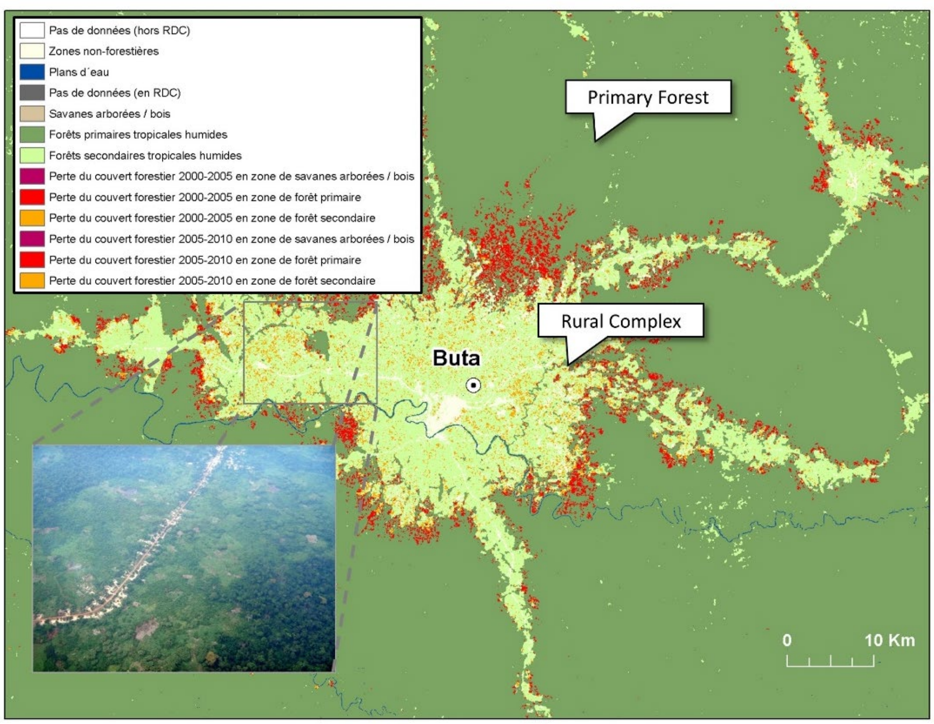


Figure 1.6: FACET map 2000-2010 at 60m resolution using Landsat satellite imagery (Potapov *et al* 2012). Zoom for the town of Buta (2°48'30.0"N, 24°44'49.1"E).

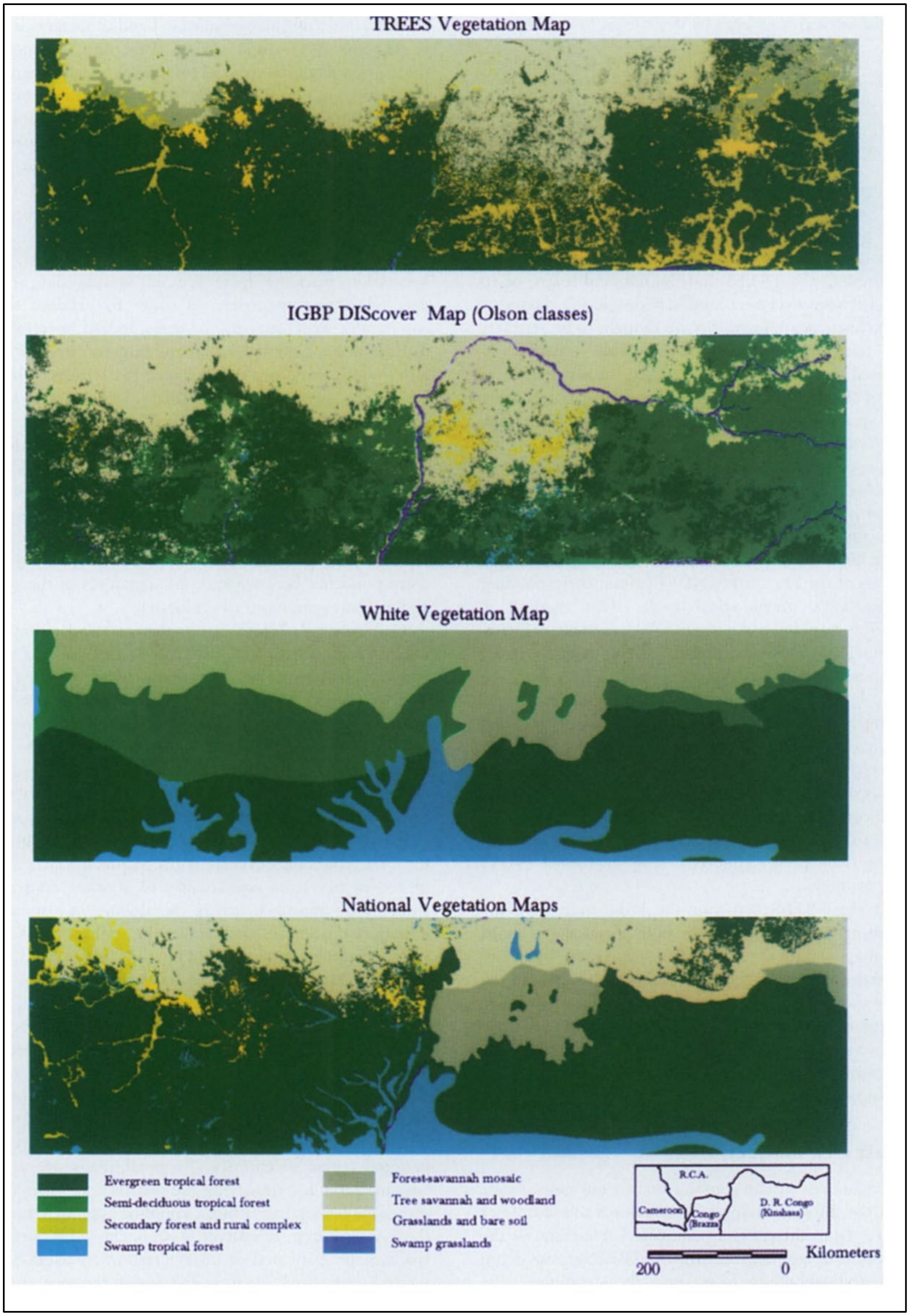


Figure 1.7: Comparison of national vegetation maps, White's 1983 map the IGBP map and the TREES map from Mayaux et al. (1999) (Mayaux *et al* 1999). Detail of the north-western part of the DRC.

1.3 Research Goals and Objectives

The goal of this dissertation research is to improve the understanding of the forest cover dynamics of shifting cultivation in the DRC in order to inform land use planning decisions at the local, regional and national level. My approach is aimed at investigating the spatial context in which forest cover loss occurs in the DRC. First by mapping the landscape spatial patterns of forest fragmentation and the rural complex footprint through time, then by defining a baseline of the proportions of land under shifting cultivation and quantifying its cycle of reuse of fallows and finally quantifying LCLU proportions in areas of new primary forest loss outside the rural complex and the area of large scale commercial land use that might be influencing shifting cultivation-driven forest cover loss.

The major research objectives are therefore the following:

- **Objective 1:** To map the rural complex, separate from it isolated forest perforations that occur in core forest and define different typologies of forest cover according to their spatial relationship to these anthropogenic footprints for the period 2000-2010;

- **Objective 2:** To quantify the area and rates of disturbed land inside the baseline established rural complex for the year 2000, in order to define its fallow periodicity, indicating land use intensity;

- **Objective 3:** To quantify the LCLU proportions in the areas of primary forest loss 2000-2015 outside of the rural complex: either expanding the rural complex footprint or in isolated forest perforation areas, and to quantify the presence of commercial land uses in these areas.

1.4 Organization of the Dissertation

The dissertation research is articulated into three research components that investigate the objectives defined above. Objective 1 is addressed in Chapter 2, objective 2 is addressed in Chapter 3 and objective 3 is addressed in Chapter 4.

In Chapter 2: I developed forest fragmentation maps for 2000, 2005 and 2010 and subsequently reclassified them in order to regroup individual land cover patches. The resulting forest fragmentation map is a necessary processing step that adds granular classification detail to binary forest/non-forest remote sensing observations from FACET, separating standing primary forest into "patch, edge, perforated, fragmented and core forest". Then, I developed the rural complex footprint map that specifically targets the holistic separation of the homogenous areas of the rural complex and of isolated forest perforations, yielding separate classes of: established rural complex (ERC) for 2000 and rural complex expansion area (RCE) and isolated forest perforations (IFP) for 2000-2010*. (*I subsequently updated these maps to 2015).

Using the resulting classes, in Chapter 3: I stratified Global Forest Change (GFC) forest cover loss pixels (then updated to 2000-2015), and sampled them by photo-interpreting very high resolution satellite imagery to estimate the area and proportions of the constituent land cover components of the established rural complex for 2000. With the area proportions of the LCLU within the stratum, I was able to estimate the average stable-state recycling rate of land in the shifting cultivation cycle. Very little commercial land use area was found in the ERC, so I posited that more commercial land use would be found in the RCE and IFP areas.

In Chapter 4: I pursued sampling new primary forest loss, now updated to the 2000-2015 period, separating loss expanding the rural complex (RCE), from that occurring in isolation (IFP). I estimated the area and proportion of LCLU in these two strata, including shifting cultivation land cover types and commercial land uses. Then I extended the analysis at the landscape-level, looking for commercial land-uses co-located with the sampled forest cover loss up to a distance of 5km from the sample points.

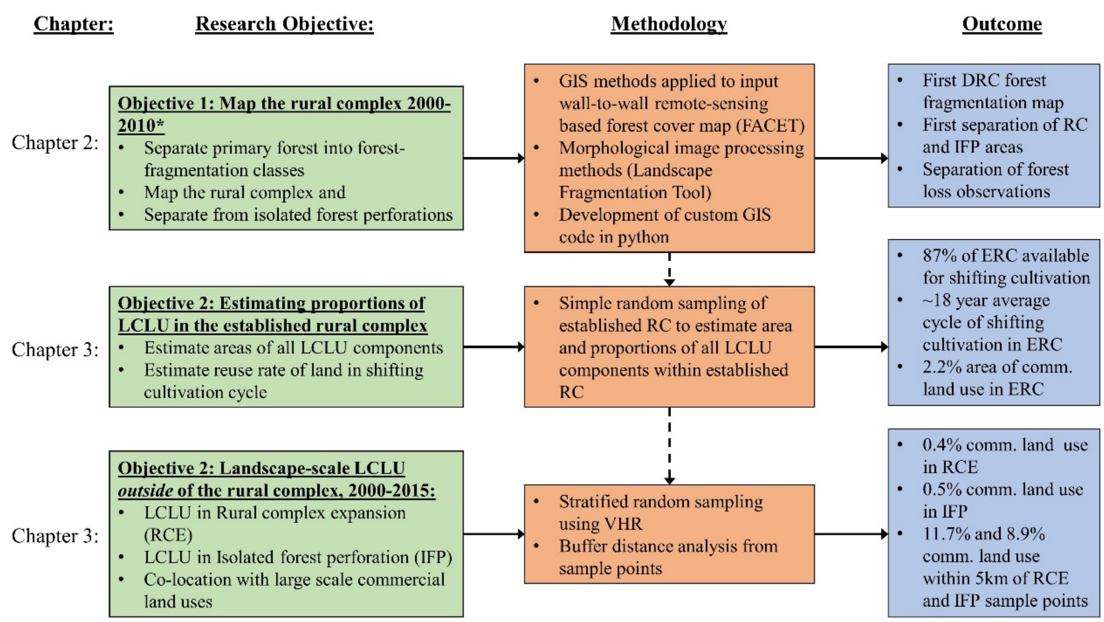


Figure 1.8: Research structure of the dissertation.

Chapter 2: Mapping the Rural Complex in the DRC 2000-2010

2.1 Introduction

Forest clearing in the DRC was characterized using a spatial model developed in a Geographical Information System (GIS), applying morphological image processing to the FACET product. This process allowed the creation of forest fragmentation maps for 2000, 2005 and 2010, classifying previously homogenous primary forest into separate patch, edge, perforated, fragmented and core forest subtypes. Subsequently I used spatial rules to re-classify the above fragmentation-focused map into a rural complex footprint map, where all the above classes are remapped into three classes: the established rural complex (ERC) (2000), the rural complex expansion areas (RCE) (2005 and 2010) and isolated forest perforations (IFP) (2005 and 2010).

The research presented here was published in 2015 (Molinario *et al* 2015), for the reference period 2000-2010, however, subsequently it was updated to 2015, using forest cover loss observations from the Global Forest Change (GFC) product *en lieu* of FACET forest cove loss observations.

In the DRC there is a shifting cultivation component to every land use, as cleared forest provides the necessary food for local subsistence of the rural communities involved in logging, commercial agriculture or mining activities as well as for urban populations. Hunting, charcoal production and the harvesting of fuelwood and other NTFP are also part of a "rural mix" that cannot be observed remotely and separately from shifting cultivation. Meyer and Turner (1992) point out that linking deforestation to its drivers is a "formidable task" as the complexity of connections between various underlying and proximate causes of forest cover loss varies greatly, and locally (Rudel and Roper 1996).

The observation of clearings can be used as a proxy indicator of the presence and intensity of these non-remotely resolvable, but important, small-holder land-use activities. The research in this chapter deals only with clearings that are observable with satellite remote sensing at 60m resolution, the vast majority of which is from shifting cultivation(Potapov *et al* 2012, Tyukavina *et al* 2018).

The investigation of landscape spatial pattern is valuable because there are strong links between ecological pattern and ecological function (Gustafson 1998), patterns of change often have characteristic signatures (Forman 1995) and the spatio-temporal analysis of patterns allowed making inferences about how they relate to underlying driving processes (Turner 1990, Gustafson 1998). Many metrics of landscape spatial pattern exist, however, some are best suited to characterize specific ecological processes within unique landscapes (Gustafson 1998, McGarigal and Marks 1995, Li and Reynolds 1995), many are functionally equivalent (O'Neill *et al* 1988) and some metrics developed for specific applications might not be portable to other ecological contexts (Gustafson 1998).

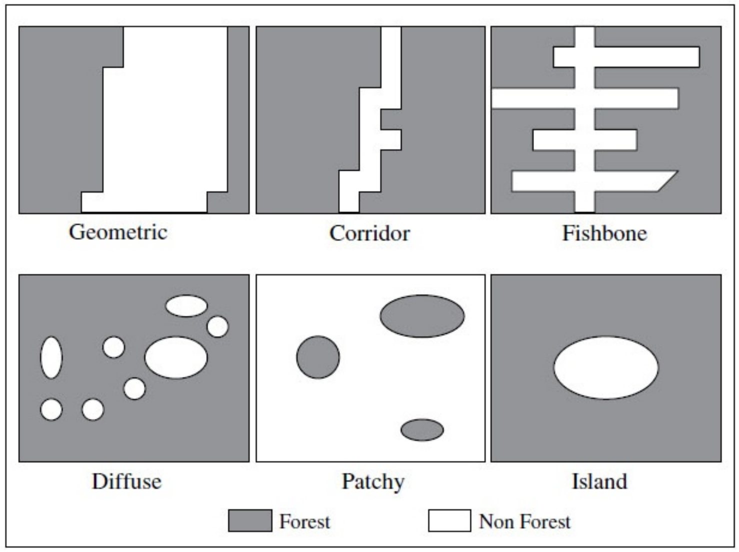


Figure 2.1: Lorena and Lambin, 2009 illustrate some of the patterns of the forest/non-forest interface in the Amazon.

Two characteristics commonly measured are landscape composition and spatial configuration: landscape composition quantifies the number of land cover classes in a landscape and their relative proportions; spatial configuration measures individual patches in their spatial neighborhoods, often using categorical maps to identify homogenous patches that have relatively abrupt transitions with adjacent areas (Figure 2.1) (Gustafson 1998). Landscape composition and spatial configuration of land cover in the DRC were both measured using morphological image processing.

2.1.1 Field Observations

Fieldwork completed in the summers of 2011 and 2012 gathered first-hand information on land cover and land use change in the rural complex in two areas of the DRC: Djolu, in Equateur Province, and Inongo, in the Mai-Ndombe district of the Bandundo Province (shown in the reference map in Figure 1.1) The support and knowledge of local experts proved invaluable in understanding variations in the stages of fallows and secondary forest. Field observations helped develop the research hypothesis and methods of this dissertation and allowed a first-hand understanding of the ecological differences of secondary and primary forest, as many of them can only be seen from the ground, inside the canopy.

The understory of secondary forest is more densely populated with smaller trees, and there are more lianas and other vines. It is apparent why a mature secondary forest, or primary forest, would be easier to cut and clear, rather than clearing a secondary forest or fallow. While the tree trunks might be of larger diameter, there are less of them, and they are more valuable for building materials and other uses.

The secondary forest class contains a significant percentage of structurally smaller vegetation (non-forest) ranging from substantially overgrown fallows (about 10 years old) which contain some trees, palms and bamboo and in general early regrowth types that are around or shorter than 5m in height that are hard to map (Potapov *et al* 2012).

The two areas visited exhibit different LCLUC dynamics associated with divergent demographics, access to markets, land cover, land use practices and socio-cultural factors. Field data collected during fieldwork in 2011 and 2012, including georeferenced quantitative and qualitative observations and geotagged photographs were instrumental in framing the concepts of this research in its proposal phase, understanding the shifting cultivation dynamic of the rural complex and aiding photo-interpretation of high resolution satellite imagery.

Fieldwork methodology:

Fieldwork methodologies were designed and then implemented in the territories of the villages of Djolu, Yokembe and Ingungu in Equateur province and on the west bank of Lac Mai Ndombe in Bandundu province (Figure 1.1). Fieldwork in Djolu was done with the assistance of the Observatoire Satellital des Forêts d'Afrique Centrale (OSFAC) and the African Wildlife Foundation (AWF), while fieldwork in Inongo was done in partnership with OSFAC and the DRC ministry of forestry (Service Permanent d'Inventaire et d'Aménagement Forestier (SPIAF)) and logistical support from ERA-Congo. Both field campaigns were financially supported by USAID.

Approximately 300 data points were collected consisting of qualitative observations characterizing land cover which improved my understanding of the spatio-temporal cycle of shifting cultivation. Quantitative measurements of the size of fields, fallows and forest patches in which the samples occurred were also taken. These measurements were taken using a Nikon digital laser rangefinder and clinometer. Approximately 1,000 geo-tagged (GPS) photos were also taken in each cardinal direction at the observed locations. Data collection was planned in a GIS by allocating a random sample of points stratified by FACET classes. These points were then reached by the field team by the fastest path possible, using off-road motorcycles on both existing paths and making new ones. Observations were taken both for planned samples as well as ad-hoc ones every 200-300 meters of travel.

Figure 2.2: A cleared forest stand near Inongo, Mai-Ndombe Province (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.3: Fieldwork near Inongo, recording the land cover of a sample site that corresponded with a recent clearing. (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.4: A secondary forest stand cleared and burned, near Inongo. (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.5: A pit used for milling wooden planes from logs felled nearby from artisanal logging, near Inongo, Mai-Ndombe District (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.6: Characteristics of sample points in field work were recorded for future analysis and reference. Land cover observed, dimensions of the clearing (if a clearing was observed), near Inongo, Mai-Ndombe District (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.7: One of the challenges of fieldwork in the DRC was transportation. Here a log bridge over a stream near Djolu, a challenge to cross on motorcycle. (0°40'20.5"N 22°27'40.0"E) (Photo credit: Giuseppe Molinario).

Figure 2.8: Fieldwork in Inongo included daily lake crossings with motorcycles on a *pirogue,* near Inongo, Mai-Ndombe District (1°55'57.6"S 18°17'25.3"E) (Photo credit: Giuseppe Molinario).

Figure 2.9: The *parasolier* tree, with a distinctive canopy that is sometimes distinguishable in high resolution satellite imagery as well. Near Djolu, Equateur Province (0°40'20.5"N 22°27'40.0"E) (Photo credit: Giuseppe Molinario).

2.1.2 Scale, Data and Area of Interest:

The maps developed are national in scale, but provide locally relevant information that is useful for comparisons at the subnational level. This was a priority goal of the dissertation, and one of its major challenges. It would have been easier to focus on a smaller geographical extent with more homogenous land cover and land use. Previously, quantitative information about shifting cultivation, the rural complex, and forest fragmentation, was only available at the local and landscape scale and in a limited number of case studies, for example Nackoney *et al* (2013) and Wilkie *et al* (1998). This proved to be a major limitation in adopting the maps and results from these studies in national or even regional land use planning policies and investments made by governments, NGOs and agencies, such as USAID. The limited knowledge of the shifting cultivation forest dynamics in the DRC was also mostly qualitative, making the comparison of shifting cultivation related forest cover loss over different areas, impossible, if not inaccurate (Ickowitz 2006, Russell *et al* 2011, Ickowitz *et al* 2015). The goal of quantifying shifting cultivation and the rural complex, numerically and nationally, was born out of this need.

Spatial resolution was kept throughout the dissertation the same as the input year 2000 primary forest and secondary forest baseline classification from FACET. The Global Forest Change (GFC) forest cover loss observations that were later added were down-sampled from 30m, to 60m resolution. The objective was to work at a scale coarse enough to allow generalization and predictability; minimizing unnecessary "noise" given sometimes by higher resolution observations (Levin 1992, Mertens and Lambin 1997) but not so coarse as to lose essential detail for the analysis (Levin 1992, Turner *et al* 1989). The analysis and output maps are the same spatial scale of the input data, but thematically finer, as they apply a series of buffering and grouping methods to classify patches of forest in the context of its spatial neighbourhood.

Throughout the dissertation the area of interest (AOI) is the region of largely contiguous primary and secondary humid tropical forest within the DRC. In this area, the rural complex is easily observable because of its separation from primary forest, as the abundant primary forest can be freely exploited in expanding smallholder agriculture. In many areas the primary forest resource is exhausted and most farming is done only within a sparse secondary forest mosaic, particularly in regions typically found along the forest/savanna interface in a belt of high population densities from 3-5 degrees latitude south (Figure 1.1). The study is focused on the spatial dynamics of primary forest appropriation into the rural complex and not of those areas having already exhausted their primary forest resource.

As a consequence, I developed spatial rules to treat areas inside the primary forest block AOI differently from areas outside it. A great deal of work went into defining the AOI: I buffered by 10km all primary forest patches larger than 1,000ha ($10km^2$), automatically filling holes, connecting land islands and manually simplifying the area to obtain a contiguous polygon bounding the core humid tropical forest zone (Figure 2.10).

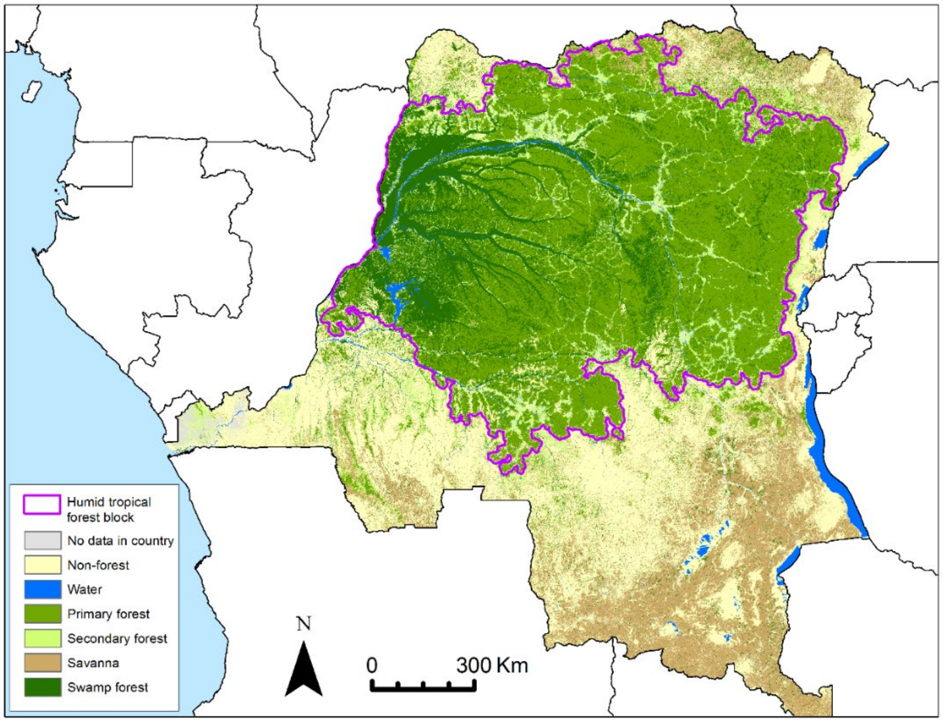


Figure 2.10: The AOI bounding the study are for the entire dissertation research.

2.1.3 *Definitions of Forest and Forest Cover Loss*

There is some debate over the exact relationship between shifting cultivation and 'deforestation', but its relationship with forest cover loss is well understood; with forest stands being cleared and replaced with fields in a rotating cycle of land use. Some authors have doubted the role of shifting cultivation as the major source of deforestation in the DRC, arguing that shifting cultivation is not a single practice, but rather a set of diverse agricultural practices with varying impacts on the forest ecosystem (Ickowitz 2006, 2011, van Vliet et al 2012). The definition of terms such as deforestation, forest degradation and forest cover loss is often at the core of these disagreements, while empirical observations from remote sensing show unambiguously that most forest cover loss in the DRC occurs in small patches associated with shifting cultivation, fuelwood and charcoal production (Defourny et al 2011, Mayaux et al 2013, Potapov et al 2012).

I chose the same definitions of ‘Forest’ and “Forest cover loss” as FACET, in which forest is defined as land with ≥ 30% canopy cover for trees ≥ 5 meters tall, woodlands have between 30% and 60% tree cover and primary and secondary forest have more than 60% canopy cover (Potapov *et al* 2012). Primary forest displays characteristics of older, mature forest and secondary forest of younger, regrowing forest. Forest cover loss is defined as stand replacement as a result of disturbance such as agriculture clearings as well as other anthropogenic and natural disturbances. Forest disturbance is a land-cover subset of ‘deforestation’, which the United Nations Framework Convention on Climate Change (UNFCCC) defines as the direct human-induced conversion of forest to non-forest, not including short-term modifications that remove trees in short-term land cover modifications (such as shifting cultivation, when there are long regenerative fallows and sparse clearings) (FAO 2007). For the UN Food and Agriculture Organization (FAO) Forest Resource Assessment (FRA) ‘deforestation’ is either the conversion of forest to another land use, or the “long-term reduction of tree canopy cover”, explicitly including shifting cultivation (FAO 2015, FAO 2007). Stand replacement disturbance is therefore usually referred to as a land cover modification: a short-term change in the structure of the existent forest land cover (Lambin *et al* 2001), however, ‘agricultural expansion’ is understood as a land use conversion (Lambin *et al* 2003).

