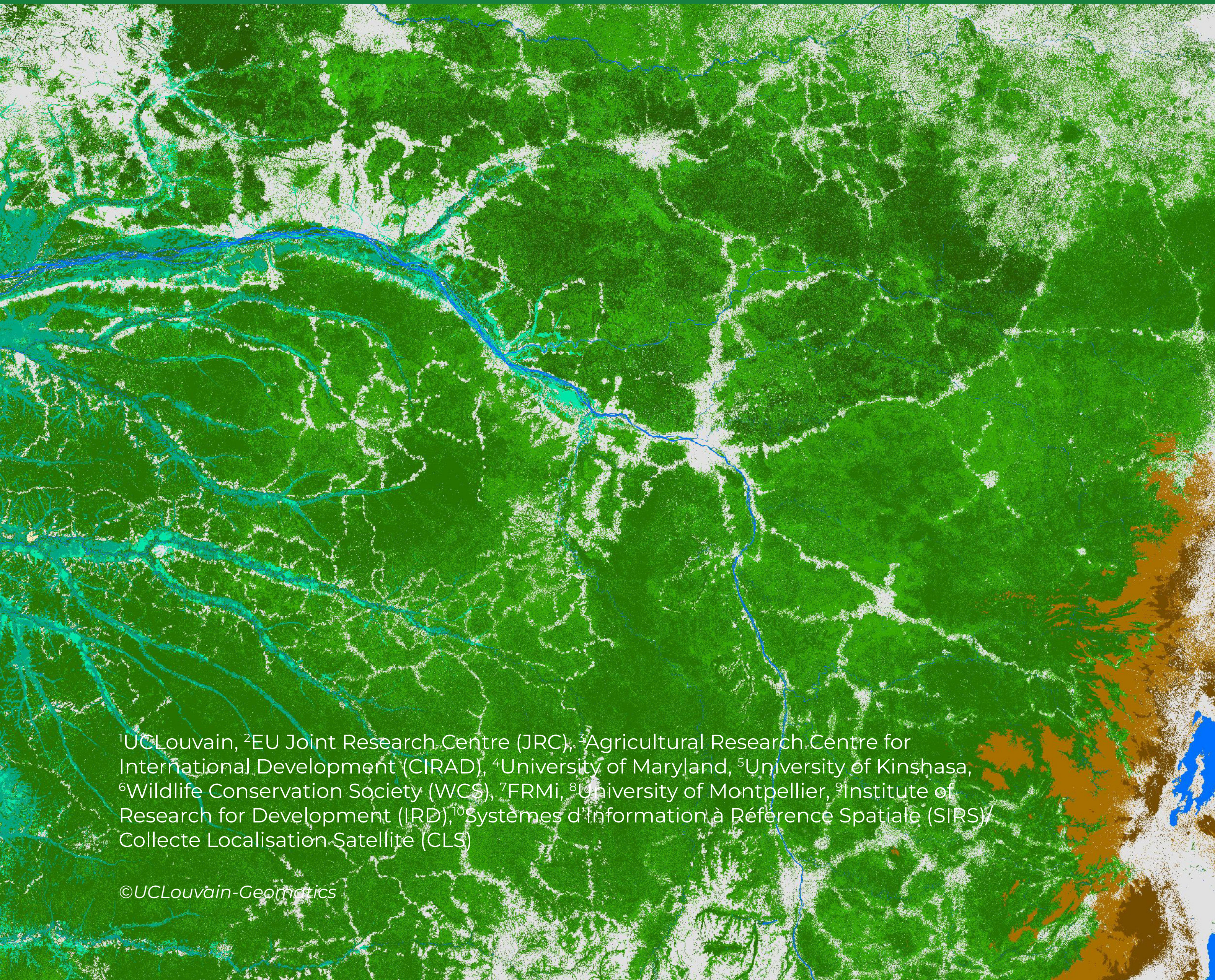
CHAPTER 1

Distribution of forest types and changes in their classification

Authors: Juliette Dalimier,[1] Frédéric Achard,[2] Baptiste Delhez,[1] Baudouin Desclée,[2] Clément Bourgoin,[2] Hugh Eva,[2] Sylvie Gourlet-Fleury,[3,8] Matthew Hansen,[4] Jean-Paul Kibambe,[5,6] Frédéric Mortier,[3,8] Pierre Ploton,[3,9] Maxime Réjou-Méchain,[3,9] Christelle Vancutsem,[2] Andreas Langner,[2] Christophe Sannier,[10] Hervis Ghomsi,[10] Quentin Jungers,[1,7] Pierre Defourny[1]