The distinction between modification and conversion depends on the temporal persistence of the disturbance which keeps a given area in its not forested state. A crucial element missing in the investigation of forest cover loss in the DRC is therefore the quantification of the spatio-temporal context which forest cover loss occurs in, and contributes to: whether disturbance occurs within an established agricultural landscape, or if it occurs instead through the appropriation of natural, undisturbed, primary forest. Only monitoring over longer time-periods can quantify the persistence with which this anthropogenic footprint occupies past primary forest areas.

2.1.4 The Cycle of Shifting Cultivation & the Rural Complex

Shifting cultivation is a characteristic agricultural practice employed in most tropical environments, where heavily weathered soils retain little or no nutrients. Typically lacking fertilization, farmers clear regenerated fallows and secondary or primary forest areas to prepare land for new crops, using the ash from burning cleared vegetation to enrich otherwise infertile soil (Miracle 1967, Nye and Greenland 1964, 1960). In these landscapes low population densities allow for the rotational use of land in shifting cultivation; the result is a mosaic of active and fallow fields and secondary forest regrowth (Conklin 1961, Ruthenberg *et al* 1971).

The cycle of shifting cultivation in the DRC varies depending on many factors (Ickowitz 2006, Miracle 1967) which qualitatively make it appear not as single practice but rather a set of agricultural practices characterized by multiple environmental and socio-economic variables. These variables modulate localized spatio-temporal cycles, which subsequently have diverse impacts on the forest ecosystem (Ickowitz 2006, 2011, van Vliet *et al* 2012). Indeed many of the variables mentioned in Chapter 1 play a role in shaping the specific farming practices occurring in a given area, and even among different farmers of the same area (Figure 2.11) (Conklin 1961, Ickowitz 2006, Miracle 1967). These qualitative factors are essential in formulating an accurate characterization of shifting cultivation in a given area, but cannot be accurately depicted or compared at the national scale. In this study trading local qualitative knowledge for quantitative wall-to-wall remote sensing observations afforded the ability to compare observations of land change throughout the country.

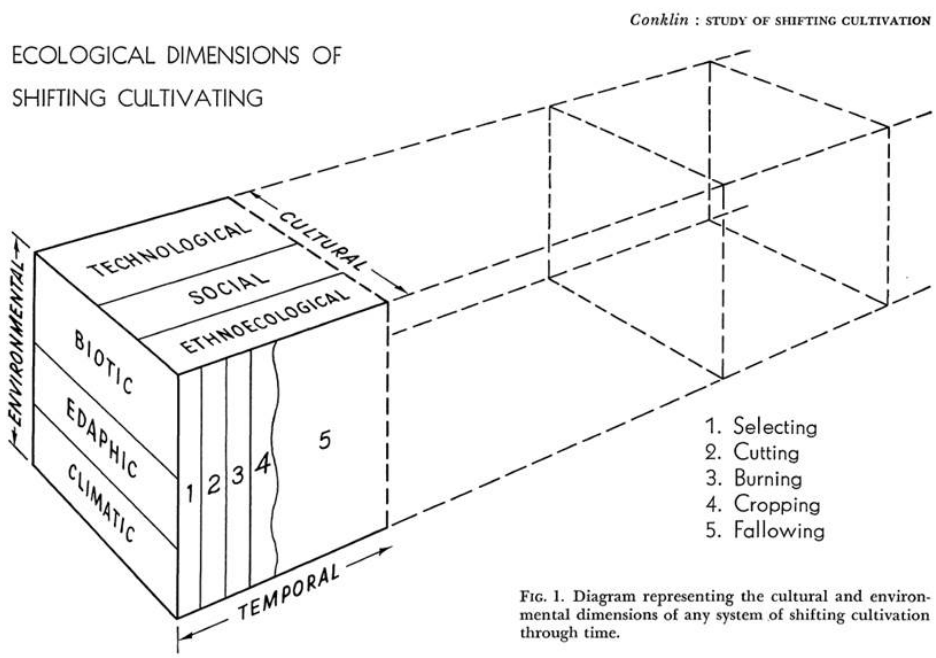


Figure 2.11: Conklin (1961) illustrates the various factors which drive variability in shifting cultivation systems.

A conceptual model of shifting cultivation in the DRC was developed based on literature review and field observations (Figure 2.12). In line with the objectives of this dissertation, the conceptual model framed the sequence of land cover and land use rotation keeping in mind the remote sensing perspective: conscious of the qualitative variables that nuance the rotational cycle, but focusing on remote sensing-observable forest clearing.

For this purpose, generally the cycle starts when a forest stand is cleared to make an initial agricultural field and larger trees are either left standing, felled and used as timber or left on the ground to decay. The resulting woody residue is left to dry, with some portion collected for fuelwood (Miracle 1967). After a period ranging from weeks to months, the slashed area is burned to clear all remaining dry vegetation and release the stored nutrients in the form of wood ash, which subsequently fertilizes the soil as well as reducing its acidity, allowing for nutrients to be more readily available to plants (Miracle 1967, Etiégni and Campbell 1991, Demeyer *et al* 2001, Giardina *et al* 2000). Combustion of vegetation residue itself, while not previously considered to have an effect on soil fertility, is now understood to have an impact both on the nutrients left in ash and on the biochemistry of soil, depending on combustion temperature (Giardina *et al* 2000). Ash from vegetation is rich in calcium, with properties similar to agricultural lime and while it contains almost no nitrogen, it is rich in both phosphorous and potassium (N-P-K) as well as many other chemicals (Etiégni and Campbell 1991). Ash left on the ground swells when in contact with water, binding it to the soil and allowing for chemicals to leach into the ground (Etiégni and Campbell 1991).

Farmers generally prefer clearing mature secondary forest or primary forest as the trees in these areas are easier to fell than those in primary forests, and there is lower density of weed seed then in younger fallows. In some areas, primary forest is usually cleared either when mature secondary forest is not available, or as a way to claim new land rights (Wilkie *et al* 1998). After burning, fields are prepared and sown; the main crop cultivated in the DRC being cassava (*Manihot esculenta*) with other popular crops including corn, sorghum and upland rice. Fruit tree orchards and cash crops such as peanuts, coffee and palm are also common (Miracle 1967, Russell *et al* 2011).

In sparsely populated areas subsequent fallows are long enough for the natural system to recover and a second clearing of a fallow field results in a similar level of productivity as the first one. Reducing fallow periods for the same field instead eventually leads to dwindling crop productivity and soil fertility (Nye and Greenland 1964). Increased demand for food production therefore leads to either higher reuse rates of fallows and secondary forest, increased expansion into primary forest, or more rarely in agricultural intensification, if the resources are available for mechanization or fertilization and there is access to markets.

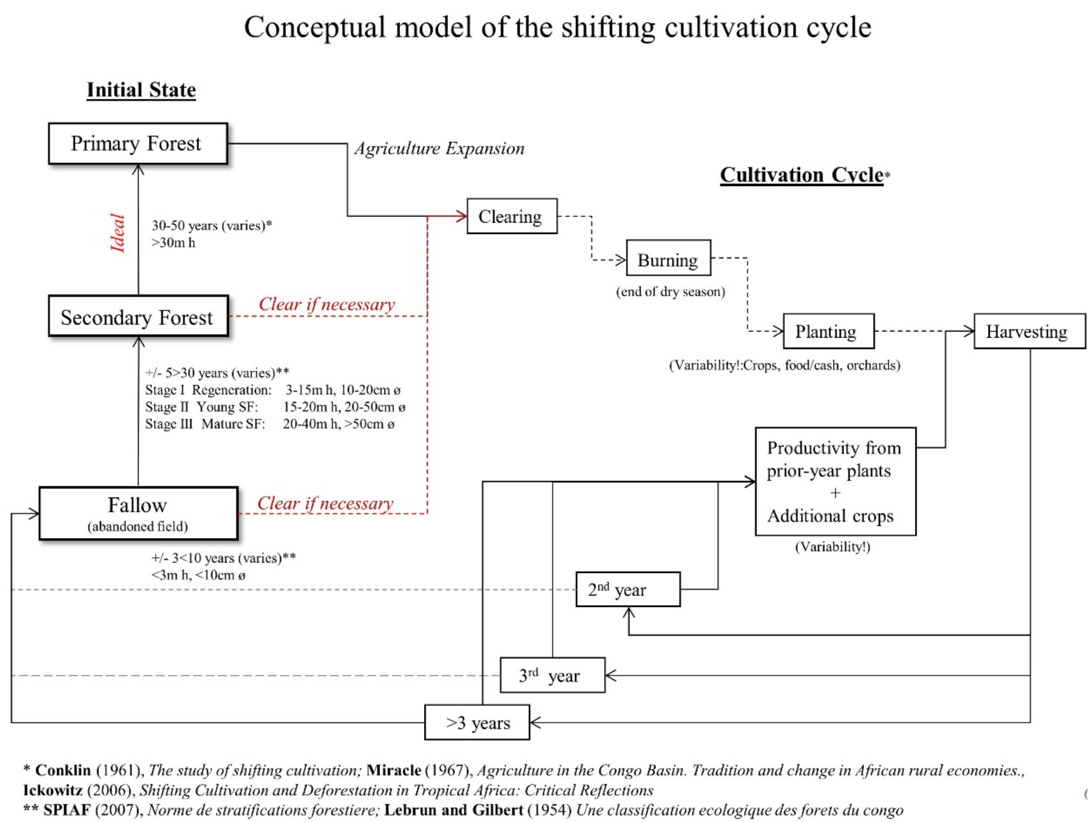


Figure 2.12: A conceptual model of the spatio-temporal cycle of shifting cultivation in the DRC.

If left alone, after a number of years, a fallow field will revert to secondary forest. The successional evolution of secondary regrowth in the DRC has been characterized as having three main stages:

- In the first, an abandoned field or mature fallow is defined as having *heliophyte* plant species 10-20 cm in diameter and 3-15 meter high with grassy undergrowth and vines.
- Young secondary forest follows and is characterized by tree heights of 15-20 meters and diameters of 20-50 cm. The species found in these fallows do not regenerate once the forest canopy closes because of the absence of light on the forest floor. Among the many species that characterize this stage, the *Musanga cecropioides*,

also known as *parasolier* (umbrella tree, in French) because of the shape and configuration of its broad leaves, is probably the best known and easiest to spot because of its abundance in young secondary forest.

- Mature secondary forest follows, and is the hardest to characterize, as it can display characteristics of either young secondary forest or primary forest. Canopy height ranges from 30-40 meters but it can have a more heterogeneous surface than primary forest, allowing some light to reach the understory.

The amount of time it takes for the forest to reach these stages is variable depending on species composition, soils, rainfall, topography and disturbance. (Lebrun and Gilbert 1954, SPIAF 2007).

Mature secondary forest can have the appearance of primary forest when observed from clearings outside the forest or with satellite remote sensing, however, the species composition and the forest structure can differ enough to allow a distinction to be made from first-hand observation within the forest itself (SPIAF 2007).

Presumably, at some point in time along the ecological succession continuum, mature secondary forest and primary forest in the DRC become indistinguishable from direct observation even within the forest itself (SPIAF 2007).

> "*La forêt secondaire représente l'ensemble de types forestiers qui succèdent à la régénération et qui constituent la phase transitoire à l'établissement de la forêt primaire.*" (SPIAF 2007)
>
> (Translation: Secondary forest represents the set of forest types that succeed regeneration and which constitute the transitional phase in the establishment of the primary forest).

Figure 2.13: An aerial view of the rural complex near Djolu, Equateur province, showing the interface with primary forest (0°40'20.5"N 22°27'40.0"E) (Photo credit: Giuseppe Molinario).

Figure 2.14: An aerial view of the rural complex near Djolu, Equateur province. (0°40'20.5"N 22°27'40.0"E) (Photo credit: Giuseppe Molinario).

Figure 2.15: An aerial view of the rural complex near Djolu, Equateur province, illustrating the rural complex mosaic around a trunk road and settlement. (0°40'20.5"N 22°27'40.0"E) (Photo credit: Giuseppe Molinario).

2.1.5 Preliminary Data Exploration

Preliminary data exploration was performed in the proposal stage of this dissertation and it ultimately informed the direction that the investigation took in this and subsequent chapters. First, the question of scale was addressed, to understand what was the ideal scale to investigate the spatial patterns of the shifting cultivation dynamic. By aggregating FACET 60m pixels into 300m, 600m, 1.5 km, 3 km, 6 km, 12 km and 24 km spatial resolution grids, the comparison of the relative amounts of primary and secondary forest and their loss, per unit of area (cell/pixel), became possible.

For example, there are 625 60m (FACET) pixels within a 1.5km aggregated cell and of these 625 pixels, *x* are primary forest loss, *y* are secondary forest loss, and *z* are swamp forest loss, etc. At first, there was no certainty that it was computationally possible to apply the methods of the Landscape Fragmentation Tool (LFT) at the nominal 60m resolution as this tool had only been previously used on small geographical extents (Parent *et al* 2007). From this analysis it emerged that the spatial patterns of the rural complex retained their morphology up until at least 600m pixels; 10x the nominal 60m resolution of the FACET product. This also indicated that although during dissertation work on the first chapter (in 2015) the GFC product became available (30m resolution), it was more than adequate to continue the investigation at 60m spatial resolution.

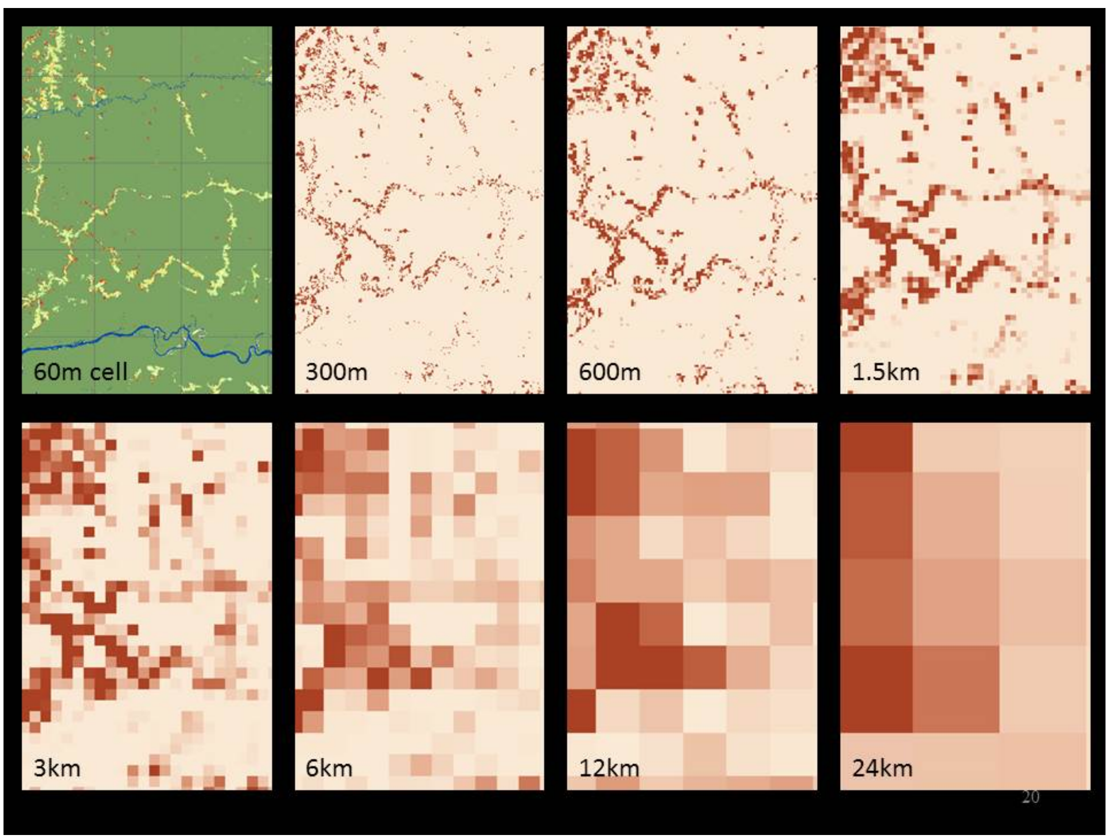


Figure 2.16: Cell size comparative analysis in the data exploration phase.

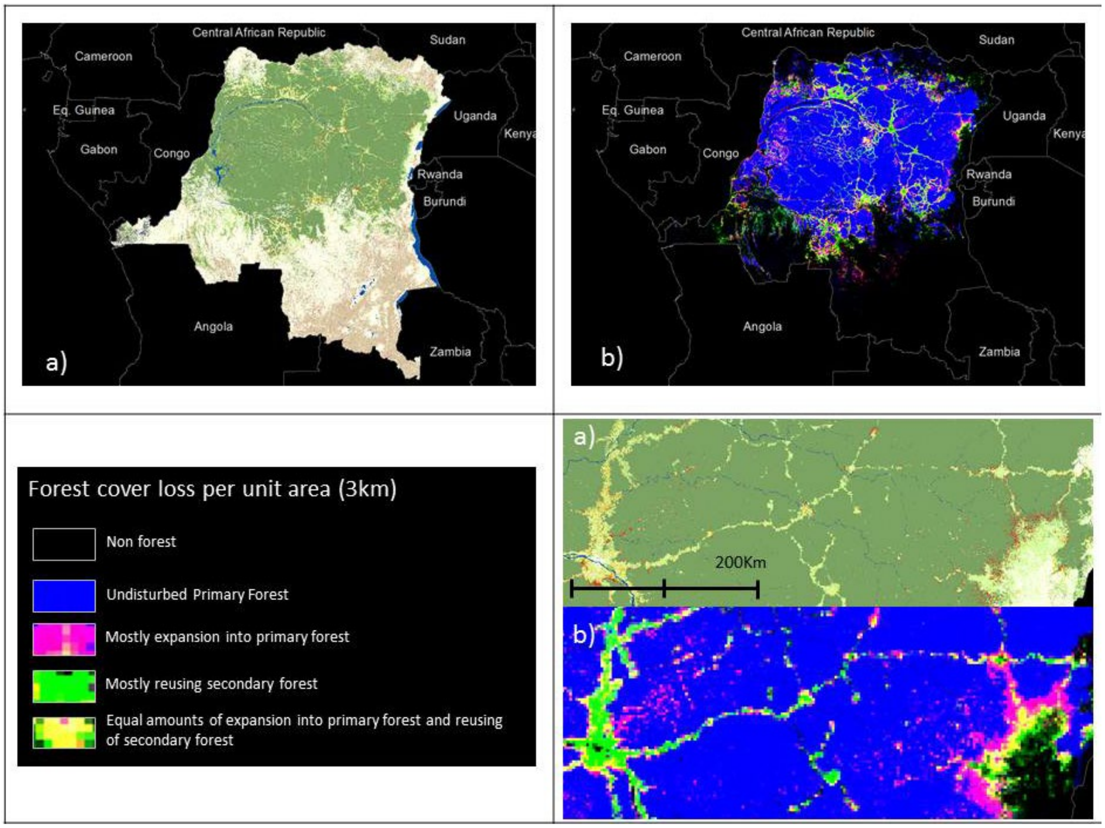


Figure 2.17: a) Standard FACET forest cover loss compared to b) the derived "Expansion vs. Reuse" forest cover loss map.

Second, the proportions of clearings in primary forest (RCE & IFP) versus secondary forest (cyclical reuse of secondary forest) per unit of area were mapped for the DRC for 2000-2005 and 2005-2010 (Figure 2.17). The proportional loss map illustrates differences in quantity of forest loss expansion into primary forest versus reuse of secondary forest. These were the first maps that illustrated spatially, at the national level, the forest dynamics of shifting cultivation and the rural complex; showing in which areas secondary forest was reused and in which new primary forest was cleared. For example in Figure 2.18:

a) Beni/Butembo, showing frontier deforestation,

b) Kisangani, showing secondary forest loss, and a north-east axis of primary forest conversion and fragmentation,

c) Buta, showing frontier and corridor primary forest cover loss,

d) Bumba, showing minimal primary forest loss,

e) Djolu and neighbouring villages showing the lattice of trunk roads and low primary forest cover loss,

f) Lac Mai Ndombe with no secondary forest loss.

This map separated reuse of secondary forest from novel clearings in primary forest (both RCE & IFP), but it highlighted a major issue, in that there were no existing methods to differentiate and separate RCE areas from IFPs. The separation of RCE from IFP areas was successfully achieved developing the more nuanced methodology that is described in this Chapter.

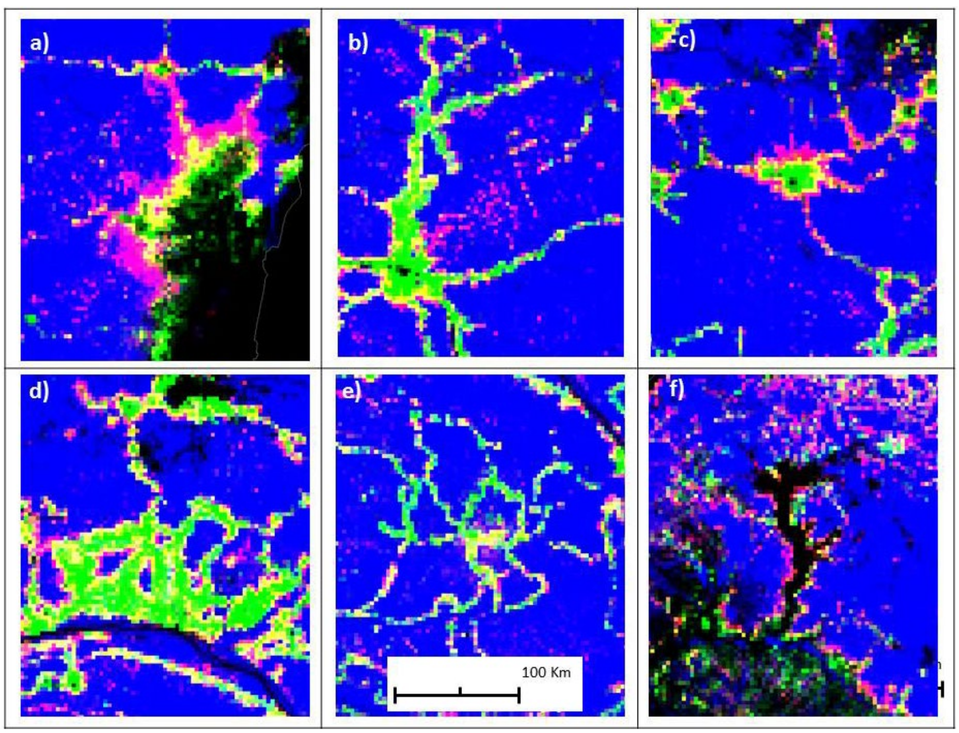


Figure 2.18: Expansion vs reuse per unit area: a) Beni/Butembo, b) Kisangani, c) Buta, d) Bumba, e) Djolu, f) Lac Mai Ndombe.

2.2 Methods

2.2.1 Data

The FACET input data uses optical satellite remote sensing in a per-pixel time-series approach which leverages the automated processing of over 8,000 Landsat ETM+ images. FACET overcomes persistent cloud cover and give us an unprecedented synoptic wall-to-wall coverage of forest cover type and loss at the DRC national level for the period 2000-2005-2010 (Potapov *et al* 2012). FACET is also a methodological precursor to the GFC product which is a global, yearly, 30m resolution, forest cover and loss product for 2000-2017 and is at the core of the World Resource Institute's (WRI) Global Forest Watch initiative (GFW) (Hansen *et al* 2013). Unlike GFC, FACET separates primary and secondary forest classes, a key characteristic necessary for mapping the baseline established rural complex area.

2.2.2 Forest Fragmentation Map

A forest fragmentation map was created using a GIS model with the Landscape Fragmentation Tool (LFT) (Parent *et al* 2007) based on research on morphological image processing by (Vogt *et al* 2007). For the purposes of this discussion the term forest represents primary forest cover and not secondary forest or woodland cover. The LFT applies a series of raster processing operations in a GIS environment to classify primary forest into separate fragmentation classes (Table 2). An edge distance parameter is applied to the input dataset and used to perform separation and inclusion operations between patches of forest and non-forest, resulting in a nuanced forest fragmentation-specific classification. Literature review, visual inspection and expert knowledge from fieldwork enabled choosing a 240m edge distance (four 60m FACET pixels) as it best represented my understanding of the spatial separation between the established rural complex areas and isolated forest perforations while being in line with edge distance parameters reviewed (Broadbent *et al* 2008).

The expansion of the rural complex and isolated forest perforations can degrade the forest through forest fragmentation, resulting in formerly intact forest ecosystems being impacted by edge effects created by clearings. Edge effects are pervasive processes in tropical forests that can lead to changes in forest ecology and habitat fragmentation as well as increasing access to interior forest (Broadbent *et al* 2008, Gascon *et al* 2000, Murcia 1995, Skole and Tucker 1993). The width of edges and the specific characteristics of edge effects depend on the ecology of the forest, local environmental variables, the abruptness of the edge and its temporal permanence (Harper *et al* 2005). Most effects occur close to the forest/non-forest boundary (Murcia 1995) and decrease in frequency and severity with distance (Broadbent *et al* 2008).

However, edges are not always anthropogenic as they are often a consequence of natural features, such as rivers, or the interaction with grasslands and woodlands at the perimeter of the primary forest block. Striving to account only for the active anthropogenic edges occurring inside the primary forest block was a primary concern. Edges at the forest perimeter can be maintained by active or historical anthropogenic disturbance, climatic differences, substrate and fire. Remotely sensed fire observations which have been used to indicate anthropogenic activity linked to agriculture and pasture management have not been used extensively in the DRC (Giglio *et al* 2003, Morisette *et al* 2005, Molinario *et al* 2014, Amraoui *et al* 2010, Justice *et al* 2002). Differentiating natural disturbances from anthropogenic ones by GIS modelling their proximity to other forest disturbances, assuming anthropogenic disturbances do not occur in isolation. The rules developed in the GIS model therefore allowed for natural non-forest areas to exist within primary forest, e.g. savanna. While these areas are absent of active forest disturbance, they are used for transportation between inhabited areas.

The LFT requires a ternary input mask of *forest*, *non-forest* and *no-data.* This input is derived from FACET classes, where primary forest *becomes fragmented,* and other classes can either *fragment* primary forest or have no anthropogenic fragmentation effect on it (*no-data)* (Table 1) Previously the absence of wall-to-wall national-scale input data had prevented this level of automation and granularity in the analysis of forest fragmentation in the DRC.

First, the input data was pre-processed and tiled (Figure 2.19 and Table 1), then processed with the customized LFT code and finally the output tiles mosaicked back into a single national-scale raster. Fragmented and core forest classes (classes 4-7) were modelled following two additional spatial rules: retaining patch connectivity if they had a minimum viable corridor width of 480m (2x240m) and if rivers between patches were < 60m wide. This allowed for land patches separated by small streams or fragmented river banks to stay connected to each other, whereas large bodies of water were allowed to separate them and fragment forest under the assumption that they could be natural barriers to the dispersal of many terrestrial species. Spatial rules were used to add back individual FACET classes that the LFT output had classified as 'no-data' (Table 3): water and no-data were added back as they were, while non-forest, secondary forest and forest loss were separated by the presence of active anthropogenic areas, becoming either class 2 or 3 in the forest fragmentation maps.

The map developed is the first automated forest fragmentation map for the DRC, with a classification granularity that can be useful for local and country level investigations on the impact of disturbance on forest intactness. This is complimentary to the Intact Forest Landscape (IFL) map (Potapov *et al* 2008) which identifies areas of intact core forest at larger scales (at national, regional and global extents) and work on "hinterland" forests (Tyukavina *et al* 2015).

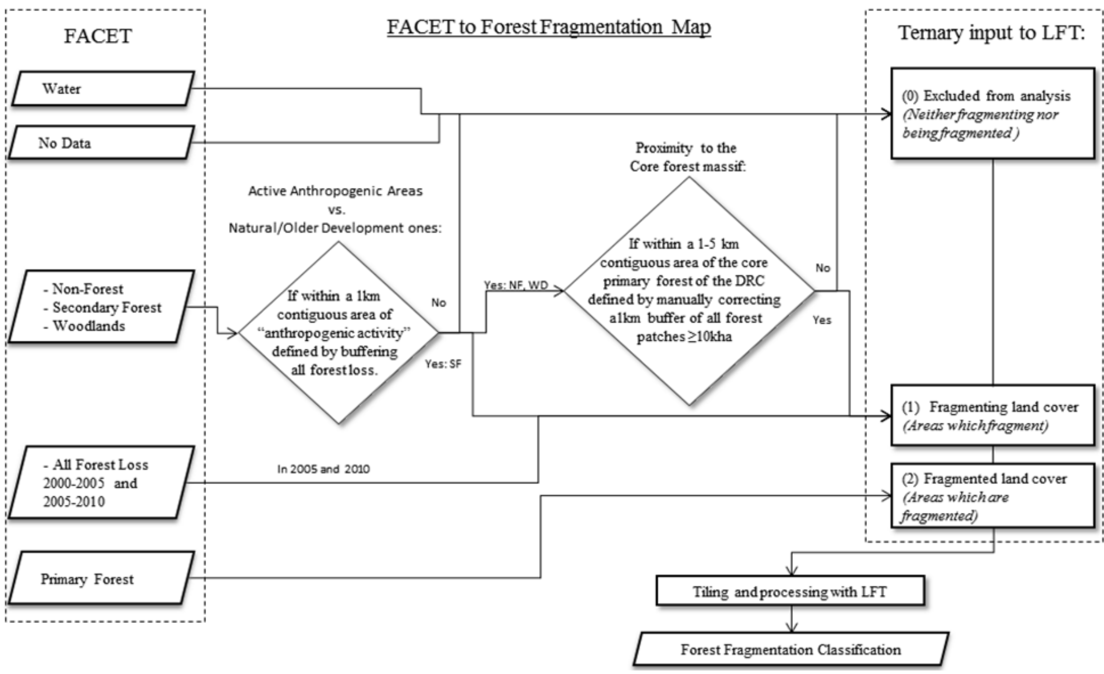


Figure 2.19: A spatial model of the rural complex based on FACET input data.

Table 1. LFT input classes.

Class code	Class name	FACET data
0	No-data	FACET classes which have no fragmentation effect on primary forest in the context of anthropogenic activity.
1	Fragmenting land cover	FACET classes that fragment primary forest. The *fragmenting* class includes only patches of: secondary forest, non-forest and woodlands, if within 5 pixels (300m) of any subsequent forest loss (2000-2010 change). Non-forest and woodlands also if they are a) within the AOI, b) within 5 pixels of the secondary forest that's within the 5 pixel buffer of forest change.
2	Forest being fragmented	FACET Primary forest only.

Table 2. LFT output classification.

Class Code	Class Name	Description
0	No-data	Everything that is not primary forest
1	Patch Forest	Primary forest completely enclosed within the input fragmenting class (within the core rural complex).
2	Edge Forest	Primary forest within 240m of the edge of the large contiguous patches of the fragmenting class: (around the core rural complex).
3	Perforated Forest	Primary forest within 240m of smaller isolated forest perforations (primary forest surrounding isolated forest perforations)
	Fragmented Forest and Core Forest (below):	*Four classes of primary forest, separated using forest patch size and connectivity rules:*
4	Small Fragmented Forest	Primary forest patch < 1,000ha
5	Medium Fragmented Forest	1,000ha > Primary forest patch < 10,000ha
6	Large Fragmented Forest	10,000ha > Primary forest patch <50,000ha
7	Core Forest	Primary forest patch > 50,000ha

Table 3. Forest Fragmentation classification for 2000, 2005 and 2010.

Class Code	Class Name
0	No-data
1	Water
2	Natural and Older Derived NF, SF and WD
3	Core Interior of Rural Complex and Forest Perforations
4	Patch Forest
5	Edge Forest
6	Perforated Forest
7	Small Fragmented Forest <1,000ha
8	Medium Fragmented Forest >1,000ha and <10,000ha
9	Large Fragmented Forest >10,000 and <50,000ha
10	Core Forest >50,000ha

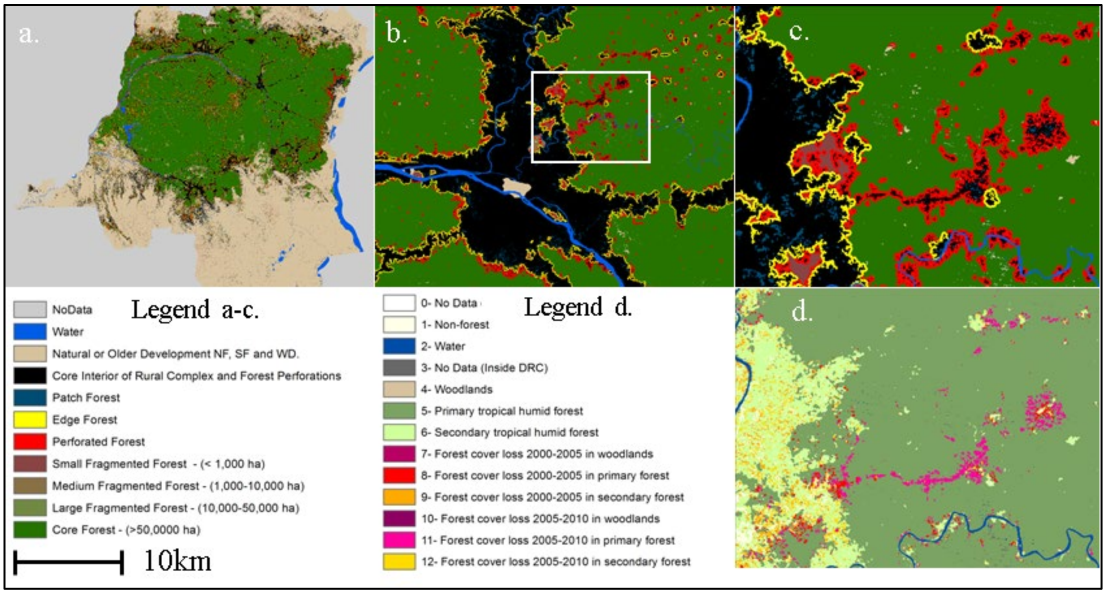


Figure 2.20: a. Forest fragmentation map 2010, b. Forest fragmentation map of the area of Kisangani, c. Detail northeast of Kisangani, d. FACET map of the same area as c.

2.2.3 The Rural Complex Footprint Map

The rural complex footprint maps for 2000, 2005 and 2010 were obtained by reclassifying the forest fragmentation maps (Figure 2.21). The rural complex footprint map group individual patches and classes in order to separate homogenous macro-areas of rural complex from those of more isolated forest perforations. The rural complex is a combination of several land cover classes previously identified in the model: some directly from FACET (some non-forest, secondary forest, woodland forest and forest loss) and some primary forest classes obtained from the output of the LFT (patch forest, edge forest, and some perforated forest). Using spatial rules of contiguity and minimum area threshold, contiguous areas of perforated primary forest that are proximate to the rural complex are aggregated with the rural complex, whereas smaller, more isolated perforations are kept separate. The assumption is that contiguous areas of forest perforation should not be considered as strictly isolated phenomena, as they previously have. Of the thresholds tested, a 625 pixel (3.75ha/ 0.0375km^2) area was used to separate groups of contiguous perforated forest. Isolated forest perforations areas are obtained by adding those classes that pertain to the actual perforation (some FACET non-forest, secondary forest, woodland forest and forest loss) to some of the LFT-identified 'perforated forest'.

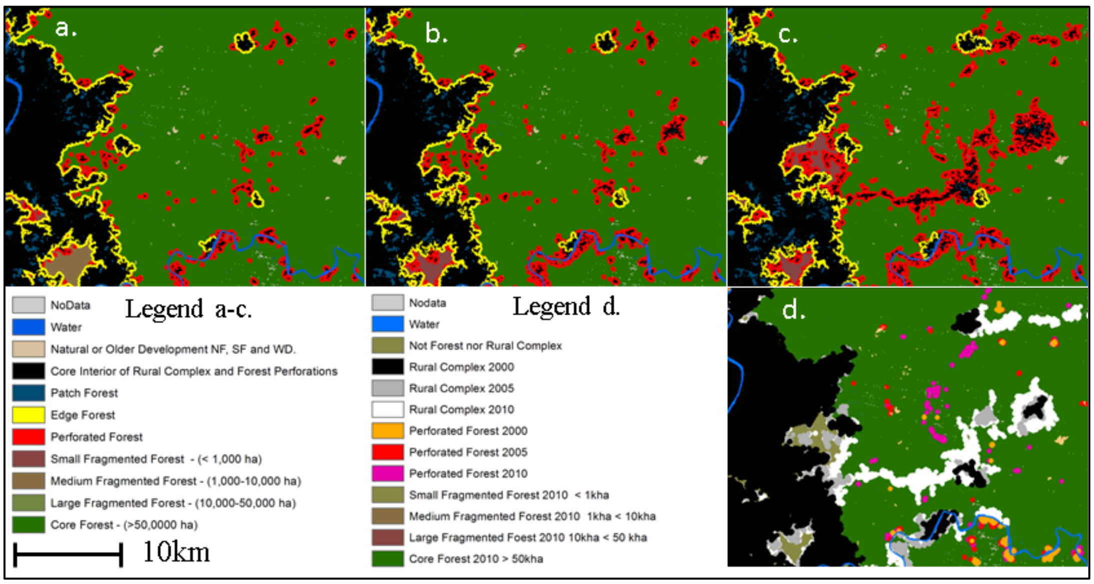


Figure 2.21: a. Forest fragmentation map for 2000, b. for 2005, c. and for 2010, d. Rural complex footprint map for 2000-2005-2010.

Table 4. Rural complex footprint map classification.

Class Code	Class Name
0	No-data
1	Water
2, 3, 4	Rural Complex 2000; 2005; 2010
5, 6, 7	Perforated Forest 2000; 2005, 2010
8	Natural and Older Derived NF, SF and WD
9	Small Fragmented Forest <1,000ha
10	Medium Fragmented Forest >1,000ha and <10,000ha
11	Large Fragmented Forest >10,000 and <50,000ha
12	Core Forest >50,000ha

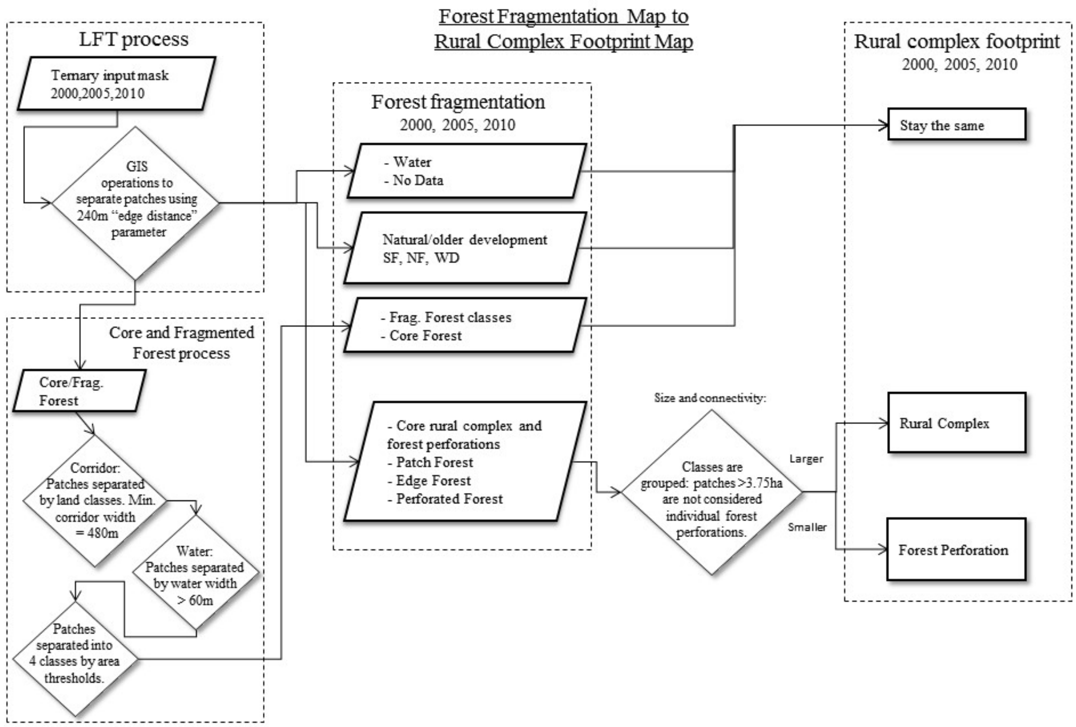


Figure 2.22: Model of the LFT to forest fragmentation to rural complex footprint.

2.2.4 Yearly Forest Cover Loss

The GFC product became available subsequently to the development of the methods for this dissertation. The methods developed here rely on the use of a baseline separation of primary and secondary forest, which is still only available from the FACET product. The increased temporal resolution of the GFC product however was an asset that was later incorporated in the methods for subsequent chapters. In this chapter, the GFC was used to stratify yearly 2000-2012 (the period available at the time) GFC forest cover loss *a posteriori* to the analysis. GFC observations increase the spatial resolution from 60m to 30m, the temporal resolution from 3 to 12 time steps and also include vegetation regrowth observations. The GFC-plotted loss observations within the stratification were the following:

- GFC 2000-2004 in classes from year 2000,
- GFC 2005-2009 in those from 2005,
- GFC 2010-2011 on those from 2010.

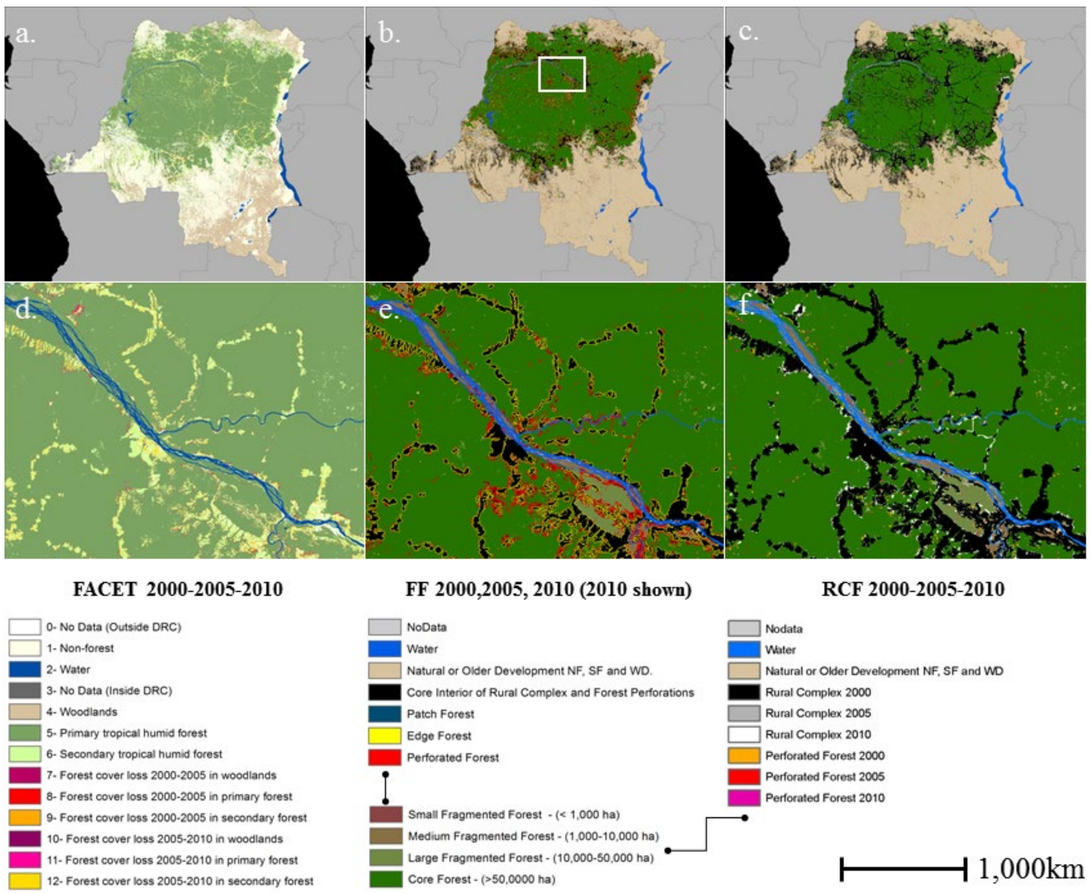


Figure 2.23: a. FACET, b. Forest fragmentation map (FF) c. Rural complex footprint map. (RCF).

2.3 Results

Results give us changes in area of edge, perforated, patch, fragmented and core forest as well as the baseline area of the established rural complex, the area of growth of rural complex expansion and the area of isolated forest perforations. Mapped typologies of forest cover dynamics are presented and discussed in the next section.

The results presented here are disaggregated by second level administrative units, Congo Basin Forest Partnership (CBFP) landscapes and protected areas from the World Database of Protected Areas (WDPA).

2.3.1 Forest Fragmentation Results

In 2000 core forest accounted for 86,868,974 ha (38%) of DRC land area (1 ha = 0.01 km^2). In 2010, of that core forest, 3,291,142 ha (3.8%) were sectioned off to smaller areas, becoming patch, edge, perforated and fragmented forest. Patch forest increased by 12.4%, edge forest by 2% and perforated forest by 53%. Of the 11 second-level administrative units, in 2010 Equateur had the most core forest, followed by Province Orientale, Nord-Kivu and Maniema. Maniema also had the most fragmented forest, followed by Province Orientale and Kasai-Occidental. The largest losses of core forest in the study period were in Nord-Kivu (-3.1%), Equateur (-2.5%) and Sud-Kivu (-2.4%).

In 2000 the 6 CBFP landscapes accounted for 32,754,657 ha (36.6%) of core forest. Of that core forest 912,234 ha (2.8%) had been lost by 2010, 0.7% less than the country average. The landscape with the highest percentage of core forest is Salonga-Lukenie-Sankuru (93%) followed by Ituri-Epulu-Aru (87%). Virunga had the highest percentage of core forest loss, while the lowest was in Salonga-Lukenie-Sankuru. Fragmented forest increased in all but one landscape, caused by the loss of viable forest corridors, eroded by expanding edge forest as well as increased forest perforation areas. Virunga and Ituri-Epulu-Aru had the highest rates of growth of perforated forest area, showing a higher-than-average move away from established rural complexes. Patch forest grew in all landscapes and by almost 50% in Ituri-Epulu-Aru, an important dynamic which highlights isolated forest patches completely enclosed by the rural complex but not reported as different from primary core forest in products such as FACET. These isolated forest patches can have fundamentally different ecological functions and habitat characteristics than core primary forest.

Of the protected areas (PA), 15 have no core or fragmented forest. Of the remaining 21 with core forest, all of them lost some during the study period, 10 of them losing more than 2%. PAs contained 13,240,495 ha of core forest in 2000 and lost 174,578 ha (1.3%) to fragmented classes by 2010. Perforated forest increased by over 10% in 10 PAs. Patch forest increased in 28 PAs, more than 50% in 6 of these, and doubling in 2 of them.

2.3.2 Rural Complex Footprint Results

The rural complex grew by 10.2% between 2000 and 2010, a yearly average rate of 1%, from 11.9% to 13.1% of the DRC total land area. This change added 2,771,238 ha of rural complex to the country. The area of established agriculture is growing, although with high variability throughout the country. Nord-Kivu and Sud-Kivu had the highest rural complex growth, probably because of the growth in population densities, and seven other provinces had over 10% rural complex growth. Kinshasa, Bandundu and Bas-Congo, as expected, saw much lower rural complex expansion rates due to the nearly exhausted primary forest resources there. In Katanga the isolated forest perforation area grew greatly in proportion to the low baseline rural complex and isolated perforation areas in 2000. Sud-Kivu, Province Orientale, Nord-Kivu, Maniema and Equateur all had perforated forest growth between 83% and 110%.

The rural complex grew in all the CBFP landscapes. Lac Tele-Lac Tumba had the largest 2010 rural complex footprint area (17.8%), followed by Maiko-Tayna-Kahuzi-Biega and Maringa-Lopori-Wamba. The highest relative rural complex footprint growth occurred in Ituri-Epulu-Aru (34.5%). Lac Tele-Lac Tumba had the highest forest perforation area, covering 2.24% of the landscape in 2010 while the highest forest perforation area growth occurred in Ituri-Epulu Aru.

Among PAs, the highest rural complex expansion occurred in the Bombolumene Hunting Reserve (45.4% of its areas in 2000) followed by Lomako-Yokala Natural Reserve, Kahuzi-Biega National Park and Tumba-Lediima Nature Reserve all in the 22%-25% range. If normalized by the amount of standing core and fragmented forest, the rural complex footprint growth seen in parks with a higher ratio of rural complex area to core forest area, such as Virunga National Park, is higher than it would seem otherwise, indicating larger impacts in those areas where rural complex expansion has more likelihood of eroding and fragmenting core and fragmented forest. Perforated forest more than doubled in at least 12 PAs.

2.3.3 Yearly Forest Cover Loss Contribution to Forest Fragmentation and the Rural Complex Footprint

The higher spatial resolution of GFC confirms that most loss occurs within the mosaic of secondary succession in the agricultural rural complex (86.4%), as previously reported (Potapov *et al* 2012). This clearing occurs by either reusing secondary forest and fallows or clearing patch and edge forest. Of the remaining forest loss 7% occurred within previous isolated forest perforations, either as the disturbance itself or within the perforated primary forest around the disturbance, only 1.6% in fragmented forest and about 5% in core forest.

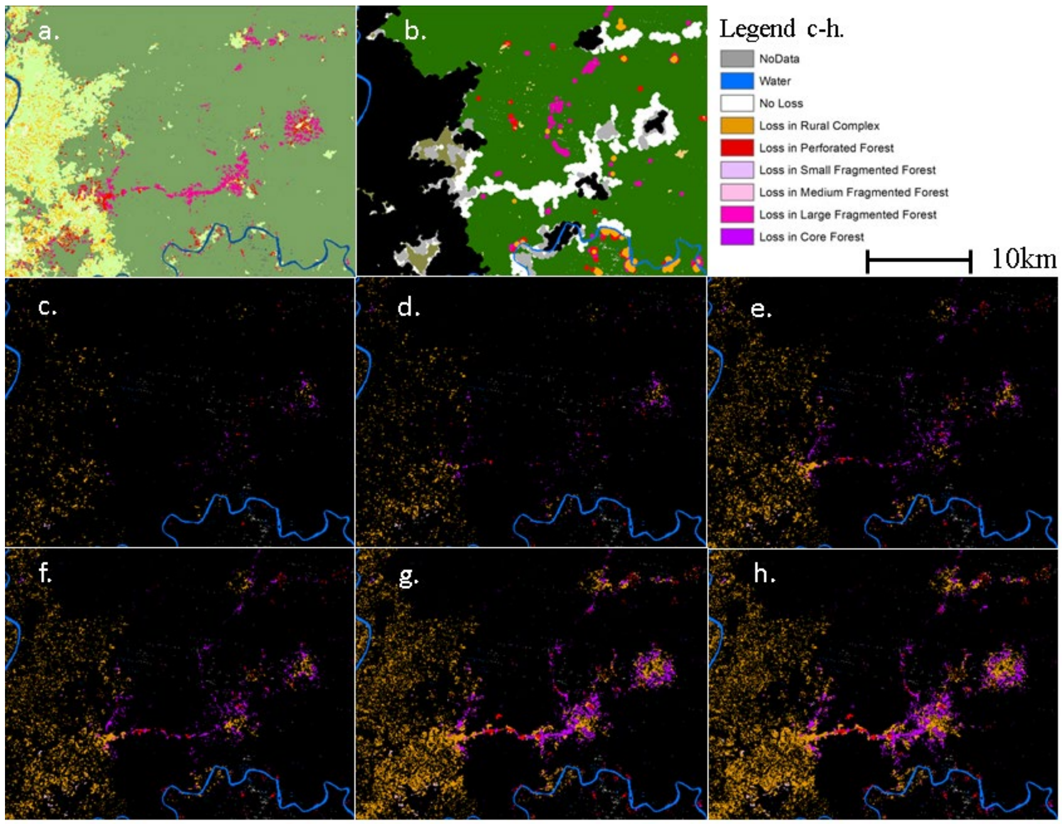


Figure 2.24: a. FACET, b. Rural complex footprint 2000, 2005, 2010, c. - h. GFC loss in the rural complex footprint map classes from 2000 to 2012 (in 2 year increments for illustration).