[1]UCLouvain, [2]EU Joint Research Centre (JRC), [3]Agricultural Research Centre for International Development (CIRAD), [4]University of Maryland, [5]University of Kinshasa, [6]Wildlife Conservation Society (WCS), [7]FRMi, [8]University of Montpellier, [9]Institute of Research for Development (IRD),[10]Systèmes d'Information à Référence Spatiale (SIRS)/ Collecte Localisation Satellite (CLS)

Introduction

The second largest block of dense moist forest after the Amazon, Central Africa's forests are an exceptional reservoir of carbon and biodiversity for the countries they cover and the planet as a whole. These forests provide a livelihood to 60 million people and help to feed 40 million more in nearby towns and cities. They play an essential social and cultural role in the lives of indigenous peoples and local communities. The ecological, economic, social and cultural importance of Central Africa's forests places them at the heart of international discussions aimed at preserving these unique ecosystems, which are vital to the health of the planet.

Forests are dynamic reservoirs of forest resources, carbon and biodiversity that grow as they expand and mature or shrink as a result of deforestation and forest degradation. To draw up effective forest management and ecosystem conservation policies, we must define the precise nature of these tropical moist forests and how they change over time. Doing so will also allow us to quantify their contribution to global carbon flows and respond to future climate challenges. National and international efforts to protect these forest ecosystems are based primarily on sustainable land use planning for both forestry and nature conservation. The international mechanism for reducing emissions from deforestation and forest degradation (REDD+) provides a framework for national efforts to reduce greenhouse gas emissions and increase the removal and long-term storage of these gases. The results of REDD+ activities are assessed on the basis of national forest reference emission levels.

The new generation of satellite imagery is a valuable source of data for the large-scale monitoring of tropical forests, which are often hard to reach. Inventory data from a large number of forestry concessions have very recently provided an overview of the functional diversity of forests, while the operationalization of the first carbon flow monitoring tower in a natural forest is a positive step forward for our understanding of forest carbon flows. However, mapping the spatial distribution of forest carbon stocks at the basin level remains a challenge due to the scarcity of field observations.

This chapter summarizes current knowledge on forest mapping in relation to their floristic composition, physiognomic features and carbon levels. It takes stock of changes in forest dynamics and analyses the impact of land use on the preservation of forest ecosystems. The last section reports on countries' engagement with the REDD+ process following the introduction of forest reference emission level mechanisms and their operational implementation at the provincial level.

1.1 Forest mapping

For decades, scientists have sought to establish a typology of forest formations that reflects the full diversity of Central African forests. Some typologies have categorized vegetation by phytogeographical zones, such as Lebrun and Gilbert (1954), Monod (1957), Letouzey (1968) and

Troupin (1966). Others, such as White (1986), are based on large chorological zones. These typologies often reflect endemic divergence in the floristic composition of the forests. Other typologies, such as the "Yangambi" typology (Aubréville 1957), differentiate between the different classes of vegetation on the basis of physiognomic features. Today, the proliferation of data sources and the diversity of environmental challenges drive the characterization of forest ecosystems according to floristic, physiognomic and carbon stock approaches to map forests' functional and structural variety, to delineate endangered natural habitats and to determine their carbon balance.

The phytogeographical study of forests focuses on their floristic composition, based on the individuals inventoried in the field. This is the case with the exceptional overview by Réjou-Méchain et al. (2021) which describes the floristic and functional composition of Central African forests. In complement to this, high spatial resolution observation data from new satellites have made it possible to understand the structure of the canopy at the forest stand level. This has, in turn, enabled the production of new maps as part of a close collaboration between national experts and Université catholique de Louvain (UCLouvain). Finally, a critical analysis of the cartographic data available on carbon stocks has allowed us to assess the state of current knowledge.

1.1.1 Floristic and functional composition of tropical forests in Central Africa

Forest management inventories carried out by 105 forestry concessions throughout Central Africa (excluding hydromorphic soil and highland areas) provided valuable information on their floristic and functional composition. Based on more than 180,000 inventory plots (about 90,000 ha total), 6 million trees over 30 cm in diameter were analysed. These trees belong to 193 well identified taxa and are representative of the majority of the individuals present in these plots.