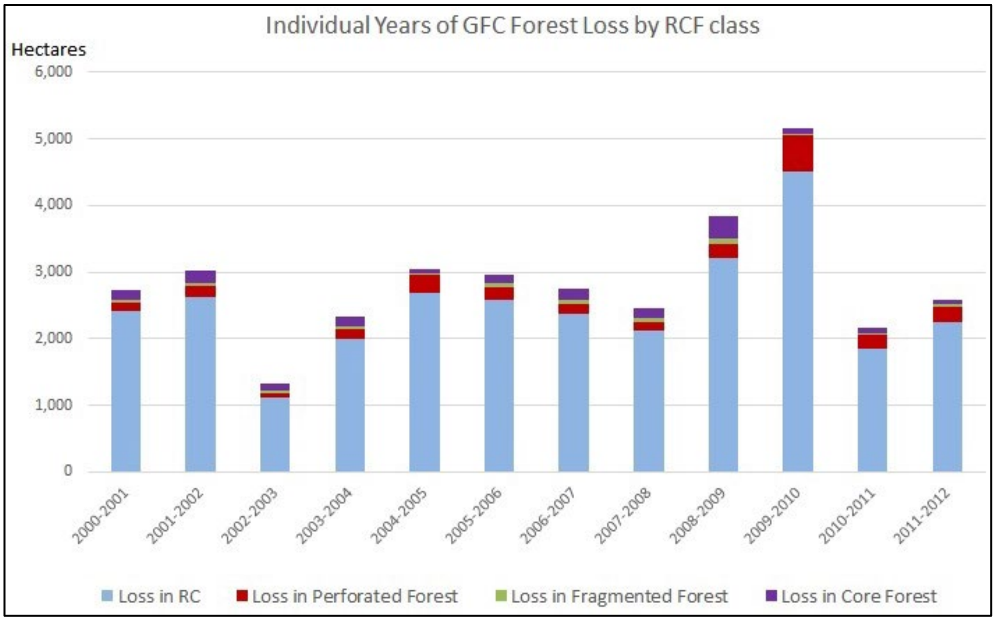


Figure 2.25: Yearly GFC forest cover loss stratified by core and fragmented forest loss.

2.4 Discussion

Mapping the extent of the established rural complex and separating it from isolated forest perforations is not possible using only a per-pixel approach. Identifying these areas requires spatial models that incorporate spatial context, like the density of forest cover loss pixels per given area, and the proximity to other clusters of forest cover loss pixels. These models are created in a GIS environment and have to be driven by the current understanding of land use dynamics in the specific area of study. In this case, the result is a classification that is useful in characterizing the historical change that has occurred in the DRC and understanding the disaggregated and contextualized impacts that ongoing forest cover loss has on forest fragmentation

Results confirm that most loss occurs in the rural complex; an area which is growing with great variability throughout the country. They also indicate that there is a proportionally faster growth of isolated forest perforations than that of the rural complex. This is concerning as more core forest is fragmented as a result of clearing occurring deeper in the forest. During the last decade there has been a growing number of shifting cultivators moving away from established areas. In the east of the country the rural complex and isolated forest perforation are both growing and moving westward driven by the need for land, food and fuel for growing populations. Growing isolated forest perforations throughout the country are either caused by shifting cultivators driven to go further from their established villages, or clearing to provide food, fuel and materials for local populations involved in commercial or artisanal natural resource extraction (DeWasseige 2015, Nackoney *et al* 2014, Ickowitz *et al* 2015).

Core forest in the DRC shrunk by 3.8% and 12.4% of primary forest became patch forest: that's primary forest that is completely enclosed by anthropogenic activity. This illustrates how the actual impact of clearing on forest ecology and habitat is higher and with greater variability than previously understood. The context of where the clearing occurs is as important as the per-pixel detection itself in correctly quantifying the impact that clearing has, as relatively small areas of clearing can have large impacts on the environment by eroding wildlife corridors or isolating forest patches.

At the CBFP (CARPE) landscape level, those with the highest ratios of existing rural complex or forest perforations to standing core forest and fragmented forest are not surprisingly the most impacted by change. Virunga, Ituri-Epulu-Aru and Maringa-Lopori-Wamba had the largest losses in core forest and expansion of the rural complex and isolated forest perforation areas. Likewise, protected areas in peri-urban areas were the most impacted by forest cover loss as they don't have much core forest to begin with and have large existing markets nearby. These areas present a different dynamic than remote areas, feeding and fuelling urban areas as well as local populations (Allen 2003, Simon 2008).

Different typologies of contextualized forest cover loss indicate what is likely to be the impact and temporal persistence that clearing has on the forest (Figures

Figure 2.26 and Figure 2.27). Whether or not a clearing is part of a more spatially pervasive phenomenon is a good indicator of how long it will take for those areas to return to a primary-like forest state if the disturbance were to cease.

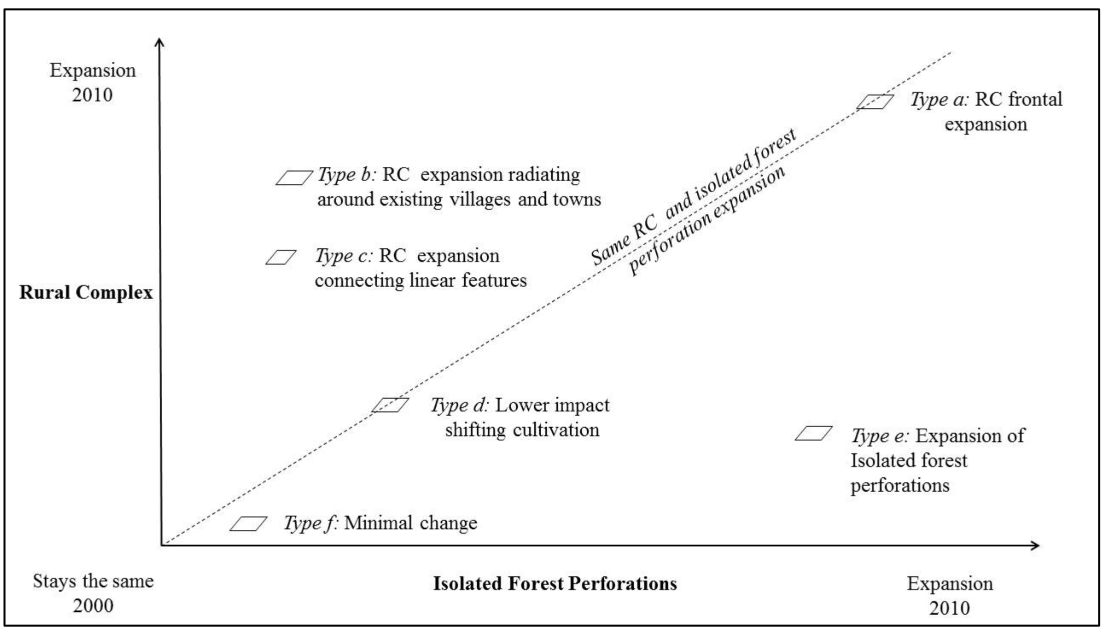


Figure 2.26: Types of forest cover loss diversified by its contribution to the rural complex and isolated forest perforations.

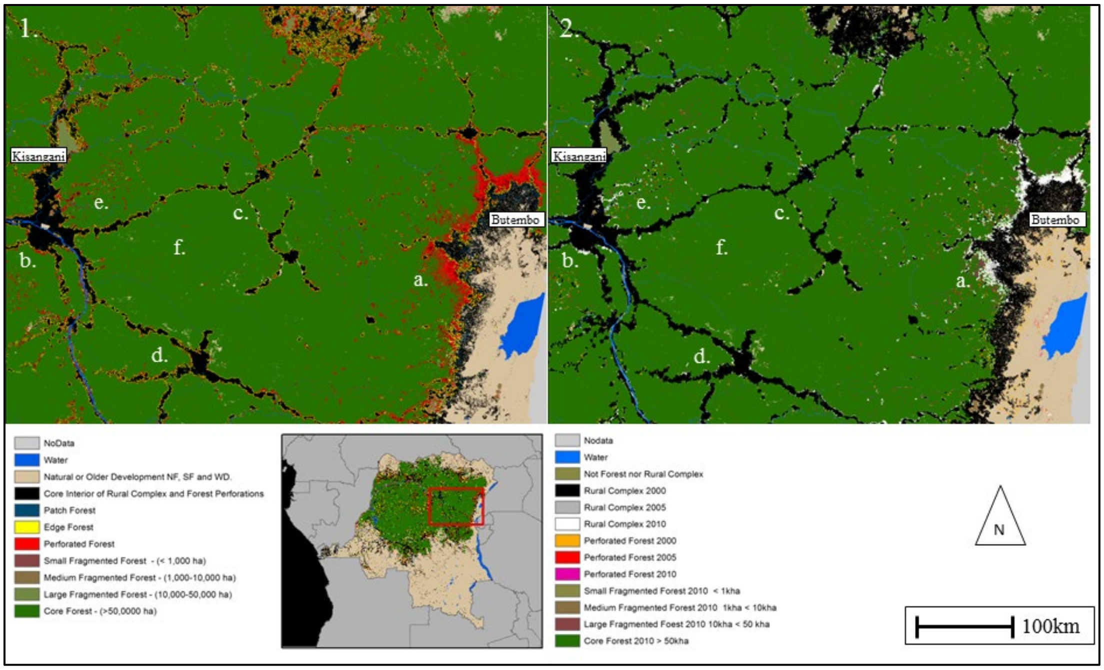


Figure 2.27: Different typologies of forest cover loss in the central-eastern part of the DRC. 1. Forest fragmentation map for 2010 and 2. Rural complex footprint map for 2000-2005-2010.

Type a: Frontal rural complex expansion

Some areas experience frontal expansions of the rural complex, which modify land cover for longer periods of time than more isolated forest perforations, impacting forest ecology and habitat in important ways (Mertens and Lambin 1997, Lorena and Lambin 2007). Nord-Kivu and Sud-Kivu have the highest rural complex growth, probably due to the large influx of Rwandan refugees which escaped the Rwandan genocide, as well as a large number of internally displaced persons (IDPs) that were forced from their native villages during the Congo war (DeWasseige *et al* 2012, Nackoney *et al* 2014). In certain areas, such as west of Beni, the density of isolated forest perforations is such that new rural complex landscapes are developed. This is probably caused by existing and changing socio-economic drivers of agricultural expansion which are also associated with increase in population density (Lambin *et al* 2001, 2003, Draulans and Van Krunkelsven 2002). The increase in population density without the intensification of food production, together with the disruption of local livelihoods and collapse of infrastructure and socio-economic structures, has led to the increase of slash and burn agriculture in a frontal expansion of the rural complex moving westwards towards previously intact primary forest areas (Geist and Lambin 2002, Forced Migration Review 2010, Defourny *et al* 2011, Potapov *et al* 2012, Hansen *et al* 2013, DeWasseige *et al* 2014)

Type b: Rural complex expansion radiating from existing villages and towns

Shifting cultivation expansion emanating from established rural complex areas and towns happens throughout the DRC, such as the area south of Kisangani. In these areas there is relatively low forest perforation, and most clearing activity is within the rural complex and at the interface with primary forest. Unlike frontal rural complex expansion, these areas are often directional and quite distinct from isolated forest perforation occurring further away from the villages.

Type c: Rural complex expansion connecting existing linear features

In many areas existing roads and paths are expanded and connected for both transit of goods and for shifting cultivation (Wilkie *et al* 2000, Lubamba *et al* 2013). The road between Bwafalinga and Opienge is an example of a transit route that is expanded during the period 2000-2010. The expansion of shifting cultivation and villages along transportation routes increases the habitat-fragmentation potential of those existing edges, and the permeation of people into intact forest tracts.

Type d: Lower impact shifting cultivation

Many areas have shifting cultivation clearings occurring within the established rural complex and within a primary forest right at its interface. The example shown is of the western side of Lubutu. In areas such as these, livelihood farming continues traditionally with relatively low environmental impact (Mather 1992, Defourny *et al* 2011, Ickowitz 2011).

Type e: Expansion of isolated Forest Perforations

These areas don't have extensive established areas of forest disturbance and represent land frontiers that are opened up either by shifting cultivators or logging or mining operations. In the case of logging and mining operations, most observable forest cover loss is still due to the shifting cultivation necessary to extract resources and feed worker populations. Sometimes these areas of clearing follow the development of new transportation routes such as logging roads, and in other cases previously isolated forest perforations are used as stepping stones to access the forest and connect trade routes and villages; as farmers and hunter-gatherers increase and expand forest access, such areas ultimately become connected to existing rural complex areas (Wilkie *et al* 2000, Russell *et al* 2011, Lubamba *et al* 2013).

Type f: Minimal change

The area between Kisangani and Opienge is an example of an area with relatively undisturbed core forest. In these areas there is little environmental pressure, change or growth in the study period and when shifting cultivation occurs traditionally it does so with an ecologically healthy period of regeneration of fallows and secondary forest and low rates of loss of primary forest (Defourny *et al* 2011, DeWasseige *et al* 2014). Primary forest fragmentation and habitat loss might not be a concern, however poaching, hunting and collection of NTFP products can still be an important issue. In some areas the abandonment of previously inhabited rural complex areas is visible, such as the area north of the road between Lubutu and Kisangani.

2.5 Conclusion

Results of this Chapter illustrate a changing forest disturbance dynamic within the DRC, at national, subnational and landscape scales. Specifically, more forest loss is occurring as isolated forest perforations associated with shifting cultivation that is associated with a number of changing land uses and socio-economic factors such as population density also caused by migration. When these forest perforations are observed to be occurring with high density per unit of area, they should not be considered isolated phenomena, as they have been previously, and should instead be contextualized as part of an expanding rural complex footprint. This contextualization is key to understanding the actual impacts of forest cover loss in the DRC.

Results indicate that some areas of shifting cultivation fragment habitats and impact biodiversity and forest ecology much more than other areas, and in specific observable patterns. At the national scale 6 typologies of forest cover loss emerged, differentiated by their impact of forest fragmentation and growing the rural complex mosaic. Particularly, small-holder livelihood shifting cultivation can either have a smaller, more sustainable impact, or have a bigger impact when associated with the expansion of existing rural complex, the creation or connection of transportation routes between villages, and the expansion in fronts of disturbance such as in the East of the DRC.

Previously, the extent and implications of forest cover loss from shifting cultivation in the DRC had been debated (Ickowitz 2011, Russell *et al* 2011), partially because of the lack of quantitative and explicit maps that illustrated differences in the appropriation of primary forest. Authors have also highlighted the need for more research linking subsistence agriculture with land cover change (Justice *et al* 2001, Zhang *et al* 2006, Defourny *et al* 2011).

The forest fragmentation map developed in this study is the first automated map of its kind for the DRC (or for any area this large, to my knowledge) and is complementary to existing products such as the Intact Forest Landscape (IFL) (Potapov *et al* 2008) which identify larger areas of contiguous intact forest (minimum area of 50,000ha [500km^2]) and allow regional and international comparisons because of its coverage. The granularity and automation of the presented fragmentation maps might make them more adequate for local investigations of the impact of disturbance on the intactness of forest in the DRC. In PES, such as REDD+, the accurate mapping of baseline land cover, such as the agricultural area used for livelihood farming, and its rates of expansion, is essential to calculate realistic future scenarios of land use that consider the necessary agricultural expansion for livelihood farming.

Mapping the contextualized spatial footprint of forest disturbances required additional steps beyond the per-pixel observation of forest cover loss and resulted in the creation of an added-value product which researchers, land managers and decision makers can use to compare areas, link forest cover loss to its proximate causes, drivers and impacts (Fortin and Drapeau 1995)) and more accurately predict future changes (Turner *et al* 1993).

However, the investigation in this Chapter highlighted a gap in the understanding of shifting cultivation and the rural complex in the country; we now have an accurate map of the areas of the rural complex and isolated forest perforations, yet we still did not have the quantification of the constituent land cover types making up the rural complex, the quantification of the temporal cycle of shifting cultivation reusing previously cleared land and the proportion of commercial land uses that make up the rural complex.

Chapter 3: Proportions of Land Cover and Land Use Classes within the Established Rural Complex of the DRC - 2000

3.1 Introduction

Forest clearing to make room for fields, only becomes a concern for longer term impacts on the forest ecosystem when the density of clearings and the frequency with which they occur surpasses the availability of land to regenerate in an optimal way. Therefore, not all shifting cultivation has negative impacts on the forest ecosystem with attendant negative repercussions on long term sustainability (Ickowitz 2006, van Vliet *et al* 2012, Moonen *et al* 2016). For example, treating shifting cultivation univocally, without accounting for local variation and the successional land cover types derived from it could overestimate the decrease in carbon stocks from deforestation by 46% (Akkermans *et al* 2013) and misinform development strategies. In Chapter 2: the complexity of the relationship between shifting cultivation and the forest ecosystem was shown quantitatively to go beyond a binary causality of shifting cultivation with “deforestation”.

To quantify the LCLU area proportions within the baseline established rural complex (ERC) for 2000 and the mean temporal recycling rate of land under shifting cultivation a simple random sample of 1,000 points in the ERC was photo-interpreted, using 3,106 high resolution satellite images that were obtained from the National Geospatial-Intelligence Agency (NGA), together with 406 images from Google Earth, spanning the period 2008-2016. Leveraging recent advances in data availability, such as free high resolution imagery available thanks to the Nextview license of the NGA, it was possible to increase the quantitative understanding of the shifting cultivation cycle and the ERC of the DRC.

Estimating the area of the constituent land cover components of the ERC it was possible to infer the mean temporal rotation rate of land in shifting cultivation at the national level. Before, this rate had been established anecdotally or determined empirically for a limited number of case studies, but not at the quantitatively at the national level (Lebrun and Gilbert 1954, Conklin 1961, Miracle 1967, Ickowitz 2006, SPIAF 2007, Akkermans *et al* 2013).

Results yielded the area estimates and proportion of area of the ERC that is occupied by shifting cultivation land cover types, like clearings, active fields, fallows and secondary forest, as well as others such as roads and settlements and primary forest. These sample estimates allowed the quantification of the ERC occupied by commercial land uses, such as plantations, mining and logging, which were found to be only a very small proportion. The land cover components of the rural complex occur in variable proportions, depending on several factors that modulate the demand for food production and other natural resources, the availability of land and the social and economic cost/benefit of cropping in a given area (Miracle 1967, Ruthenberg *et al* 1971, Mayaux *et al* 1999).

Once estimated the area available for shifting cultivation in the ERC the average temporal rotation period was determined. It would take 18 years for all land available for shifting cultivation in the established to be cleared once, without spilling out into primary forest. Additional pressure on land would there fore result in either the cultivation of non-preferred land types within the rural complex (such as wetland forest), or expansion of agriculture into nearby primary forests, with attendant impacts on emissions, habitat loss and other ecosystems services.

3.2 Data & Methods

3.2.1 Study Area and Data

The ERC area of the DRC is the target region from which a simple random sample of points was selected. Land cover in these points was photo-interpreted using high resolution satellite imagery (Figure 3.1). More precisely, the ERC is the area of the rural complex that has not expanded during the period 2000-2014. This target region was created by updating the rural complex map produced in Chapter 2 (Molinario et al. 2015) by adding forest cover loss data through 2014 from the Global Forest Change (GFC) data of Hansen et al. (2013). A sample of 1,000 points was then randomly selected within the target region with a uniform probability density for selection over the entire region (Figure 3.2).

A number of steps were involved in acquiring and preparing the satellite imagery used for photo-interpretation of the sample points. High resolution imagery was acquired freely, under the conditions of the NextView license, from the Commercial Imagery (CI) archive of the National Geospatial-Intelligence Agency (NGA) through the NASA Goddard Space Flight Center (GSFC) (Neigh *et al* 2013). The entire archive acquired for the DRC is composed of 31,224 images. One of the challenges of working with this archive is that it is composed of data from various sensors, with heterogeneous naming conventions, metadata, number and characteristics of bands and spatial and temporal resolutions. The archive was composed of mainly DigitalGlobe imagery: WorldView 1, WorldView 2, WorldView 3 and Orbview 5 (a.k.a. GeoEye 1). The spatial resolution of imagery varied from 0.5 meter pixels (WorldView 1) to 1.65 meter pixels (Orbview5). The sample intersected 3,106 images, or 17% of the entire archive acquired (Figure 3.3); 95% of the images used spanned the 2008 - 2016 period.

Google Earth imagery was used to supplement photo-interpretation when NGA imagery was available, and was used in lieu of it when it was not. Google Earth imagery varied in spatial resolution, with only Landsat-resolution imagery covering many of the sample points; in those cases the sample point was flagged as no-data as photo-interpretation was not possible.

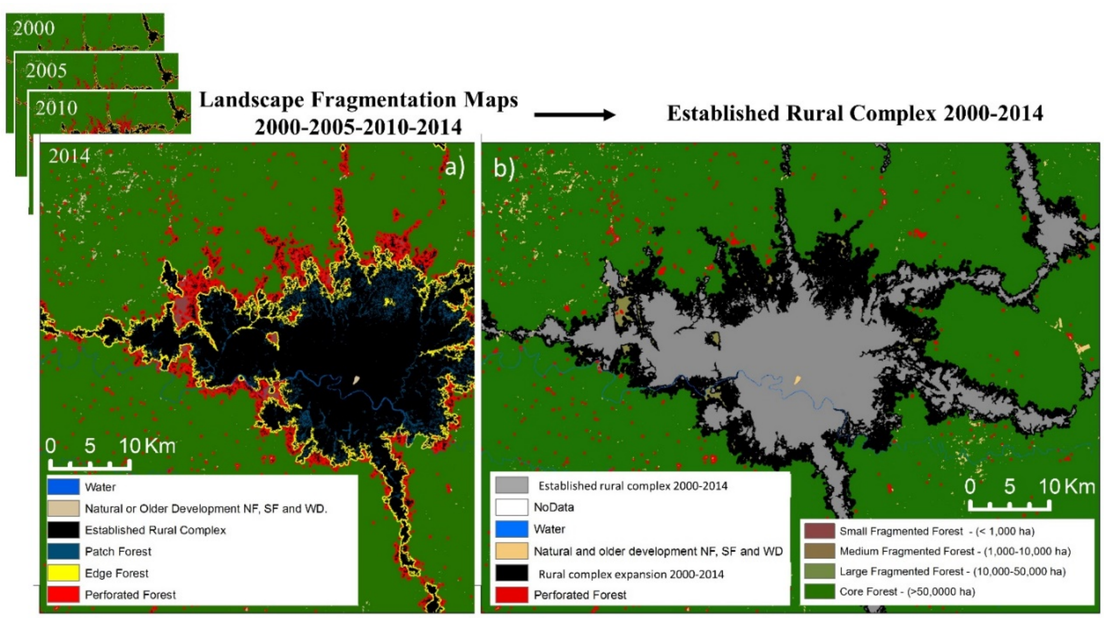


Figure 3.1: The baseline established rural complex target region 2000-2014 was extracted from the rural complex footprint maps (b) that were reclassified from the forest fragmentation maps (a), both published by Molinario et al. (2015) and augmented with GFC data from Hansen et al. (2013). In this example the target region is represented by the grey area in b).

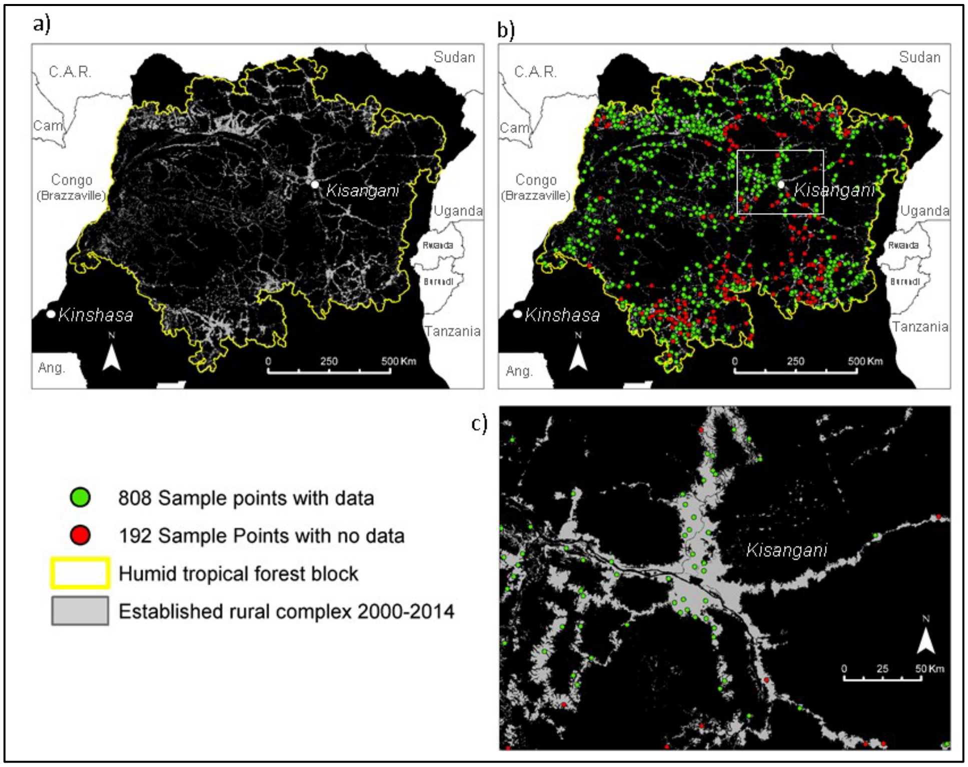


Figure 3.2: a) The baseline rural complex (2000-2014), b) a simple random sample of 1,000 sample points (only n=808 had data) and a detail c) of the area of Kisangani.

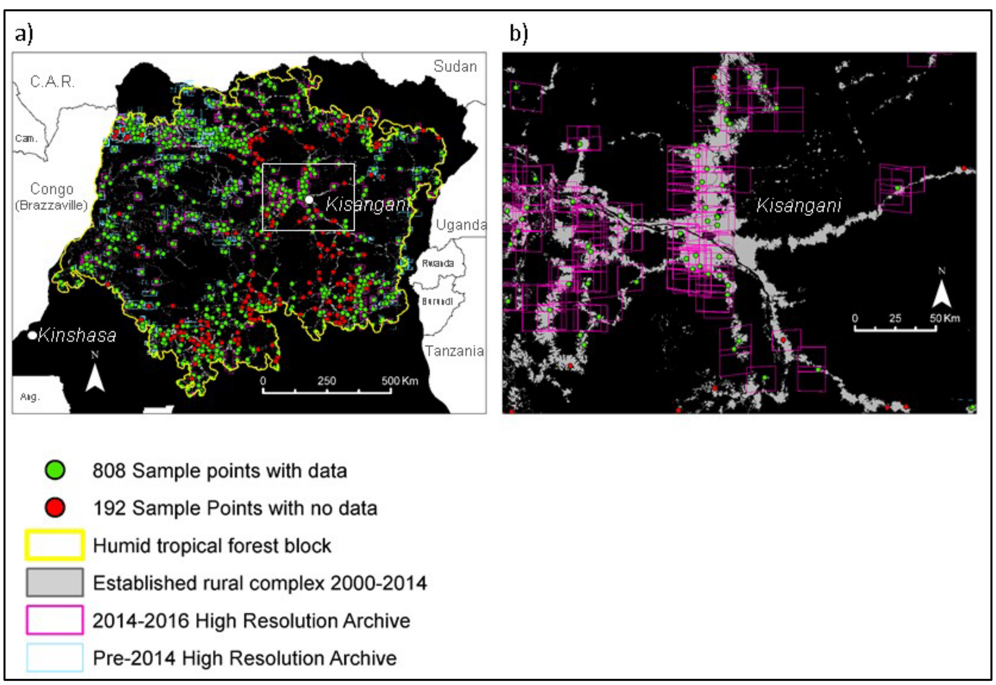


Figure 3.3: a) Image footprints overlapping the sample points. Sample points not intersecting the image archive were either photo-interpreted with Google Earth or flagged as no-data. b) A zoom box of the area of Kisangani.

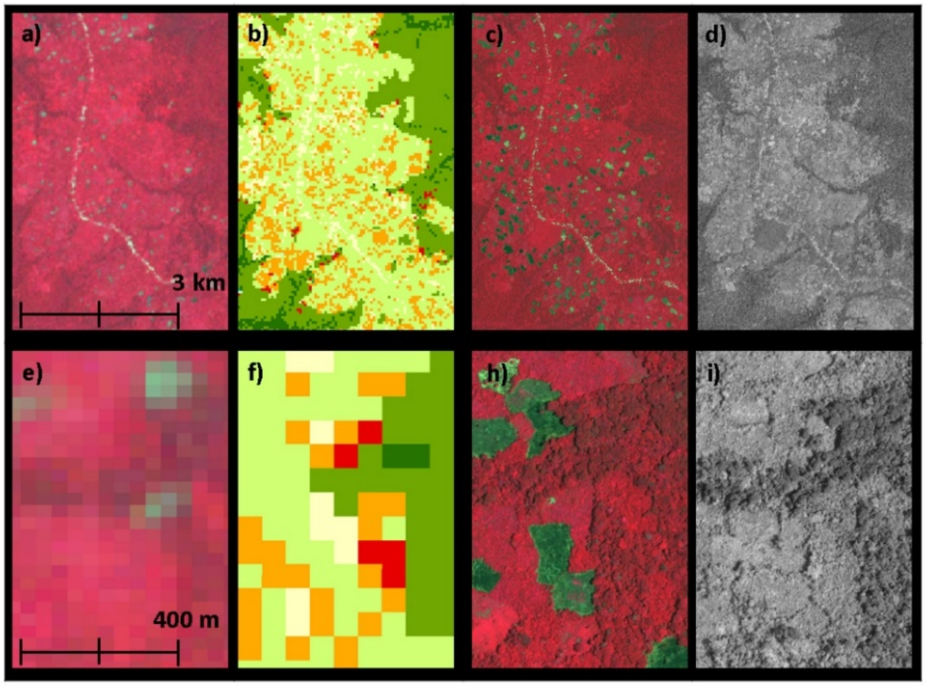


Figure 3.4: An example that illustrates the different spatial resolution of satellite imagery mentioned in the article, centered on 0°49'49.43"N 22° 1'47.54"E between the villages of Linza and Yangendji. a) Landsat image viewed in false color (30m)[12/30/2009], b) FACET (60m)[2000-2010], c) Orbview 5 [GeoEye 1] (1.6m)[4/7/2010], d) Worldview 1 (0.5m)[1/13/2015 and the enlargements of the same images e) to i).

Table 4. Temporal distribution of the latest available imagery for the interpreted sample points.

Year	Number of sample points	% of all interpreted sample points
Pre 2008	15	1.9%
2008 - 2014	220	27.2%
2014 - 2016	546	67.6%
No Date	27	3.3%
Total	808	100%

3.2.2 Methods

The images were footprinted, intersected with the sample points and photo-interpreted. The intersecting imagery was orthorectified using code developed by the Polar Geospatial Center (PGC) of the University of Minnesota (PGC 2017). A Digital Elevation Model (DEM) created using data from the Shuttle Radar Topography

Mission (SRTM) (SRTM 2014) was used, with no-data pixels filled with the Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) DEM data (ASTER 2009). Using the same PGC code, the imagery was converted from the native National Imagery Transmission Format (NITF) to Tagged Image File Format (TIFF). The imagery was then manually photo-interpreted using ENVI software.

The sample points did not overlap any of the available NGA imagery in 39% of the cases. In other cases, while the imagery was available, the sample point might have been covered by cloud, cloud shadow, or bad-data artefacts. In those cases, Google Earth was used in lieu of it. However, as even in Google Earth high resolution imagery was not always available, ultimately 19% of the sample points were flagged as no-data (192 sample points). The remaining n=808 sample points (81% of the original sample) were photo-interpreted to determine the land cover of the pixel containing the sample point. In the rare cases in which a sample point had multiple-date high resolution images available, the most recent one was used to make the interpretation of its latest land cover.

The sample points were assigned a land cover label according to a 14-class legend (Table 5) developed empirically from preliminary photo-interpretation, literature review and expert opinion based on observable land cover characteristics (Styger *et al* 2007, Lebamba *et al* 2009, Akkermans *et al* 2013). The sample points were also assigned a rating for interpretation confidence of high, medium or low. The confidence of the photo-interpretation varied as a function of several characteristics of the observed land cover, for example the spatial structure of canopy (primary forest having larger crowns, greater tree height as evidenced by adjacent shadows, and a more differentiated canopy than secondary forest) as well as the color of the canopy (primary forest having darker foliage compared to secondary forest). The photo-interpreter used expert judgment that included experience of two field campaigns in the DRC forest to interpret the imagery and assign confidence flags to the photo-interpretations, as illustrated in Table 6 and further addressed in the Discussion section. Examples of the imagery photo-interpreted can be seen in Figures Figure **3.5**, Figure **3.6** and Figure **3.7**. In photo-interpreting the sample, the legend in Table 5 was used, conforming with the class definitions of Potapov et al. (2012), in which forest is defined as land with ≥ 30% canopy cover for trees ≥ 5 meters tall, woodlands have between 30% and 60% tree cover, and primary and secondary forest have more than 60% canopy cover.

The sample-based estimate of the proportion of area land cover class $\boldsymbol{i}$ within the rural complex is:

$$\boldsymbol{p_i} = \frac{\boldsymbol{n_i}}{\boldsymbol{n}}$$

Where $\boldsymbol{n_i}$ = number of sample points identified as class i and n=sample size.

The estimated area of class $\boldsymbol{i}$ is given by the following equation:

$$\boldsymbol{A_i} = \boldsymbol{A_{tot}} \times \boldsymbol{p_i}$$

Where A_{tot}= 127,796 km2 is the total area of the established rural complex.

Both the estimator of the proportion of area (pi) and the estimator of the area (Ai) of each class are unbiased estimators ((Cochran 1977), Chapter 3). The formula for estimating the variance of the estimated proportion is the following:

$$\boldsymbol{V}(\boldsymbol{p_i}) = \frac{\boldsymbol{p_i}(\boldsymbol{1} - \boldsymbol{p_i})}{\boldsymbol{n} - \boldsymbol{1}}$$

The standard error formula for the estimated proportion of area of class *i* is:

$$\boldsymbol{SE(p_i) = \sqrt{V(p_i)}}$$

The standard error for the estimated area of land cover class *i* is:

$$\boldsymbol{SE(A_i) = A_{tot} \times \sqrt{V(p_i)}}$$

The standard errors quantify the uncertainty or precision of the sample-based estimates. Clearly the standard error decreases as a function of the square root of the sample size n (e.g., a four-fold increase in sample size will halve the standard error) and the standard error also depends on pi. The sample size of n=1,000 was based on the expectation that for pi=0.10 (10% of the area represented by a class), the standard error would be approximately 0.01 (or 1% of the area represented) and this standard error was deemed acceptably small for my purposes.

Table 5. The 14 land cover classes attributed to the sample points: class name, description and the land cover type with which it potentially can be confused in photo-interpretation.

Class Code	Class Name	Description	Potential confusion with:
1	No-data	No imagery available with sufficient resolution, or no-data within that imagery, or obscuration of the sample by clouds or cloud shadows or bad data artefacts	None
2	Water	Rivers, streams, ponds and lakes	None
3	Roads and settlements	Roads, paths, communal areas along roads, buildings, huts	None
4	Grassland	Natural grassland/savanna areas	Active and fallow agriculture
5	Clearing	A forest or fallow field that has been recently cleared	None
6	Active agriculture	A field where crops are currently grown	Fallows
7	Young fallow	A field recently left fallow	Active agriculture
8	Old fallow	An overgrown fallow field	Young fallow and secondary forest
9	Commercial agriculture	Plantation land use associated with tree crops such as palm oil	None

10	Secondary forest	A forest stand with over 60% tree cover of trees ≥ 5 meters tall; canopy consists of small, relatively uniform tree crowns resulting in a bright spectral response	Mature secondary forest and primary forest
11	Mature secondary forest	A forest stand with over 60% tree cover of trees ≥ 5 meters tall; canopy consists of varying crown size and vertical distribution resulting in a moderately dark spectral response	Secondary forest and primary forest
12	Primary forest	A forest stand with over 60% tree cover of trees ≥ 5 meters tall; canopy consists of highly varying crown size and vertical distribution resulting in greater canopy shadowing and a dark spectral response	Secondary forest and mature secondary forest
13	Wetland forest	A forest stand with over 60% tree cover of trees ≥ 5 meters tall located in proximity to water bodies and associated floodplains	Primary forest and secondary forest
14	Other	Other land cover type	N/A

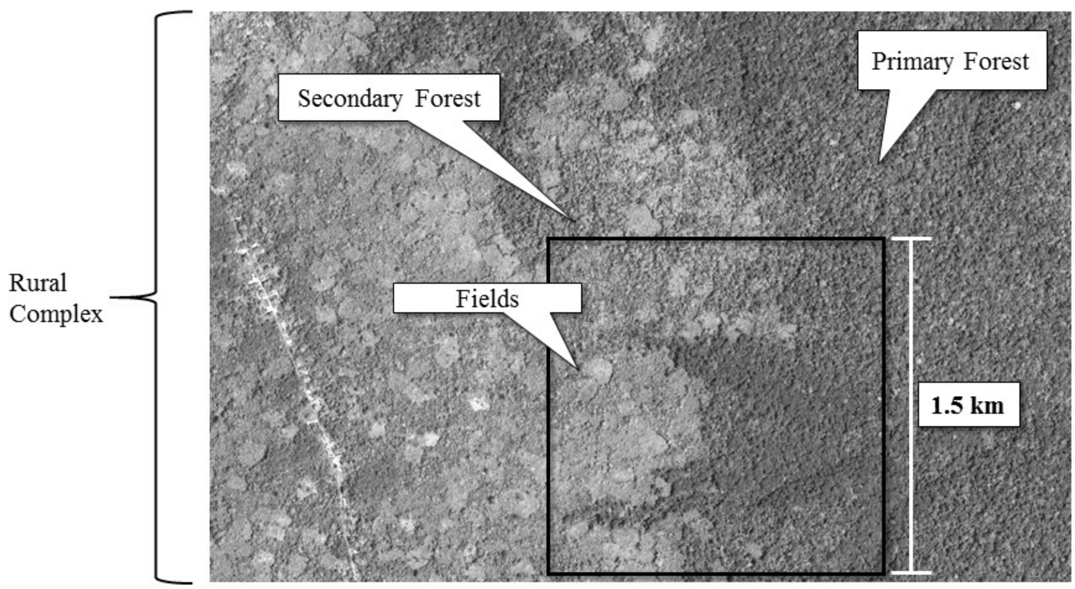


Figure 3.5: An example of the rural complex seen at 50cm resolution in a panchromatic Worldview 1 image.

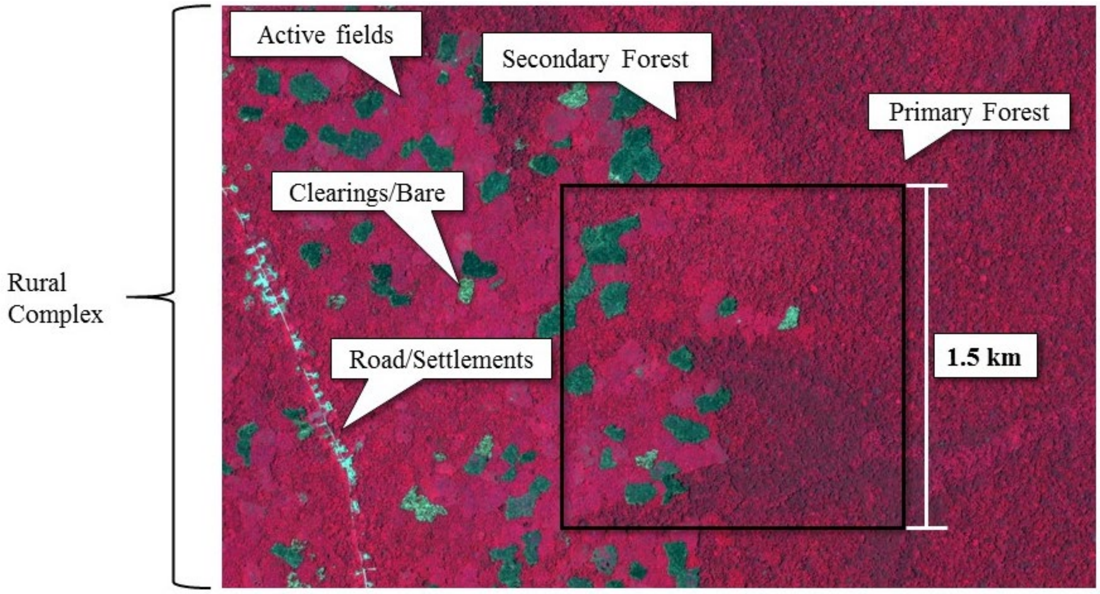


Figure 3.6: The same area seen with a multispectral Orbview 5 image in a false color combination.

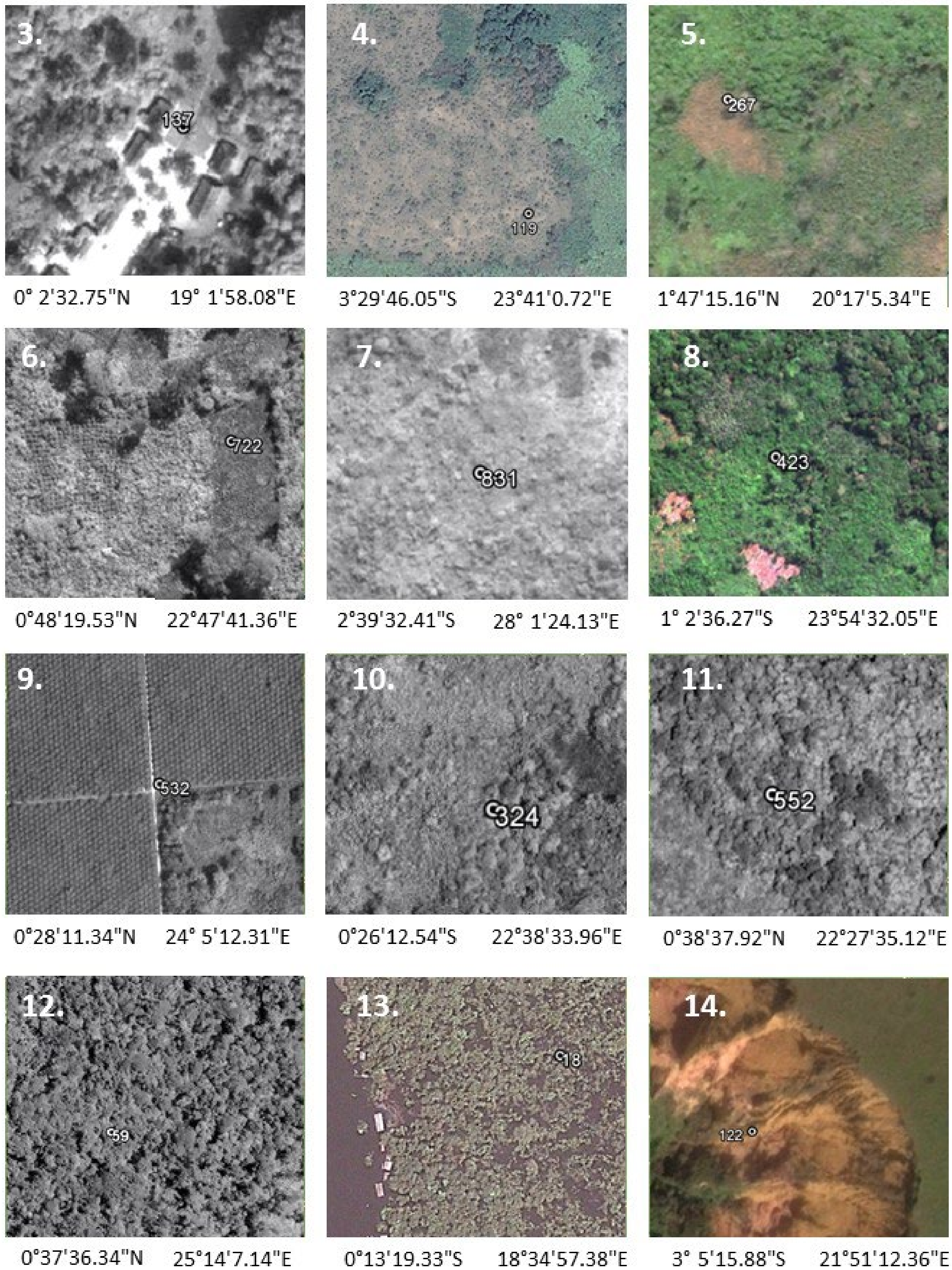


Figure 3.7: Examples of sample points interpreted in classes 3-14, not including: 1) no-data and 2) water.

3.3 Results

Based on the sample data, an estimated 76% of the established rural complex is composed of a land cover mosaic that is the product of current and past shifting cultivation: clearings, active fields, fallow fields and secondary forest. This means that if added to primary forest, 87% of the established rural complex is available to be farmed in future shifting cultivation (Figure 3.8).

The sample points were categorized into three confidence groups: 40% of all sample points were high confidence, 49% were medium confidence, and 11% were low confidence. Since 192 sample points were no-data, only 808 points comprise the subset of the sample on which the results are tabulated. The disaggregation of each land cover type by confidence group (Table 6) shows which land cover types potentially have more confusion in their photo-interpretation. For example, 85% of settlements and roads are high confidence, while only 22% of active agriculture is high confidence, whereas 64% of active agriculture sample points are medium confidence and 15% are low confidence.

While the majority of non-forest land cover sample points within the rural complex were anthropogenic, in some cases they were part of natural non-forest land cover such as river banks, landslides and even an Inselberg in the Ituri forest. In other cases, such as in grasslands, the non-forest land cover may have been part of a historic anthropogenic land cover modification.

Table 6. The estimated percentages of each land cover class and distribution of each class disaggregated by interpreter confidence rating. The % of total area is 100*pi and the SE for the % of area is 100*SE(pi).*

Class (*i*)	*High Confidence* Cnt	*High Confidence* % of class	*Medium Confidence* Cnt	*Medium Confidence* % of class	*Low Confidence* Cnt	*Low Confidence* % of class	**Full Sample** **Cnt**	**Full Sample** **% Area**	***SE*** **% Area**	A_i **(km²)**	***SE(Ai)*** (km²)
Water	1	100	0	0	0	0	1	0.1	0.1	158	158
Road/Settled	17	85	1	5	2	10	20	2.5	0.6	3,163	699
Grassland	42	84	7	14	1	2	50	6.2	0.8	7,908	1,084
Clearing	20	54	13	35	4	11	37	4.6	0.7	5,852	940
Active Ag.	18	22	53	64	12	14	83	10.3	1.1	13,128	1,366
Young Fallow	6	11	30	57	17	32	53	6.6	0.9	8,383	1,114
Old Fallow	52	33	81	51	27	17	160	19.8	1.4	25,306	1,793
Commercial Ag.	15	83	3	17	0	0	18	2.2	0.5	2,847	664
Sec. Forest	98	41	128	53	14	6	240	29.7	1.6	37,959	2,056
Mature Sec. Forest	8	22	25	68	4	10	37	4.6	0.7	5,852	940
Primary Forest	30	34	46	53	11	13	87	10.8	1.1	13,760	1,394
Wetland Forest	13	76	4	24	0	0	17	2.1	0.5	2,689	646
Other	2	40	2	40	1	20	5	0.6	0.3	791	353
Grand Total	**322**	**40**	**393**	**49**	**93**	**11**	**808**	**100**		**127,796**	

*The values in the table are rounded.

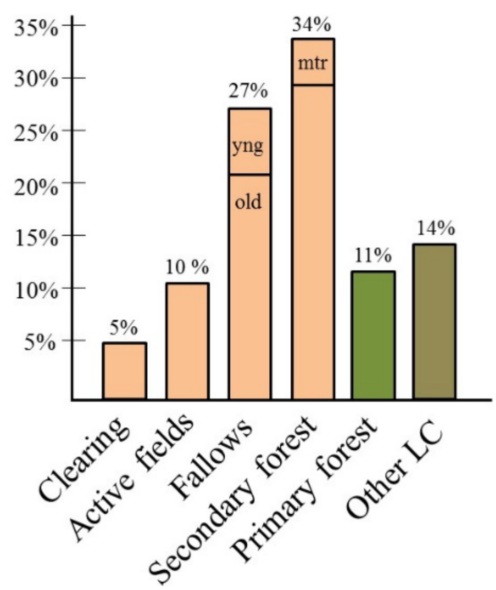


Figure 3.8: Distribution of area of land cover classes within the rural complex. An estimated 76% of the rural complex is already part of the cycle of shifting cultivation, and of the remaining area an estimated 11% is primary forest. This means that 87% of the rural complex is the estimated area available for agriculture. “mtr” = mature, “yng” = young.

Table 7. Estimated percentage of area of each land cover class disaggregated by year of imagery used.

	Pre 2008			2008-2013			2014-2016			No Date		
Class	Count	% of class	% of time period	Count	% of class	% of time period	Count	% of class	% of time period	Count	% of class	Total Count
Water	0	0	0	0	0	0	0	0	0	1	0.1	1
Road/Settled	1	5	7	8	42	3	10	53	2	1	0.1	20
Grassland	0	0	0	13	28	5	33	72	6	4	0.5	50
Clearing	1	3	7	11	31	4	24	67	4	1	0.1	37
Active Ag.	2	3	13	26	32	10	53	65	10	2	0.3	83
Young Fallow	0	0	0	16	32	6	34	68	6	3	0.4	53
Old Fallow	5	3	33	29	19	12	119	78	22	7	0.9	160
Commercial Ag.	0	0	0	3	17	1	15	83	3	0	0	18
Sec. Forest	5	2	33	63	27	25	169	71	31	3	0.4	240
Mature Sec. Forest	0	0	0	17	47	7	19	53	3	1	0.1	37
Primary Forest	1	1	7	26	31	10	56	68	10	4	0.5	87
Wetland Forest	0	0	0	8	47	3	9	53	2	0	0	17
Other	0	0	0	0	0	0	5	100	1	0	0	5
Grand Total	15	**2**	100	220	**27**	100	546	**68**	100	27	**3**	808

3.3.1 Distance Sub-Population Estimates

Estimates of the proportion of area represented by the land cover classes are produced for each of three subregions defined by distance to the edge of established rural complex. The subregions were defined so that all three represented approximately an equal area (i.e., each subregion had an equal number of sample points). This resulted in the first subregion being defined as within 180m of the rural complex edge, the second subregion covering the area between 180m and 725m from the edge, and the third subregion being the area beyond 725m of the edge (Table 8). There is a clear trend that shows more clearings and fallow fields in the interior of the rural complex (>725m distance subregion), further from the interface with primary forest. Active agriculture and secondary forest, however, have similar proportions throughout the rural complex while the proportion of mature secondary forest is less in the innermost region

(>725m). The proportion of primary forest is almost double in the subregion within 180m of the edge of the established rural complex as it is in the other two subregions, indicating its prominence in the land cover mosaic in this permeable interface area.

Table 8. Estimated land cover percentages for three subregions defined by distance to the established rural complex edge (<=180 m, 180 to 725 m, and > 725 m).

	<= 180m			180m >= 725m			>725m			
Class	**Cnt**	**% area within class**	**% area within subregion**	**Cnt**	**% area within class**	**% area within subregion**	**Cnt**	**% area within class**	**% area within subregion**	**Total**
Water	0	0	0	0	0	0	1	100	0	1
Road/Settled	3	15	1	11	55	4	6	30	2	20
Grassland	17	34	5	20	40	7	13	26	5	50
Clearing	6	16	2	12	32	5	19	51	7	37
Active Ag.	29	35	9	21	25	8	33	39	12	83
Young Fallow	16	30	5	16	30	6	21	39	8	53
Old Fallow	52	33	16	46	29	17	62	38	23	160
Commercial Ag.	5	28	2	6	33	2	7	38	3	18
Sec. Forest	77	32	23	90	38	34	73	30	27	240
Mature Sec. Forest	14	38	4	14	38	5	9	24	3	37
Primary Forest	40	46	12	24	28	9	23	26	8	87
Wetland Forest	6	35	2	6	35	2	5	29	2	17
Other	0	0	0	3	60	1	2	40	1	5
Grand Total	**265**	**33**	**100**	**269**	**33**	**100**	**274**	**34**	**100**	**808**

3.4 Discussion

The footprint of the rural complex needs to be accurately mapped among other reasons because it is an area of high carbon dynamics. Tyukavina et al. (2013) estimated that aboveground carbon loss of secondary forests was greater than that of primary forests in DRC. As the rural complex is the site of rotational clearing secondary regrowth, it should be a focus of any PES program aimed at avoiding deforestation and degradation, such as REDD+. To this end, previous work modelling and mapping the spatial patterns of the rural complex in the DRC (Molinario *et al* 2015, Harris *et al* 2017) leveraged novel wall-to-wall per-pixel satellite remote sensing-based inputs (Hansen *et al* 2013). In doing so, it became obvious that higher resolution imagery was necessary to quantify the proportions of the constituent land cover and land use components of the rural complex in all its areas; the stable, established, region that is investigated here, as well as the areas actively expanding into primary forest that are investigated in Chapter 4 (Molinario *et al* 2015). Using the data and methods outlined, a simple random sample of the ERC stratum proved to be sufficient to produce an enhanced, quantitative estimation of the land cover and land use components of the ERC and assessing the mean rotational rate of its land under shifting cultivation.