The abundance distribution of all these taxa, averaged over 10 x 10 km grid areas, was modelled on the basis of 24 climatic variables, information on soil types (sandy or clay) and a human pressure index, over an area covering 85% of the dense terra firme forest in Central Africa.

Three major floristic gradients were identified via a factorial correspondence analysis of the predicted abundances of taxa on a regional scale: (1) the most pronounced floristic gradient strongly correlates with climate, separating areas with a cool dry season and low light (Atlantic area) from areas with a high rate of evapotranspiration (northern limit of Central African forests); (2) the second floristic gradient strongly correlates with seasonality and maximum temperature, contrasting equatorial areas with a low water deficit and areas with a high water deficit towards the tropical limits; (3) the third floristic gradient shows more local floristic variation, mainly due to human impacts.

By replacing the floristic composition of the stands taking into account the average values of three major functional traits – wood density, deciduousness and maximum potential height of the tree species (voir la figure 1.1) – several trends appear. Average wood density (voir la figure 1.1A) is highest on sandy soils, on the borders of Cameroon, the Republic of the Congo and the Central African Republic – an area known for Carnot/Bambio sandstone – where tree species subject to conservative resource-use strategies predominate. This average value is lower in areas with higher human pressure, because stands are mainly composed of fast-growing taxa. These disturbed areas also have a high proportion of trees that can reach a large diameter. These two findings indicate that forests affected by human activity are dominated by long-lived pioneer taxa, characterized by low wood density, but high potential volume. Moreover, a marked deciduous gradient extends from the

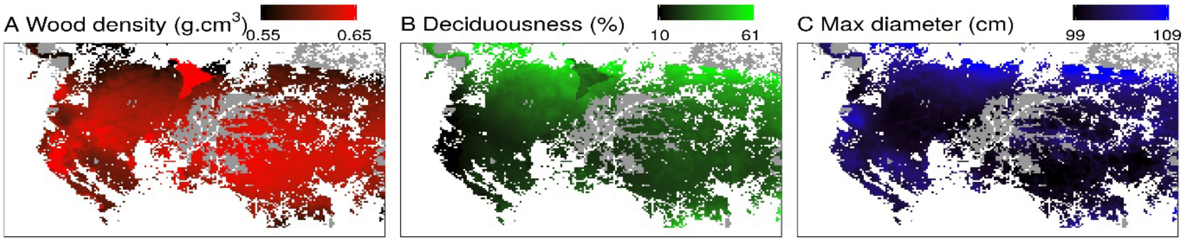


Figure 1.1: Predicted functional composition of Central African forests. A-C, predicted values of community-weighted functional traits. The grey areas represent forested areas outside of the calibration range.

evergreen forests of the Gabonese coast to the northern limit of the Central African forests (voir la figure 1.1B), except on sandy soils.

By combining these findings, we identified 10 major floristic types present in the region (see Figure 1.2). The strongest floristic dissimilarity emerged between Atlantic forests (types 1-3) and other forest types (types 4-10), within which semi-deciduous forests were clearly distinguished (types 4-6). Functional convergence was observed between forest types with significant floristic dissimilarity, as was divergence between those with floristic similarity. For example, although they have a regional species pool similar to that of semi-deciduous forests (types 4 and 6), Carnot/Bambio sandstone forests (type 5) have a functional composition closer to remote forest groups (e.g. types 2, 3, 7 and 8), with high wood density and low deciduousness. The type of soil changes the relative species abundance, with poor sandy soils favouring certain functional traits. Conversely, although Atlantic forests (types 1-3) have little taxonomic affinity with forests in the east-central and southern regions (types 7 and 8), they have a similar functional composition due to more similar climatic conditions. This confirms that, while the taxonomic composition of stands is linked to biogeography, their functional composition can converge under similar environmental conditions.

The floristic and functional characteristics of the stands make them more or less vulnerable to possible future changes in climate and human activity over the coming decades. Modelled to 2085, the ecological vulnerability of the stands – taking account of their sensitivity, exposure and capacity to adapt to climate change – appeared to vary independently of human pressure. This means that Central African stands are subject independently to the dual threats of climate and human activity. The findings show that this combined vulnerability will be high for the forests of the Gabonese coast, in large areas of DRC and on the northern frontier of the forest domain. The forests of Cameroon and the south of the Republic of the Congo appear to be vulnerable mainly due to the high level of human pressure expected by 2085. On the other hand, the Sangha trinational forest complex and the north-eastern part of Gabon seem to be the least vulnerable areas in the region. Predictions suggest that the majority of forests in DRC, comprising the majority of Central African forests, appear to be vulnerable to climate change, human pressure or both factors combined.