Several challenges arose when photo-interpreting the sample points. One of the difficulties was that 19% of the sample points had no available imagery to allow an interpretation. This was sometimes due to the fact that imagery was not available neither in the NGA archive nor on Google Earth, while in other cases available imagery was too coarse, had bad-data artefacts, or was obscured by cloud cover and cloud shadow. Cloud cover, in particular, is a consistent problem in tropical environments (Ju and Roy 2008, Kovalskyy and Roy 2013) and it can only be overcome by mosaicking all available cloud-free observations from different dates (Potapov *et al* 2012, Hansen *et al* 2013) or having more frequent observations from optical sensors. Integrating cloud-piercing synthetic aperture radar data (SAR) data such as Sentinel-1 would aid in the land cover mapping of tropical areas (Wulder *et al* 2008, Malenovský *et al* 2012), but would need to be demonstrated as suitable for this application.

A key issue with high resolution satellite imagery is that these data remain rare despite improvements in the availability of imagery. Planet's acquisition of Terra Bella and RapidEye and concurrent launch of 88 cube-sats (Butler 2014, Planet 2017a, 2017b) combined with the free availability of DigitalGlobe's archive to United States Government-affiliated researchers (Neigh *et al* 2013) offers the possibility of enhanced earth observation monitoring at higher spatial resolutions but the operational capacity of these systems needs to be demonstrated. The temporal resolution of high spatial resolution data is pledged to be on-par with the daily return rates of medium resolution imagery (e.g. MODIS) after the operationalization of Planet's constellation of ~100 microsatellites. Thus far, most land cover mapping and monitoring within reasonable timeframes (e.g., annually) is currently feasible using medium spatial resolution sensors such as Landsat and Sentinel-2 (NASA 2017, ESA 2017). The larger data volumes of wall-to-wall, cloud free, high resolution imagery for the tropics would also pose significant limitations. Costs are also a limitation, compared to publicly free global imaging systems such as Landsat (Wulder *et al* 2012). The future accessibility of very high spatial resolution, given that such data exists exclusively within a commercial model, is not guaranteed with implications on the ability of governments and civil society to operationally monitor land resources.

For these reasons, high resolution imagery remains limited for wall-to-wall scientific research in the tropics, lending itself primarily for sample-based or localized case studies. In this study, two-thirds of the available NGA data were acquired between 2014 and 2016, however all available data was used. This period to represents a snapshot in time of the established rural complex for circa 2015. If the study was repeated at decadal time-scales, for example, it would be possible to document changes to the land use components of the rural complex, with implications for the sustainability of Congo's swidden agricultural system.

Another issue was the confusion in the photo-interpretation of certain land cover types, despite the use of the highest resolution data currently available (50 cm). This interpretation confusion was most prominent among certain land cover types; for example, active fields were often flagged as low confidence, because mature crops in the shifting cultivation cycle (generally second or third year crops) were hard to distinguish from young abandoned fallows. Similarly, mature secondary forest was often flagged as low confidence because it was sometimes difficult to distinguish from primary forest. In some cases, it was a certain tell-tale spatial pattern that showed an area of 'brighter' forest closer to the edge of an active agricultural area that helped classify the sample point as secondary forest. In most cases, both panchromatic and multispectral high resolution imagery for the same sample point were not available. When they were, the strengths of the two types of imagery were leveraged: the spatial resolution of the panchromatic image to assess the spatial pattern of the sample point, and the spectral information of the multispectral image to interpret the land cover of the sample point. False-color band combinations were used to enhance photo-interpretations of sample points that had confusion, when multispectral imagery was available in the NGA archive. All the multispectral imagery in Google Earth was true color imagery; only available in the visible spectrum bands.

All results should be interpreted with these caveats in mind. There is important variability within the national averages reported. While these findings offer the best and most up-to-date quantification of the constituent land cover components of the rural complex, they are not intended to replace the higher accuracies of in-depth localized case-studies, in which one could address the highly nuanced qualitative socio-economic factors that drive the specific mixture of land cover and land use in a specific area (Rudel and Roper 1996, Mather *et al* 1998, Geist and Lambin 2002). Despite that, the estimate of a 5% clearing proportion of the established rural complex nationally echoes the estimate of 4.9% bare soil reported in a Landsat-based investigation of the successional cycle in the area of Kisangani (Akkermans *et al* 2013).

The estimates produced for the subregions defined by distance to the established rural complex edge showed that quantitatively the composition of land cover within these subregions fit the spatial and temporal model of the shifting cultivation cycle in the DRC previously published in Molinario et al. (2015), which was based on extensive literature review, expert opinions and field-work. The shifting cultivation dynamic at the edge of the rural complex is dependent on the appropriation of primary forest, whereas in the interior of the rural complex, primary forest is no longer readily available, and fallows and secondary forest must be reused.

3.5 Conclusion

The research in this Chapter contributes quantitative estimates of the area and proportion of land use and land cover classes within the established rural complex of the DRC that were not previously available at the country level. At the current annual clearing rate (5%), it takes ~18 years for all the available land for shifting cultivation in the established rural complex to be cleared at least once. When land use pressure increases, the increased demand for food and other resources can only lead to either intensification or extensification of the extraction of natural resources. For agriculture, such intensification is possible only through fertilization or mechanization, expansion of shifting cultivation in less-preferred areas of the rural complex (such as wetland forest), or expansion outside of the rural complex, either at its edges or in more isolated forest perforations (Molinario *et al* 2015). Results and the discussion of their limitations and caveats, indicate that the land cover and land use maps that are used to establish the baseline emissions in projects such as REDD+ need to map carefully the boundaries of the established "permanent" agricultural areas, as these are permeable, shifting, and contain a variety of successional stages of forest regrowth and forest degradation within them.

In a small number of cases, the sample points were part of a commercial land cover change dynamic, such as plantations. The estimate of the area of the ERC occupied by commercial land uses is 2.2%. However, neither logging nor mining were found in the sample, which suggests that logging and mining dynamics are largely absent in the established rural complex. It should be expected that plantations, logging and mining occur further from the historically inhabited agricultural core area of the rural complex, where the extractive resource base is located or where competition for land is less intense. Results pertain only to the land uses that are discernible in the photo-interpretation of high resolution satellite imagery. Whether the observation of a clearing or an active field is linked to land uses such as palm-oil plantations, logging concessions, or mines, or the production of foodstuffs and gathering of fuel for distal populations in urban areas, was not determined, but should be the object of future research.

Chapter 4: Contextualizing Landscape-Scale Forest Cover Loss Outside of the Established Rural Complex – 2000-2015

4.1 *Introduction*

In Chapter 3: (Molinario et al. 2017) estimated that only 2% of the established rural complex (ERC) area was occupied by large-scale commercial operations, positing that new, rural complex expansion (RCE) areas and isolated forest perforations (IFP) may be more likely associated with extractive commercial land uses. In order to test this hypothesis we set out to establish the proportion of forest cover loss outside of the (ERC). I set out to quantify the proportions of LCLU classes within the new forest cover loss areas occurring outside of the established rural complex, as either rural complex expansion (RCE) or isolated forest perforation (IFP) during the period 2000-2015.

I photo-interpreted very high resolution satellite images in a stratified random sampling design. First I interpreted sample points within the RCE and IFP strata, and then I photo-interpreted the landscapes around them, within concentric distance buffers. The concentric distance buffers around each sample point were at a distance of 100m, 500m, 1000m and 5000m.

The motivation to contextualize forest cover loss and degradation holistically stems from the understanding that it is not sufficient to observe forest cover loss at the pixel-level, but it's also necessary to quantify the spatial and temporal characteristics of the successional vegetation types that replace a patch of cleared forest (Akkermans et al 2013) and to identify what other proximate and underlying drivers influence land cover and land use change (LCLUC) (Butsic *et al* 2015). Several authors cite how the influence of commercial land uses, settlements and transportation routes can reach far beyond their physical boundaries (Wilkie and Carpenter 1999, Asner *et al* 2006, Moonen *et al* 2016).

Massive population growth is predicted and their reliance on shifting cultivation has led to projections that estimate dwindling if not vanishing forest resources in the country by the end of the century (Tyukavina *et al* 2018). Ultimately, the expansion of the rural complex is particularly important to model and understand because almost all cleared land appropriated into the rural complex mosaic is not returned to pristine forest areas till decades later, if at all (van Vliet et al 2012).

Both artisanal and large scale commercial operations for logging, mining and plantations have an influence on land use change that goes beyond the area that is traditionally and conservatively understood as their footprint, which is the land area visibly occupied by that operation itself. These artisanal and commercial activities provide essential economic benefits and development pathways, but also have important social and environmental impacts that need to be understood and planned (Lambin *et al* 2001, Rudel *et al* 2005). These operations draw in worker populations, their families and at times an entire network and community of supporting providers of services, ranging from general stores to prostitution (Acker 2005, Geenen 2011, Butsic *et al* 2015).

4.2 <u>*Data & Methods*</u>

4.2.1 Data

The FACET map (Potapov *et al* 2012) together with forest cover loss observed in the GFC product (Hansen *et al* 2013) provided the necessary data to map the baseline ERC for 2000 in Chapter 2, and the growth of and separation of rural complex expansion (RCE) and isolated forest perforation (IFP) areas in subsequent epochs (2005, 2010, 2015). This map was initially published in (Molinario *et al* 2015), and then updated from 2010 to 2015 with GFC forest loss observations in place of deprecated FACET forest loss observations. This map was used to determine where new forest cover loss had occurred during the period 2000-2015 and to characterize these areas as either RCE or IFP. DigitalGlobe (DG) imagery obtained from Google Earth (GE) was used for photo-interpretation of the sample points within the RCE and IFP. The National Geospatial Intelligence Agency (NGA) very high resolution satellite imagery archive archive available through the NextView license agreement (Neigh *et al* 2013) was considered, but ultimately declined, for filling in the sample points for which photo-interpretation was not possible, due to the absence of data in Google Earth. The reason being that the NGA archive is predominantly composed of panchromatic imagery, which is sufficient for photo-interpreting the land cover at each sample point (as was done in Molinario et al. 2017), but is excessively time consuming to use when attempting to photo-interpret the land cover within the landscape-scale buffers.

4.2.2 Methods

Sampling Design

The RCE and IFP areas sampled are within the area of interest (AOI) published in (Molinario et al 2015), defining the humid tropical forest block of the DRC. This map was updated from the initial 2000-2014 time period presented in Chapter 2, to 2015, using new forest cover loss observations available from GFC. Sample points were chosen by simple random sampling from a population of GFC forest cover loss pixels (30m) within the RCE and IFP areas, then converted to vector points. For each of the two areas, 500 sample points were initially selected and photo-interpreted using high spatial resolution imagery (Figures Figure **4.2** and Figure **4.3**). The list of sample points was randomly ordered and photo-interpreted in that random order. Imagery was not available for photo-interpretation of all sample points, an issue revisited in the Discussion section.

Image Interpretation Protocol

The legend for photo-interpreted land cover categories is shown in Table 1 and is composed of an initial set of classes photo-interpreted in the previous study of Molinario et al. (2017), plus an additional set of classes necessary for the novel landscape-scale photo-interpretation. A land cover category was assigned to each sample point (Figures Figure **4.4** and Figure **4.5**), and the presence and spatial dominance of additional land cover types was assigned to each of four concentric circular buffers around each sample point at 100m, 500m, 1km and 5km (Figures Figure **4.6** and Figure **4.7**). For each buffer area, the photo-interpreter recorded the first five most dominant land cover types in the buffer, yielding a matrix of up to 21 photo-interpreted land-cover observations for each sample point and its associated buffered areas (1 land-cover class for the sample point, and up to 20 classes in the four circular buffer areas). Not all sample points would have 20 recorded classes. For example, if a clearing was the interpreted class at the sample point, a building was observed in the 100m buffer area surrounded by primary forest, and nothing else throughout all the other buffer areas, the photo interpreter only recorded the presence of these land cover types: sample point – clearing, 100m buffer – settlement and primary forest, 500m buffer – primary forest, 1km buffer – primary forest and 5km buffer – primary forest. In the cases where there were more than 5 land cover types within the buffers, only the 5 most spatially dominant classes were recorded. This was done by visually separating each circular buffer into 4 quadrants, and interpreting the size (dominance) of each land cover type detected (Figure 4.6).

The class "rural complex" was used from the 100m buffer outwards, when all the land cover types associated with the rural complex were detected within the buffer (i.e., clearings, active and fallow fields, secondary and primary forest). Because of the minimum patch size of all these individual typologies of land cover, it was rare for them to all be present within the smallest buffer of 100m, whereas this land cover mosaic was frequently found in all other buffer sizes. The presence of some land uses such as larger commercial land uses, roads, settlements and well established rural complex mosaics was easy to identify in the available multi-spectral imagery, even when photo-interpreting at smaller scales.

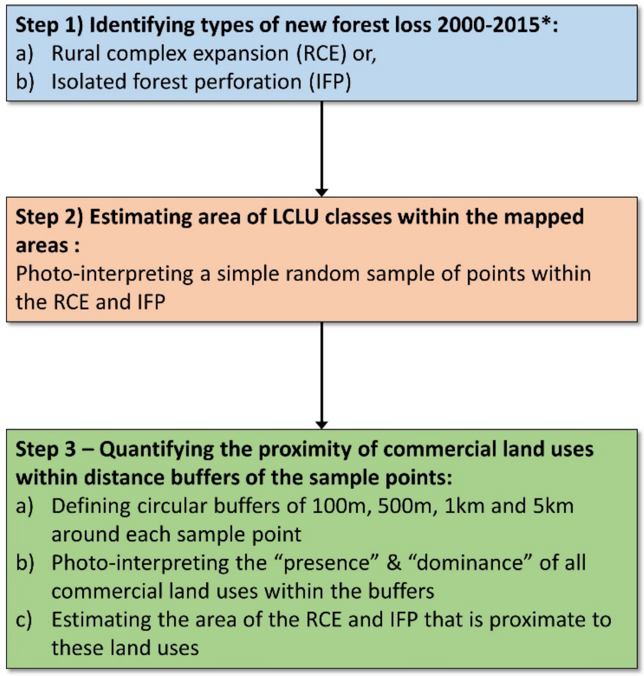


Figure 4.1: The methods of this chapter can be summarized in three steps. *Step 1) builds upon the map published by (Molinario et al 2015). In Molinario et al. 2017 the area of each LCLU type within the established rural complex for 2000 was estimated; Step 1) pertains to new forest loss during 2000-2015 that occurred outside of the established rural complex.

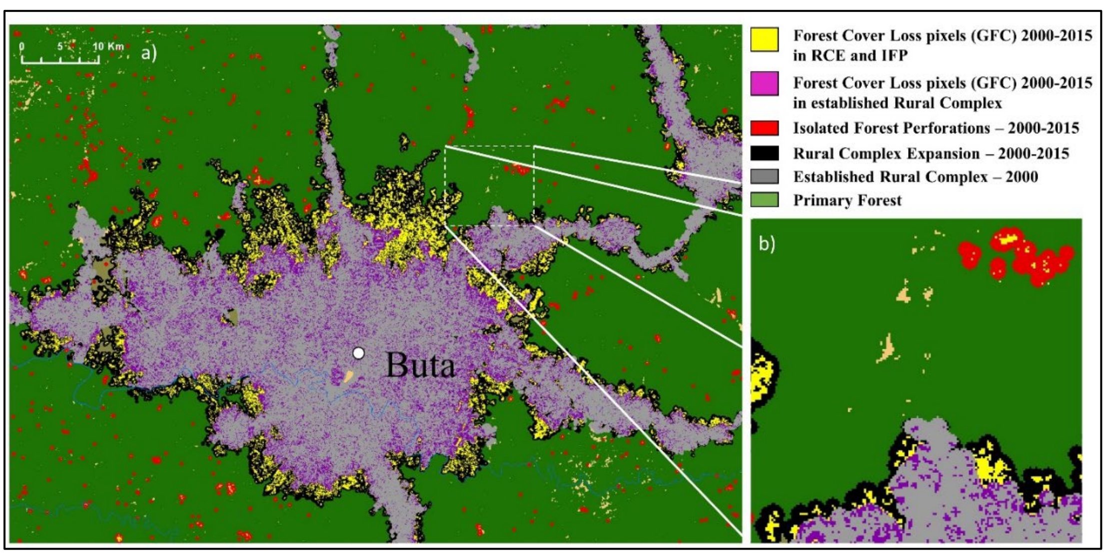


Figure 4.2: a) The separation of GFC forest cover loss pixels in three areas: 1) in the baseline "established rural complex" for the year 2000 which was sampled in Molinario et al (2017), 2) in the rural complex expansion area (RCE) and 3) in isolated forest perforations (IFP). Buta (2°49'01.93''N, 24°45'56.12''E); and b) a closer detail for illustration.

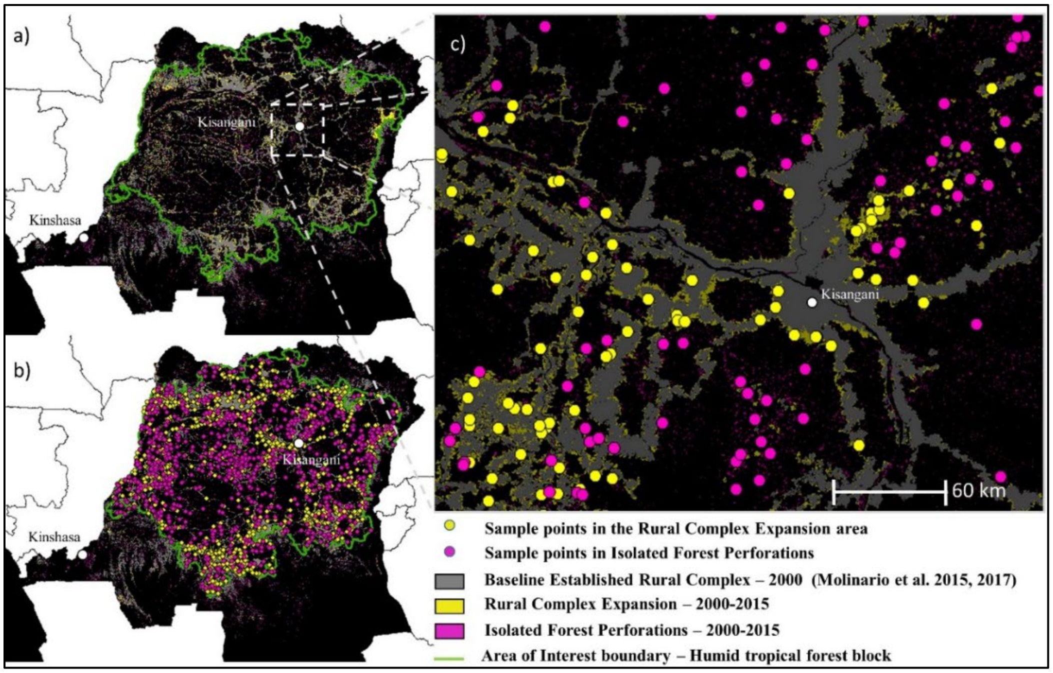
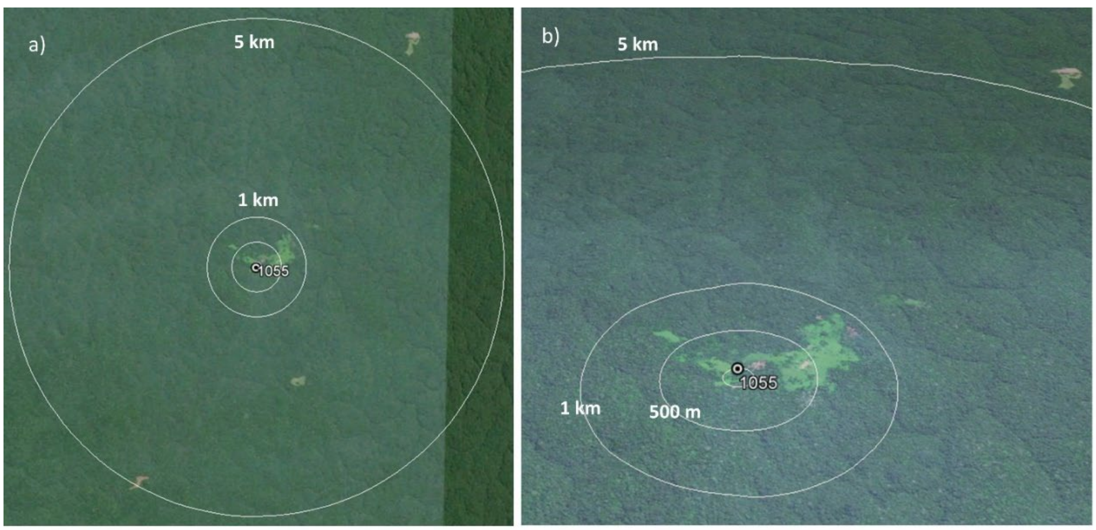


Figure 4.3: The stratification at the country level is visible in a), in b) the simple random sample point distribution in the RCE and IFP and in c) a detail of Kisangani illustrates the sample distribution in the two mapped areas. The black area, within the AOI represents primary forest, and is colored this way simply to help visualization of the sample points.

Figure 4.4: Sample 1036: The photo-interpretation of this point is labeled as "clearing", although visualizing the 100 m radius circular buffer area aids the interpretation by adding context to the sample point. In this instance a number of shifting cultivation mosaic land cover types: clearings, active and fallow fields, secondary forest (3° 4'52.34"N, 20°38'17.95"E).

Figure 4.5: Examples of land cover visually interpretable in the imagery on Google Earth: On the left, an area is being burned to clear vegetation residue and fertilize the soil, next to areas of active agriculture; on the right a patch of secondary forest that has been cleared.



Final Interpretation						100					500					1000					5000					
pntid	Year	Land Cover	Confidence	LC class code	LC class name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Notes
1055	14	yng	mid	10	Young fallow	yng	sec	act	prim	.	prim	rc	.	.	.	prim	sett	path	road	rc	prim	wet	grass	sett	.	very isolated ag. perforation - screenshot

Figure 4.6: a) and b) (oblique view) Example of the photo-interpretation of a sample point and its buffers: In this example (point 1055), the imagery is from 2014, the centroid is “young fallow” and the first *slot* of the interpreted land cover in each buffer shows the dominance of: young fallow in the 100m buffer, primary forest in the 500m, 1km and 5km buffer. The presence of other land cover types is noted in order of their spatial dominance, or presence, in the buffer. (Located at 4°29'15.23"S, 23°39'28.05"E).

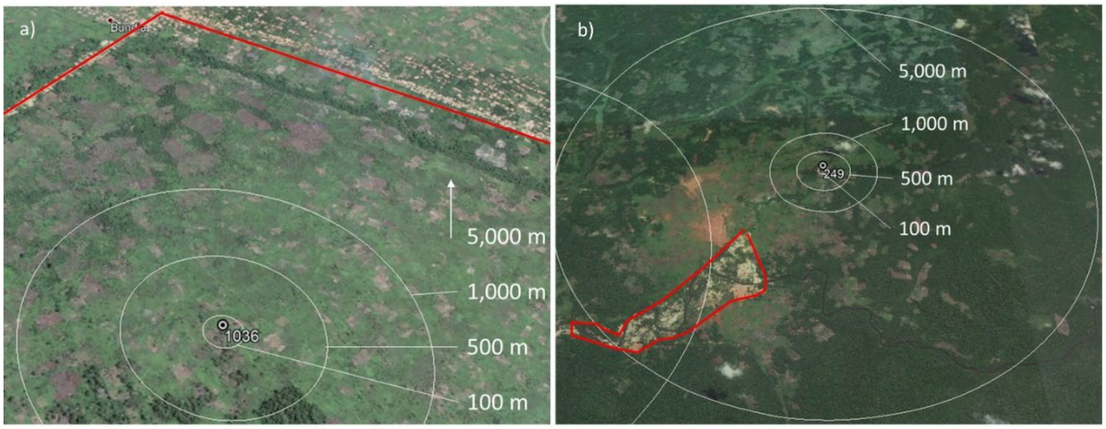


Figure 4.7: a) and b) illustrate the goal of contextualizing forest cover loss within its broader land cover and land use landscape. In a) a large trunk road and settled area is within 5km of the sample point, in b) a large gold mine is within 5km of the sample (Sample point 1036 located at 3° 4'52.34"N, 20°38'17.95"E; sample point 249 located at 4°20'4.63"N, 23°42'6.38"E).

Table 9. The legend of land cover classes that can be attributed to each sample point and their buffers in photo-interpretation.

Class Code	Class Name	Description	Potential confusion:	Observed at what scale?
1	No-data	No imagery available with sufficient resolution, or obscuration of the point by clouds, shadows or bad data	None	All
2,3,4	Water, rivers, ponds	Water, rivers and ponds	None	All
5,6,7	Roads, paths, settlements	Major roads, paths and settled areas		All
8	Clearing	Forest or fallow field that has been recently cleared	None	All
9	Active Agriculture	Field where crops are currently grown	Fallows	500m<
10,11	Young & old Fallows	Field either recently left fallow or overgrown	Active ag.	500m<
12	Secondary Forest	Forest stand with over 60% tree cover of trees ≥ 5 meters tall; canopy consists of small, relatively uniform tree crowns resulting in a bright spectral response	Primary forest	All
13	Rural Complex	Land cover mosaic of roads, rivers, settlements, clearings, and active agriculture, secondary and primary forest patches.		>100m
14	Primary forest	Forest stand with over 60% tree cover of trees ≥ 5 meters tall; canopy consists of highly varying crown size and vertical distribution resulting in greater canopy shadowing and a dark spectral response	Sec. forest	All
15, 16, 17	Wetland, gallery and woodland forests	Wetland forest: a stand with over 60% tree cover of trees ≥ 5 meters tall proximate to water bodies & associated floodplains; Gallery forest: were once wetland forest, and remain unaltered as they are wet and low-lying, usually surrounded by derived savanna/grassland or rural complex landscapes. Woodland forest: is	Primary and sec. forest	All

		more sparse, at the edges of the humid tropical forest, interfacing savannas		
18	Grassland	Natural and derived grassland/savanna areas	Active ag. and fallows	All
19	Croplands	Agriculture that is semi-permanent, with larger field area and more regular boundaries; not usually found in the rural complex mosaic.	Active ag.	All
20	Commercial Agriculture	Plantation land use associated with crops such as palm oil	None	All
21	Mines	Clearings and operations that have the appearance of mines: terraces, pits and ponds clustered together with sometimes worker camps nearby	Clearings	All
22	Logging	Logging concessions, roads, skid trails.	Clearings	All
23	Other	Other features that are rare and do not fit in any other class, like natural landslide area, Inselbergs, etc.	n/a	All

4.2.3 Estimating Proportion of Area

The results of the photo-interpretation were used to estimate the proportion of each land cover class within each of the two RCE and IFP areas, and the proportion of area of large-scale commercial land uses such as plantations, logging and mining co-located within 100m, 500m, 1 km and 5 km buffers of the sample points. The estimated proportions were converted into estimates of the area of each land cover class, and the standard error of each estimated land cover class was also computed. The formulas are below.

The estimated proportion of area of land cover class i is:

$$p_i = \frac{n_i}{n} \quad (1)$$

Where n_i = number of sample points identified as class i and n=sample size. The estimated area of class i is given by the following equation:

$$A_i = A_{tot} \times p_i \quad (2)$$

Where:

- RCE A_{tot}= 46,779 km^2 (the total area of the RCE in the AOI in 2015) and,
- IFP A_{tot}= 25,428 km^2 (the total area of the IFP in the AOI in 2015).

Both the estimator of the proportion of area (p_i) and the estimator of the area (A_i) of each class are unbiased estimators (Cochran 1977, Chapter 3). The formula for estimating the variance of the estimated proportion is the following:

$$V(p_i) = \frac{p_i(1-p_i)}{n-1}$$

(3)

The standard error formula for the estimated proportion of area of class *i* is:

$$SE(p_i) = \sqrt{V(p_i)}$$

(4)

The standard error for the estimated area of land cover class *i* is:

$$SE(A_i) = A_{tot} \times \sqrt{V(p_i)}$$

(5)

The standard errors quantify the uncertainty or precision of the sample-based estimates. Clearly the standard error decreases as a function of the square root of the sample size *n* (e.g., a four-fold increase in sample size will halve the standard error) and the standard error also depends on p_i.

4.3 <u>*Results*</u>

The total rural complex expansion (RCE) area in 2015 was 46,779 km2 and the total area of isolated forest perforations (IFP) was 25,428 km2. These areas are composed of GFC-observed forest cover loss areas in the period 2000-2015, together with "edge" primary and secondary forest and non-forest as mapped holistically and shown in (Figure 4.2) (Molinario et al 2015). Between 2000 and 2015, 36,905 km2 of GFC loss occurred in the baseline established rural complex for 2000 (81% of all GFC loss for the period), predominantly in secondary forests, 7,338 km2 (16%) occurred as primary forest loss in the RCE area and 1,137 km2 (3%) in IFP.

The estimated proportions of the constituent land cover and land use components of the the RCE and the IFP areas for 2000-2015 are shown in Table 2. The dominant land cover in the RCE is primary forest (34%), followed by secondary forest (29%), old fallows (14%) and clearings (9%). In the IFP, the dominant land cover is primary forest (41%), followed by secondary forest (22%), old fallows (10%) and clearings (9%). In the RCE, compared to the IFP, there is less primary forest (-7.5%), more secondary forest (+6.7%), more old fallows (+4%) and slightly less clearings (-0.3%) (See Table 10). The total percentage of shifting cultivation land cover components (secondary forest, fallows, clearing and active agriculture) in the RCE is 64% and in the IFP it is 51%. If we add the proportions of primary forest, respectively in the RCE and IFP the proportion of available land for future shifting cultivation is theoretically 98% in the RCE and 92% in the IFP. Clearings account for 9% of both the RCE and IFP.

Table 10. Estimated area percent area of land cover classes in the RCE and IFP.

Class (i)	Class Code	RCE Count	RCE % Area	*SE* % Area	*Area* (km^2)	*SE* (km^2)	IFP Count	IFP % Area	*SE* % Area	*Area* (km^2)	*SE* (km^2)	*RCE-IFP (%)*
Primary For.	*14*	93	33.9	2.86	15,878	1338	91	41.4	3.32	10518	844	-7.5
Sec. Forest	*12*	78	28.5	2.73	13,317	1275	48	21.8	2.78	5548	708	6.7
Old Fallow	*11*	37	13.5	2.06	6,317	966	21	9.5	1.98	2427	504	4
Clearing	*8*	24	8.8	1.71	4,097	799	20	9.1	1.94	2312	493	-0.3
Active Ag.	*9*	21	7.7	1.61	3,585	752	10	4.5	1.40	1156	357	3.2
Young Fallow	*10*	16	5.8	1.42	2,732	663	13	5.9	1.59	1503	404	-0.1
Grassland	*18*	3	1.1	0.63	512	294	3	1.4	0.78	347	199	-0.3
Road &Settled	*5,6,7*	1	0.4	0.36	171	170	4	1.8	0.90	462	229	-1.4
Commercial Ag.	*20*	1	0.4	0.36	171	170	-	-	0.00	0	0	0.4
Wetland For.	*15*	-	-	0.00	-	0	8	3.6	1.26	925	321	-3.6

Woodland For.	*17*	-	-	0.00	-	0	1	0.5	0.45	116	115	-0.5
Logging	*22*	-	-	0.00	-	0	1	0.5	0.45	116	115	-0.5
Grand Total		274	100%		46,779	170	220	100%		25,428		

The results of the LCLU proportions within the buffers of the sample points are fairly similar in composition (Table 3). In the 100m buffer of the IFPs, compared to that of the RCE area, active agriculture is more dominant and surrounded by a less established (younger) shifting cultivation mosaic (less clearings, active agriculture, fallows and secondary forest). When considering their most proximate surroundings, as expected, the land cover adjacent to the IFPs is more pristine with less signs of anthropogenic activity. In the 100m buffer of the IFPs, we do find more settlements, more logging, wetland forest and woodlands, but less commercial agriculture, than in the buffer areas, however, many of these LCLU classes with smaller proportions are within the uncertainty bounds defined by the standard errors (Table 11).

In the buffered area of the IFP, compared to that of the RCE, there is more primary forest throughout and there is less rural complex mosaic, including roads and settlements, more grassland and more wetland forest. The inverse relationship between proximity to the rural complex and forest intactness is what would be expected and validates our stratification map (Molinario et al 2017) (Table 11).

Table 11. Percent land cover estimates for the sample points, compared to dominant land cover in the concentric circular buffer areas around them.

		RCE					IFP				
Class	**Code**	**Point**	**100m**	**500m**	**1km**	**5km**	**Point**	**100m**	**500m**	**1km**	**5km**
All primary forest types	14,15, 16,17	*33.9*	*45.1*	*70.9*	*78.5*	*73.8*	*45.5*	*54.1*	*87.3*	*87.7*	*87.7*
Secondary forest	12	*28.5*	*20.4*	*5.5*	*1.1*	-	*21.8*	*15.0*	*0.5*	*0.5*	*0.5*
Old fallows	11	*13.5*	*10.2*	*0.7*	-	-	*9.5*	*7.7*	-	-	-
Clearings	8	*8.8*	*8.7*	*2.2*	-	-	*9.1*	*7.3*	*0.5*	*0.5*	-
Active fields	9	*7.7*	*3.6*	-	-	-	*4.5*	*2.7*	*0.5*	*0.5*	-
Young fallows	10	*5.8*	*3.6*	-	-	-	*5.9*	*3.6*	-	-	-
Grasslands, der. Savannas & cropland	18,19	*1.1*	*0.4*	*0.4*	*0.4*	*0.4*	*1.4*	*1.4*	*3.2*	*2.7*	*2.7*
Roads, paths, settlements	5,6,7	*0.4*	*0.4*	*1.1*	*0.4*	-	*1.8*	*2.3*	*0.5*	-	*0.5*
Rural complex (all elements of the RC mosaic)	13	-	*7.3*	*18.2*	*18.9*	*23.6*	-	*5.5*	*6.4*	*6.4*	*6.4*
Commercial ag.	20	*0.4*	*0.2*	*1.4*	*1.8*	*2.4*		*0.4*	*0.2*	*0.4*	*0.6*
Mines	21		*0.0*	*0.0*	*1.4*	*2.6*		*0.0*	*0.6*	*1.0*	*1.8*
Logging	22		*0.0*	*0.2*	*0.0*	*1.0*	*0.5*	*0.6*	*0.6*	*0.6*	*1.4*
Tot. Commercial land uses	**20,21, 22**	***0.4***	***0.2***	***1.6***	***3.2***	***6.1***	***0.5***	***1.0***	***1.4***	***2.0***	***3.8***
other	23	-	-	-	-	*0.4*	-	-	-		-
Total											

The estimated proportion of area in the RCE with commercial land uses within 5km is 11.5% whereas in the IFP it is 8.8% (Table 11). Many sample points that occurred in primary forest were proximate to large anthropogenic disturbances, whether the rural complex, plantations, mining or logging (Figures Figure **4.8**,Figure **4.9**, Figure **4.10** and Figure **4.11**). When mining was detected it was within rural complex landscapes (Figures Figure **4.12** and Figure **4.13**).

Figure 4.8: Point 201 (oblique view) is primary forest, with a palm oil plantation within 5km (4°20’51.24” S, 20°24’19.54” E).

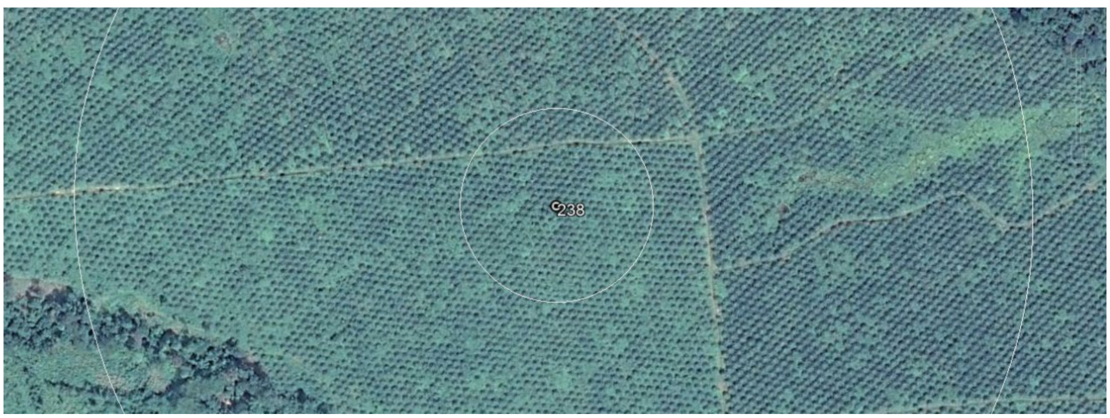


Figure 4.9: Point 238 is in a vast palm oil plantation big enough to occupy most of its 1km buffer (6°37’54.61” S, 20°53’44.84” E).

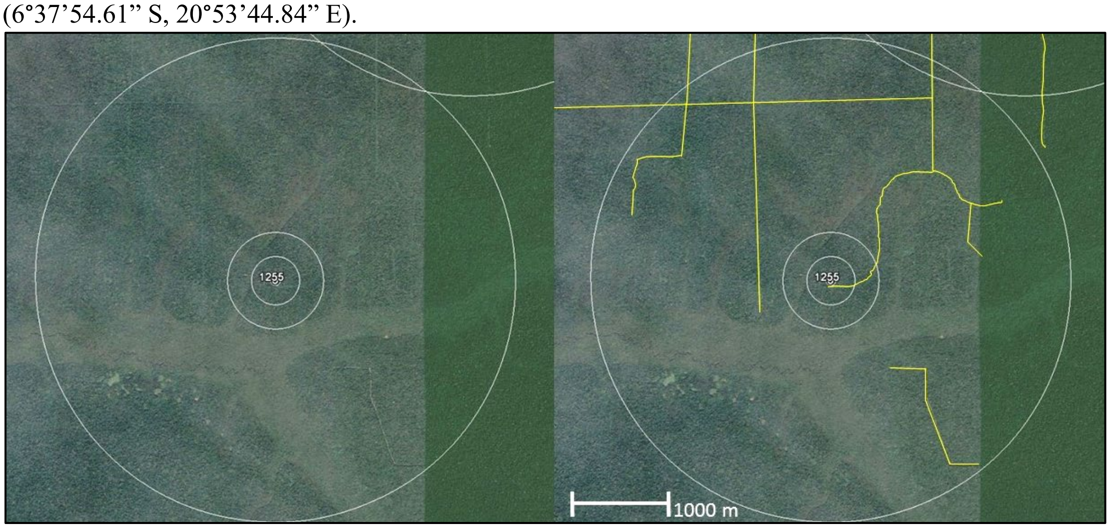


Figure 4.10: Point 1255 is secondary forest, on an old logging road that has regrown, the network of abandoned logging roads are highlighted on the right for illustration (1°53'47.77"N, 21°58'36.09"E).

Figure 4.11: Point 1255 in closer detail. The abandoned and regrown logging road clearly visible (1°53'47.77"N, 21°58'36.09"E).

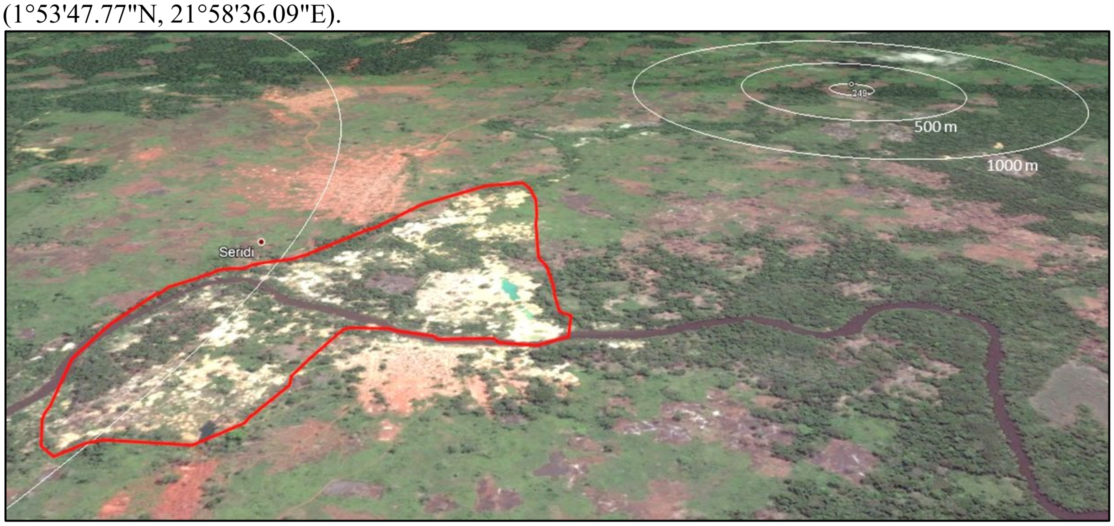


Figure 4.12: Gold mines (Oblique view) within 5km of sample 249, outlined in red, near Seridi, in the Bas-Uele Province, Bondo territoire (4°20'4.63"N, 23°42'6.38"E).

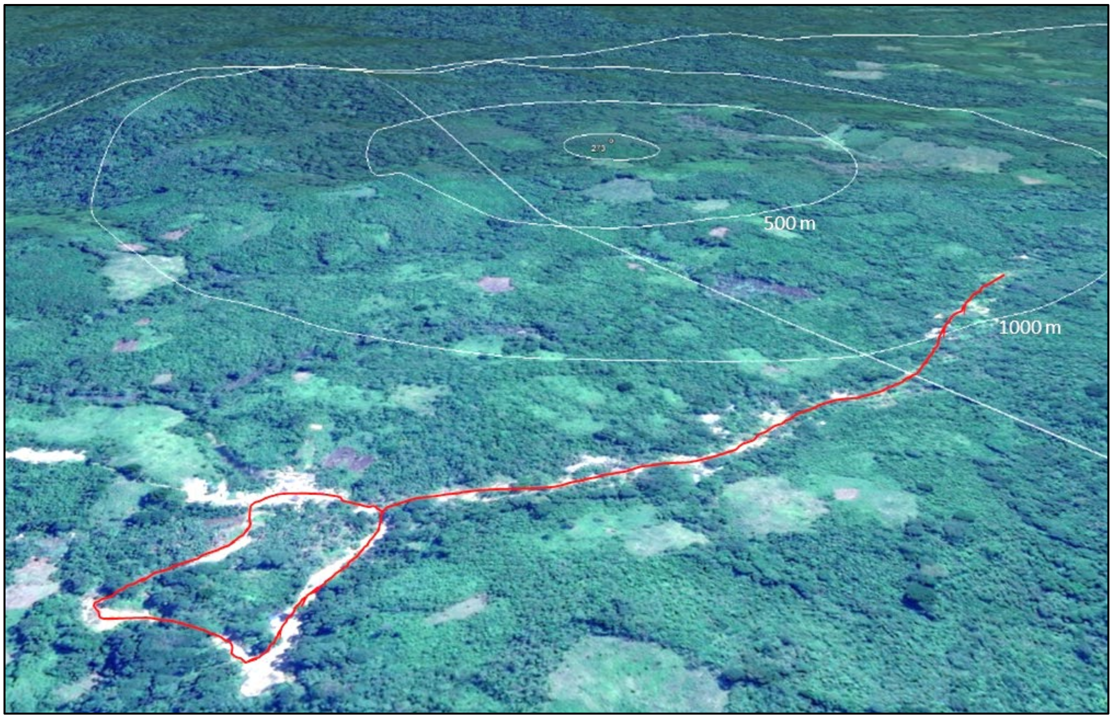


Figure 4.13: Another example of a Gold mine within 1-5km of sample 273. (Oblique view).

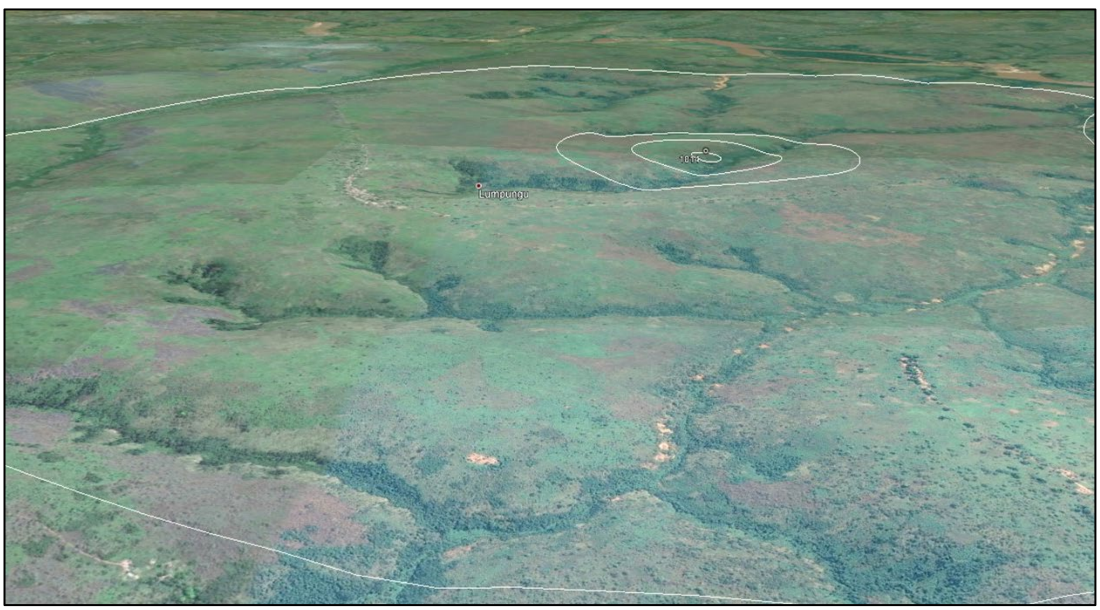


Figure 4.14 Sample point 1014 is part of the Isolated Forest Perforation strata, however, it is part of a gallery forest landscape at the edges of the tropical humid forest block, where isolated forest perforations within core forest, become "isolated forest *patches*" within derived savanna landscapes (6°37'54.61''N, 20°53'44.84'').

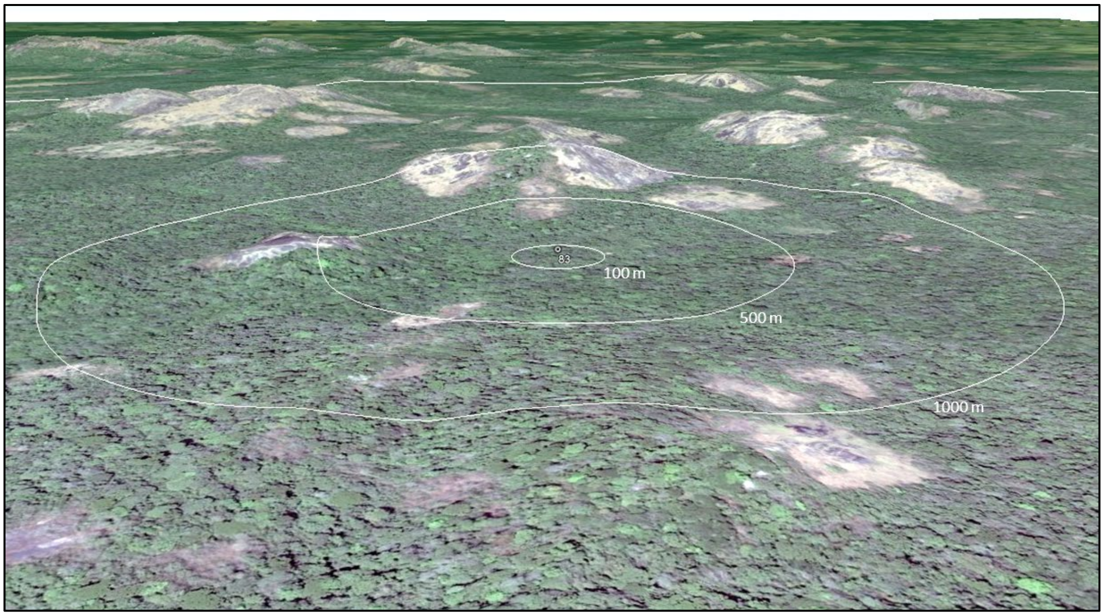


Figure 4.15: An Inselberg landscape in the Ituri Forest in the buffer of sample 83 (2°48'54.57''N, 29°08'18.94''). (Oblique view).

4.4 _Data Issues_

High resolution satellite imagery acquisitions are needed to accurately interpret land cover. Planet labs aspirations to acquire and provide such imagery (Planet 2017a, 2017b), as well as datasets from DigitalGlobe (Neigh *et al* 2013) could prove to be useful for the photo-interpretation of land cover over large areas (Finer *et al* 2018). However, the cost of acquiring and processing commercial high resolution imagery needs to outweigh the limitations of coarser resolution free imagery such as Landsat. Novel cloud-based solutions for accessing high resolution imagery include DigitalGlobe's EV-WHS under the auspices of the NextView license agreement that make imagery available to US-government affiliated researchers through the National Geospatial Intelligence Agency (NGA). However, this platform does not facilitate efficient use for fast photo-interpretation of hundreds of sample points in the cloud as it is oriented instead towards a standard manual “select and download” paradigm. Other platforms like DigitalGlobe’s GBDX might fulfill these requirements, but at a cost, and while nascent initiatives like Radiant Earth Foundation’s earth observation platform will provide free imagery, their efficiency for photo-interpretation and adequacy of the available image archive is yet to be tested (Lesiv *et al* 2018). The photo-interpretation protocol, could also be improved in speed for larger sample populations using specific and custom tools (Bey *et al* 2016).

Google Earth imagery was more frequently available in higher radiometric quality, spatial and temporal resolution in areas close to larger settlements and trunk roads. In more isolated areas, imagery was often Landsat-scale only, sometimes either extremely bright or dark with cloud and haze cover. The percentage of sample points with no data in the rural complex area was 45.2%, whereas in isolated forest perforations no data occurred for 56% of the sample points Figure 4.18. However, if we consider only the samples within 10km of the established rural complex, then the no data proportion becomes 45.1% in the RCE as opposed to 53.3 % in the IFP, for a total no data percentage in the sample of 48.8% (Figure 4.17). Furthermore, the imagery available in the RCE was also more recent; 57.6% of it taken since 2015, versus only 45.1% in the IFPs. It seems that GE has more recent imagery closer to settlements. This should be noted and addressed in sample-based studies that use the GE platform to photo-interpret land cover.

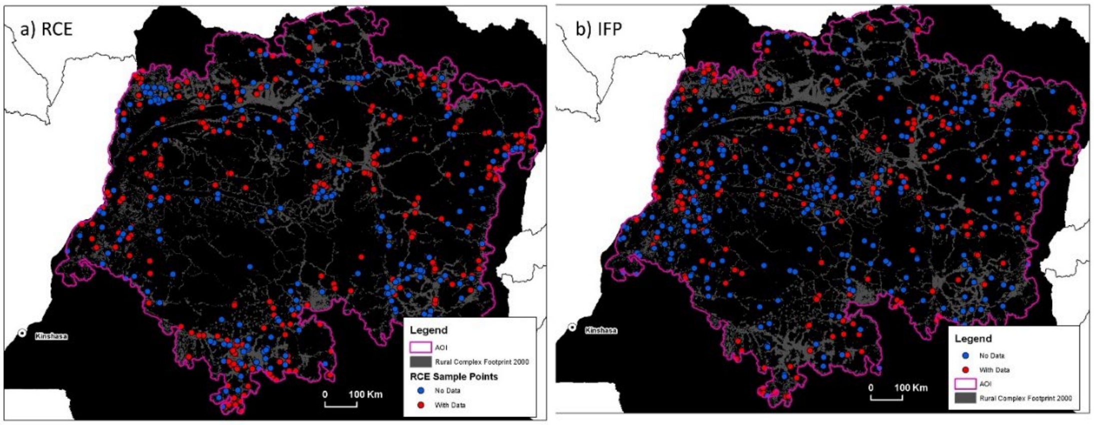


Figure 4.16: The distribution of no-data sample points within the sample appears to be geographically random and not clustered.

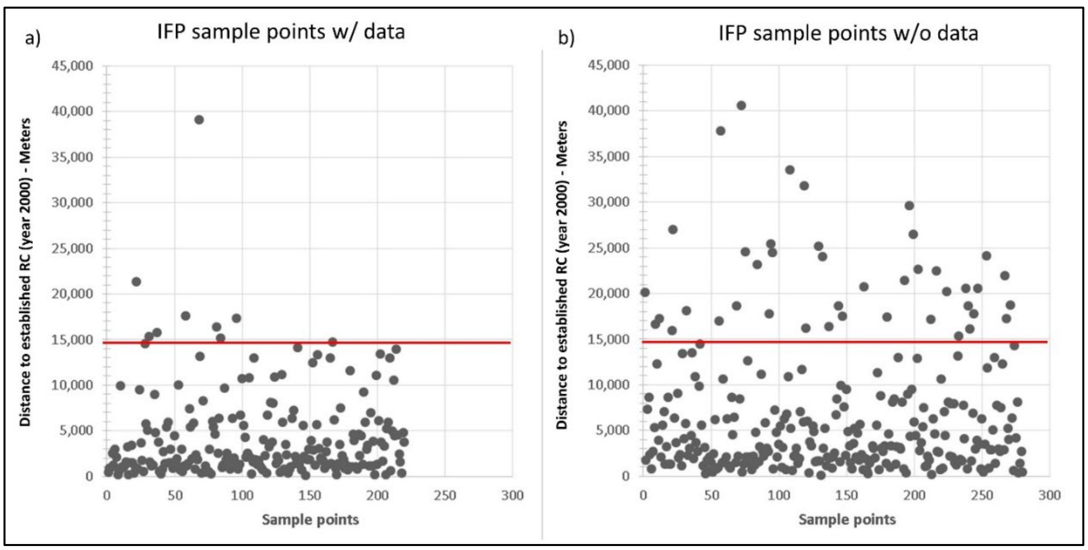


Figure 4.17: IFP sample points by distance to the established rural complex: a) IFP w/data, b) IFP w/o data. The red line shows the 15km mark.

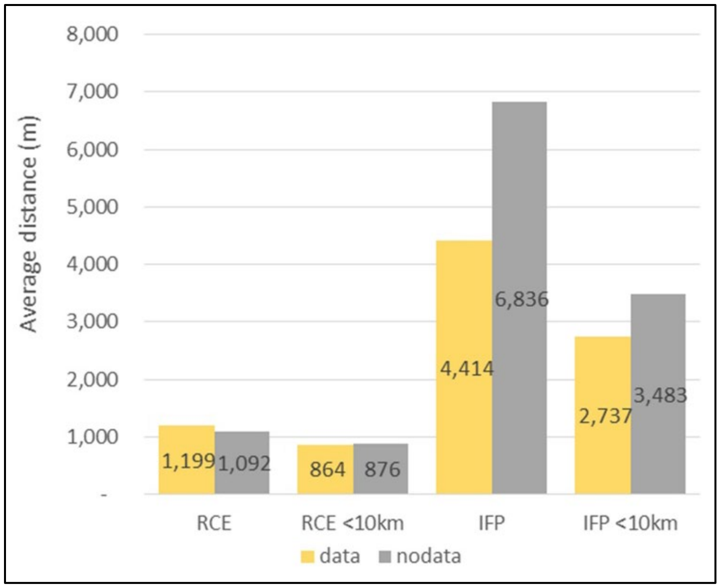


Figure 4.18: The IFP samples with no-data are on average a third further from the established/settled areas as the IFP samples for which there is data. There is more data in Google Earth the closer to settlements in the DRC.

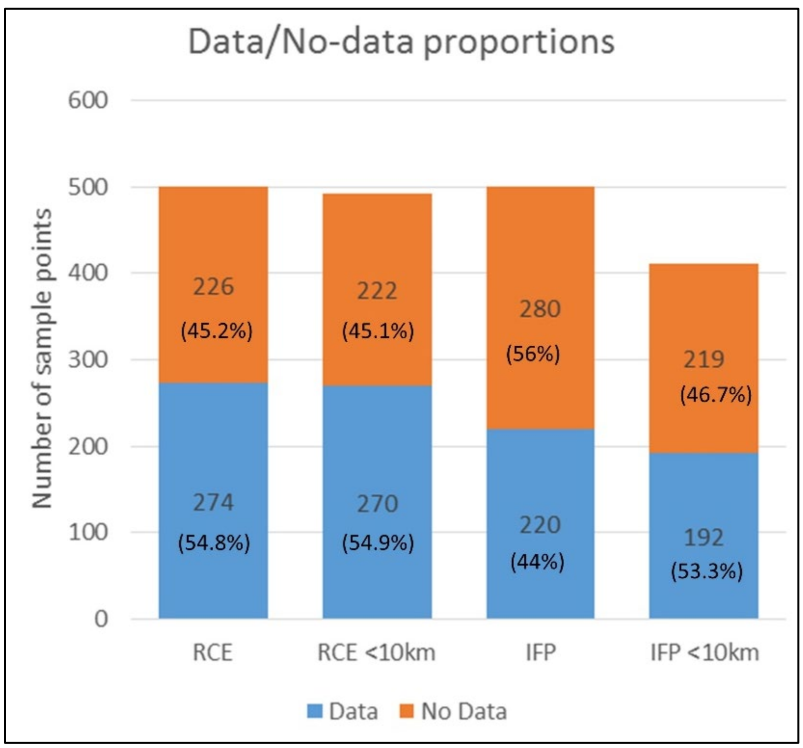


Figure 4.19: Number and percentage of sample points with, and without data allowing photo-interpretation.

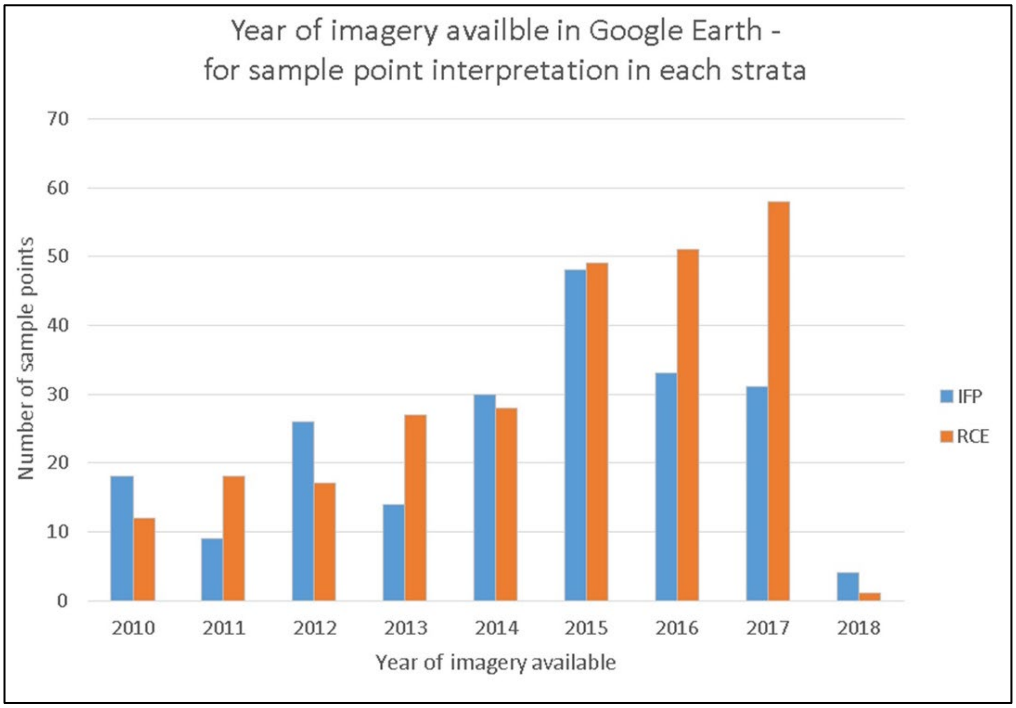


Figure 4.20: Temporal distribution of imagery available in Google Earth for photo-interpretation. Imagery available for samples closer to settlements was newer, while for samples further from settlements it was older.

Finally, our purpose was to describe the RCE and IFP holistically, and not to monitor individual LCLUC transitions at the pixel level. For example, a 2015 GFC forest cover loss pixel used to select the area to sample could then be photo-interpreted with imagery from 2014. For our purposes this is acceptable. The collective sum of all the interpretations allows us to trade space for time, and assert the quantitative LCLU proportions of the RCE and IFP, for the 15 year period of the study. If for example, the process was to be repeated subsequently at decadal intervals, the results would inform the decadal change of LCLU composition of the studied areas.

4.5 *Discussion*

Results support the conclusion that currently shifting cultivation remains the primary driver of deforestation in the DRC, and although commercial land uses are present, their impacts are dwarfed by the reliance of the population on shifting cultivation for food and the rural complex mosaic for food, building materials and energy needs. These results echo what was recently found by Tyukavina et al. (2018).

Comparatively, in Chapter 3 it was estimated that in the ERC the percentage of land used in the shifting cultivation cycle was 76% and 11% was primary forest, meaning that 87% of the established rural complex is available for future shifting cultivation. With the derived annual clearing rate of 4.6%, the theoretical reuse rate for all land to be cycled through the shifting cultivation cycle once, was ~18 years (Molinario *et al* 2017). With the above proportions quantified, and assuming the 2000-2015 clearing proportion to be indicative of a theoretical annual clearing rate, land in the RCE would take approximately 11 years to be cleared once (98%/9%) and in the IFP 10 years (93%/9%). The difference lies in the almost double clearing rate compared to the ERC, which is to be expected as the sampling population in this Chapter was comprised of GFC forest cover loss pixels, whereas the areas sampled in Chapter 3 for the ERC contained mostly secondary forest as well as forest cover loss and non-forest pixels that were mapped using FACET's classification. If we assume a lower clearing rate, equal to the one found in the established rural complex (4.6%). Then the reuse period of land in the RCE would be 21 years and 20 in the IFP, compared to 18 in the established rural complex. This means that with proportions of primary forest as high as 41% in the IFP, and with average clearing rates of 4.6%, the temporal reuse period of land would still not be long enough for all fallows to reach primary-forest like maturity (30-50 years) (Conklin 1961, Miracle 1967, (SPIAF) 2007), and farmers will have to farm more frequently secondary forest and older fallows. Even if all land in the RCE and IFP was available for shifting cultivation, if we consider clearing rates somewhere between 4.6% and 9% then it would take between 21 and 11 years for all land available to be cleared once.

In addition to the analysis of the LCLU inside the RCE and IFP, our results show also the landscape-scale presence of large scale commercial land uses. While only 0.4% -0.5% of the RCE and IFP sample points are strictly co-located with commercial land uses like mining, logging or plantations, 8.9%-11.7% of them have large scale commercial land uses within 5km. Commercial land use operations such as logging, mining and plantations have broad repercussions on the forest ecosystem as these activities attract affiliated communities by giving them a new economic incentive. Often, new rural complex areas are formed when informally mined minerals are transported via informal routes (Geenen 2011), such as in the north-east of Kisangani.

Larger commercial land uses, like mining operations for example, provide livelihoods for miners but also for their families and entire support communities that are present because livelihoods are possible within a context of extreme poverty. These services include: transport, catering, and leisure, so much so that in some cases the internal economy is dependent on the mined minerals for business transactions, with gold being used also to pay a tax to the village chief (Geenen 2011). The food, energy and building material needed for these worker populations come from shifting cultivation. Pollini (2014)found that each household managed 1-3 active fields along with 5-10 plots that are at different phases of fallow, for about 5-10 ha of land in total. This all adds up to a substantial footprint of these commercial operations that goes well beyond their clear-cut boundaries.

Future research should look at the density of the rural complex; its comparative size compared to the settlements it surrounds, as this characteristic can be an indicator of degradation of the rural complex area and also an indicator of food security. Households closer together participate in inter-household cooperation and are able to improve food and nutrition security, whereas more isolated households (households with high pressure on productive individuals) are at danger for food insecurity and malnutrition (Kismul *et al* 2015). Populations in the cities attract resources produced in rural areas and transported to these larger markets by road and river. A study found that 75%-95% of bushmeat harvested in rural areas is consumed by hunters and neighbors, whereas 80% of bushmeat hunted within 10km of urban areas was sold to markets (Dupain *et al* 2011).

Results validate the previously published map of the rural complex, its growth and separation from isolated forest perforations (Molinario *et al* 2015). Indeed, throughout the sample buffer area, up to 5km around it, the IFP has more primary forest and less rural complex areas, including roads and larger settlements. The rural complex expansion has a larger proportion of area of LULC classes associated with longer-term shifting cultivation agricultural landscapes, such as: active agriculture, fallows and secondary forest. The RCE also has more commercial plantations. The IFP instead has a greater proportion of area of primary forest, more individual settlements (bush camps and other outposts) and more logging areas. It also has more grassland and wetland areas close to it.

Agriculture intensification is often proposed in the DRC to be a 'land sparing' alternative to shifting cultivation, but the academic debate regarding this continues

(Rudel *et al* 2009, Ickowitz 2006). Some aid organizations active in the DRC believe that supporting small farmers might help reduce the risk of larger scale deforestation carried out by loggers, large scale plantations and other investors. This results in aid projects proposing alternatives to development. But while some farmers appreciate alternatives offered, others express concern, especially women, who in a series of interviews for a USAID project expressed concerns that many alternatives require more labor, which they are unable or unwilling to provide. In this study women were found to be the main agricultural labor force. Market incentives were found to be the major driver of agricultural intensification (Pollini 2014).

REDD+ aims to curb deforestation and habitat reduction, while at the same time providing a source of income for communities, monetizing and therefore, it is thought, protecting the common community forests. Yet, national REDD+ policies rarely include the complexity of shifting cultivation within rural complex LCLU mosaics, adopting a simple land-sparing hypothesis (Pirard and Belna 2012). REDD+ has been criticized for being another type of "land grabbing"(Carter *et al* 2007), sometimes referred to as "green-grabbing": a land acquisition and transaction that works within inherently corrupt socio-political systems where the rule of law is not adequately solid to guarantee that the monetary and power transactions between private and public groups occur transparently and fairly (Fairhead *et al* 2012). Some authors have asked whether REDD+ projects in the DRC are merely a distraction from the goal of avoiding future large scale industrial plantations and logging for world markets, such as palm oil (Megevand 2013).

Multi-scale studies of deforestation, like the one presented here, are seldom performed because it is difficult to obtain consistent datasets, particularly at local scales (Moonen *et al* 2016). *"Results reveal that given lack of cross scale studies, policy makers are lacking context specific relevant information at local scales needed to design efficient effective and equitable policies"* (Moonen *et al* 2016). To effectively intervene in LCLUC trajectories, a mere description of patterns and identification of causal effects does not suffice. (Moonen *et al* 2016). Therefore, the only way to correctly internalize the economic, social and environmental effects of large-scale commercial operations such as logging, plantations and mining, is to contextualize these within their landscapes, and to attempt to include the forest cover loss and degradation that they cause and enable, into their footprints.

4.6 *Conclusion*

Between 2000 and 2015 the total percentage of shifting cultivation land cover components (secondary forest, fallows, clearing and active agriculture) in the RCE was 64% and in the IFP 51%. If we add the proportions of primary forest, respectively in the RCE and IFP the proportion of available land for future shifting cultivation is theoretically 98% in the RCE and 92% in the IFP. Clearings account for 9% of both the RCE and IFP. During the study period 81% of GFC-observed forest cover loss occurred in the established rural complex, 16% in the rural complex expansion area and 3% in isolated forest perforations. A very small proportion of the rural complex expansion area, and of the isolated forest perforation area, is occupied by commercial land uses (0.4% and 0.5%). The combined percentage of area (0.9%) of large scale commercial land uses in these areas of new primary forest cover loss is therefore even lower than the 2.2% found in the baseline established rural complex for 2000 (Molinario *et al* 2017). However we posit that this finding does not mean that there is considerably lower commercial land use in the rural complex expansion area and isolated forest perforations, but rather that these land uses are dwarfed by the reliance of DRC's population on shifting cultivation and the lack of infrastructure that allows core forest areas to remain impractical or impossible to exploit for natural resources. If we extend the analysis to up to 5km distance around sample points, 11.5% of the area of the RCE and 8.8% of the area of the IFP has commercial land use within it.

Chapter 5: Discussion, Conclusions, & Future Research

5.1 Main Findings

This dissertation has focused on the secondary succession cycle of shifting cultivation in the DRC, and its geographical footprint, the rural complex. Each chapter built on the previous one, quantifying and contextualizing spatio-temporally forest cover loss from shifting cultivation in the DRC for the period 2000-2015.

Large scale LCLU change dynamics in the DRC, such as commercial operations for export, are currently dwarfed by the reliance of rural populations on shifting cultivation. However, large-scale commercial land uses lead to increased forest loss beyond just the footprint of the activity itself, as their worker populations and communities rely on the forest resources for for food, materials and energy. The maps and the sample-based LCLU estimates confirm that where isolated perforations lead, the rural complex follows and brings with it commercial land uses, settlements, roads and a semi-permanent agricultural area.

In Chapter 2 use of Landsat spatial resolution satellite data enabled the mapping of the first wall-to-wall forest fragmentation map and rural complex footprint map of the DRC. Both in national-scale yet in locally relevant detail. A gap was filled in the study of land cover and land use change in the country by relating forest cover loss to shifting cultivation and the rural complex in a holistic and unambiguous footprint. The rural complex is growing as well as isolated forest perforations and existing core forest is becoming fragmented and decreasing in size. Forest loss in some areas was found to fragment habitats more than in others, and as such it might impact biodiversity and forest ecology disproportionately. Six different types of rural complex expansion and forest perforation were characterized in the DRC, ranging from rural complex areas with minimal disturbance to surrounding primary forest, to areas of frontal and pervasive anthropogenic encroachment into core primary forest. Between 2000 and 2010 the rural complex grew by 10% from 12% to 13% of the DRC's land area, at an average yearly rate of 1%, while perforated forest grew by 74%, from 0.8% to 1.5% of DRC's land area in 2010 at an average yearly rate of 0.7%. Core forest decreased by -3.8% at an average yearly rate of -0.4% per year, from 38% to 36.6% of the 2010 land area. The growth of isolated forest perforations by 74% is particularly concerning, as these represent a greater threat to the fragmentation of habitats and provide outposts that attract more farmers and eventually result in rural complex landscapes.

In Chapter 3 the use of a simple random sampling scheme using photo-interpretation of high resolution imagery provided an elegant and efficient method to quantify LCLU within the established rural complex for the year 2000. The results are the first quantitative results on the LCLU composition of the rural complex and estimates of the proportion of active shifting cultivation within it (76%) and the area available for future shifting cultivation (87%). Trading space for time, and assuming the average annual clearing rate of 4.6%, I estimated that it would take ~18 years for all land in the established rural complex to be cleared once. This sets a baseline of land use intensity that can be monitored at regular intervals and can provide further parameters to tune models estimating future forest cover loss in the country.

In Chapter 4 a similar sample-based methodology allowed the estimation of LCLU *outside* of the established rural complex, in primary forest cover loss areas for the period 2000-2015. Results validate the map of the rural complex from Chapter 2, estimating that there is less active shifting cultivation and more primary forest in the rural complex expansion areas and isolated forest perforations. Interestingly a smaller proportion of large-scale commercial land uses was found in the rural complex expansion areas and isolated forest perforations compared to the established rural complex (<1% compared to 2%). At the same time the concentric buffer distance analysis around each sample point reveled that between 9% and 12% of primary forest cover loss outside of the established rural complex is within 5km of large scale commercial land uses. Perhaps even more informative is the opposite fact, that up to 91% of the sampled points did not have any large scale commercial land uses within 5km.

Previously, the extent and implications of forest cover loss from shifting cultivation in the DRC had been debated (Ickowitz 2011, Russell et al 2011), partially because of the lack of quantitative data and explicit maps that illustrated the differences in its appropriation of primary forest, such as the those developed in this dissertation.

5.2 Considerations and Future Research

Future research should focus in two directions: monitoring ongoing LCLUC in the country, building robust indicators of land use intensity and land degradation that can be routinely assessed at regular intervals in order to evaluate the current environmental conditions in the country, and building accurate and high resolution models that can estimate future forest loss and degradation. To do so, existing and historical connections between population density, migration, conflict, infrastructure and urbanization and its effects on forest fragmentation and degradation need to be understood and mapped.

This could be done by incorporating into analysis population density maps (Afripop, Landscan, or others) and conflict event and internally displaced people (IDP) camps growth data (ACLED). A settlement map of the DRC could also prove to be instrumental in advancing the research of forest degradation in the DRC. Such geographical layers could explain rural complex abandonment that is mapped in this study and more accurately map the relationship between settlement size, population density and rural complex extent; or in other words, investigating the size of the semi-permanent agricultural area the settlement has throughout time. Monitoring this dynamic through time would indicate areas where settlements and rural complex areas have grown together and areas where one has grown but not the other, potentially indicating the need or success of land use plans in effect. Going back as far as the Landsat archive will allow (1984) would also prove to be very interesting in characterizing the rural complex change dynamic.

Mapping the rural complex footprint and isolated forest perforations, at regular intervals in the future will help define the trends of primary forest appropriation into the rural complex, and of forest fragmentation. There are plans at the World Resources Institute to continue the work presented in this dissertation by developing predictive models of forest cover loss and forest degradation in the Congo Basin.

In Chapter 2 many isolated forest perforations were mapped, and then sampled in Chapter 4 with high resolution satellite imagery. Some of these areas had extremely remote settlements, sometimes as far as 10-15km from the first observable sign of human presence. These areas could be the object of future research, investigating connections with conflict and possibly the need for some ethnic clans and religious groups to avoid persecution and relocate to remote areas to ensure their survival.

The use of forest gain (regrowth) from GFC could also be important in advancing the understanding of the land change dynamics of active and inactive rural complex areas. This dissertation only used forest cover loss observations to map the rural complex, so areas of active regrowth of forest are not mapped and could indicate additional dynamics of change in the rural complex footprint.

Existing research also points at the importance of distance and accessibility to markets as a modulating driver for what and how resources are extracted from given areas (Bwangoy *et al* 2010, Potapov *et al* 2008, Lubamba *et al* 2013, Defourny *et al* 2011), therefore investigating how agricultural areas feed and fuel accessible markets is of paramount importance, especially in peri-urban areas. The dynamic of forest cover loss in peri-urban areas will be evermore important with estimated population increase and urbanization. Future research should investigate this dynamic, targeting where forest cover loss is high and not related to small-scale livelihood farming.

5.3 Concluding Thoughts

Enormous advances in the wall-to-wall remote sensing of forest cover have allowed us over the last 6 years to have a more detailed and synoptic view of the forest landscape in the DRC (Potapov *et al* 2012). The mapping methods developed in the DRC for FACET were extended globally, and doubled in spatial resolution in the GFC product (Hansen *et al* 2013). Interactive information from these remote sensing products was made available with unprecedented tools developed by Google and by the World Resources Institute (WRI) Global Forest Watch (GFW). As of 2013, the world had never had as much detailed and timely maps on forest extent and forest loss, at the global level.

These maps provide the basic building blocks for analyzing and understanding forest cover loss in any given location, but cannot by themselves provide spatial context to explain whether the loss occurring is part of interconnected dynamics or isolated ones. I see therefore the role of satellite remote sensing research groups not only as data providers but also as enablers of analyses in novel cloud-based interactive GIS and remote sensing platforms like Google Earth Engine, WRI's Global Forest Watch and even nascent initiatives like Radiant Earth Foundation.

Chapter 2 was published in 2015 in a peer-reviewed paper titled: "*Forest cover dynamics of shifting cultivation in the Democratic Republic of Congo: a remote sensing-based assessment for 2000–2010*", cited 22 times and downloaded over 4,000 times. Chapter 3 was published in 2017 in a peer–reviewed paper titled: "*Quantification of land cover and land use within the rural complex of the Democratic Republic of Congo*", cited 5 times and downloaded over 2,000 times. Chapter 4 was submitted for publication in the fall of 2018, with the title: "*Contextualizing Landscape-Scale Forest Loss in the DRC 2000-2015*".

This research was extended by the World Resource Institute to the Republic of Congo, and updated to 2015. A blog post on WRI's Global Forest Watch highlights its uses in informing land use planning decisions (de Araujo Barbosa *et al* 2018) and an article written about it on Mongabay (Cannon 2018) highlights the need for holistic forest cover loss analyses that tease apart cyclical livelihood forest clearing from more permanent land use conversions.

Data and maps from this research were made available online, in a Website and WebGIS portal I developed (Molinario 2015). All the code developed (mostly in python) for this dissertation was made publicly available on github (Molinario 2018). I hope that UMD Global Analysis and Discovery (GLAD) can continue providing these satellite-based datasets and maps and that WRI or other organizations can continue championing the use of these data in land use planning and LCLUC mapping and monitoring. Monitoring and projecting future change in the rural complex footprint and isolated forest perforations in the DRC will be key to planning for the dramatic population increases that are estimated. .

This dissertation research provides this necessary context to forest cover loss observations in the DRC, while retaining a quantitative, national-scale perspective. It provides methods for holistically grouping and separating forest cover loss observations that indicate different dynamics occurring. It is clear that it is necessary to not only have the per-pixel satellite remote-sensing based wall-to-wall maps of land cover, but also the added-value research products that contextualize and explain forest cover loss observations quantitatively. The people better positioned to do this type of analytical work should work closely with the producers of the remote sensing based maps, so that a dialogue and inter-pollination of ideas can flourish. In addition to that, providing all the data developed in interactive and open formats (such as Google's Earth Engine, WRI's GFW and the UMD-GLAD website) allows for stakeholders everywhere to be able to investigate the LCLUC issues pertaining to forest cover loss in their area of interests, for free. It should be noted that at the very base of all this work is the opening of the USGS Landsat archive, without which the synoptic wall-to-wall mapping of forests would not be possible. Similarly, access to free archives of very high resolution satellite imagery would greatly improve the speed and efficacy with which researchers can map and monitor forest cover loss.

Ultimately, in the DRC, low rates of deforestation mask the real threats to forests in the country, with much higher rates than the national average in heavily populated regions with a strong agricultural sector and subsistence farming. War, poverty and collapsed government and infrastructure have stifled the country and created a fundametal insufficiency of institutional capacity for natural resource management. Furthermore, massive population increase in the DRC is projected, and under a business as usual scenario of land use it is estimated that nearly all the tropical humid forest in the country will be gone by the end of the century (Tyukavina *et al* 2018). Contextualizing forest cover loss in terms of its contribution to the expansion of the human footprint in the DRC takes us a step further in quantifying resulting impacts on human development and maintenance of ecosystem services.

Glossary & Acronyms

AOI: Area of Interest

CARPE: Central Africa Regional Program for the Environment

FACET: *Forêts d'Afrique Centrale Evaluées par Télédétection*

FAO: Food and Agricultural Organization of the United Nations.

GFC: Global Forest Change product

GSFC: NASA's Goddard Space Flight Center

NASA: The United States' National Aeronautics and Space Administration

NTFP: Non-timber forest products

OSFAC: *Observatoire Satellital Forêts d'afrique centrale*

PES: Payment for ecosystem services

REDD+: Reduced Emissions from Deforestation and Degradation

UNFCCC: United Nations Framework Convention on Climate Change

USAID: United States Agency for International Development

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