1.1.2 Detailed mapping of forest types

The large-scale mapping of forest types aims to inform a number of national and provincial applications related to the sustainable management and conservation of forest ecosystems in the Congo Basin. From 1999 to 2012, several vegetation maps were published based on satellite observations; their resolution gradually increased from 1 km to 300 m (Mayaux et al. 1999; Mayaux

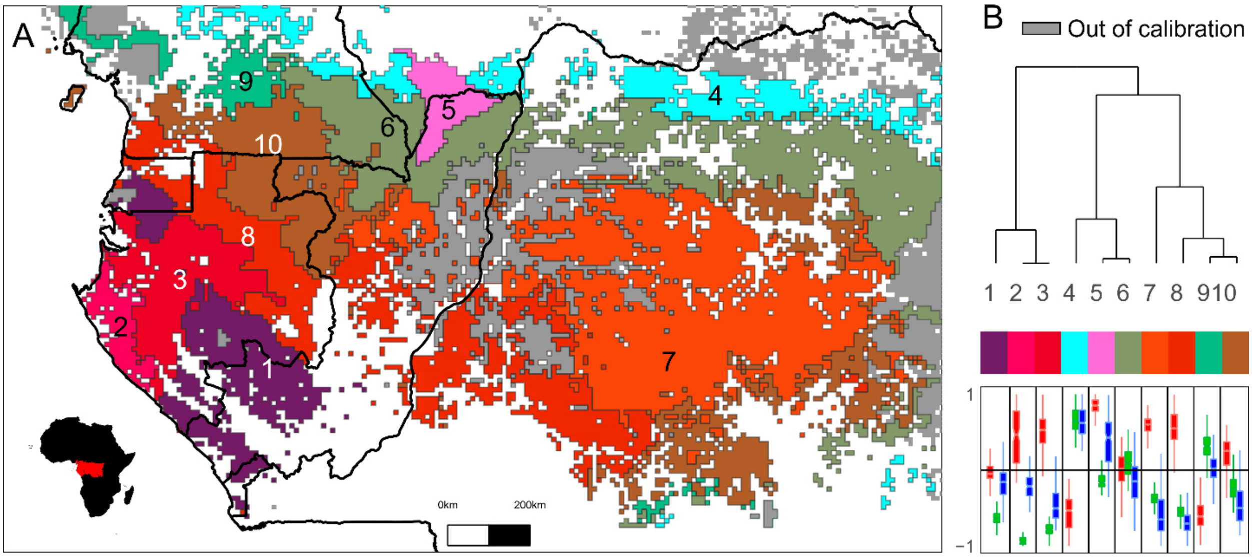


Figure 1.2: Main types of forest in Central Africa based on functional composition. A, Classification of forest types obtained via hierarchical clustering of predicted floristic gradients. The colours represent the averages of the three functional traits of the species in each type of forest, namely wood density (red), deciduousness (green) and maximum diameter (blue). Similar colours therefore indicate a similar functional composition. B, Taxonomic relationships between forest types illustrated by a dendrogram (top) and a boxplot of standardized predicted functional composition (bottom), with wood density in red, deciduousness in green and maximum diameter in blue. Names of forest types: (1) evergreen Atlantic highland, (2) evergreen Atlantic coastal, (3) evergreen Atlantic inland, (4) semi-deciduous marginal, (5) evergreen/semi-deciduous on sandstone, (6) semi-deciduous, (7) central evergreen, (8) mixed evergreen, (9) degraded evergreen, (10) transitional semi-deciduous/evergreen. Deciduousness (simultaneous loss of all leaves in one year) is an individual-level botanical characteristic. Country boundaries are shown in black and forests outside the calibration range are shown in grey.

Source: Réjou-Méchain et al. (2021)

et al. 2004; Vancutsem et al. 2006; Verhegghen et al. 2012; Gond et al. 2015), providing a preliminary synoptic overview of the forest on a regional scale. The new mapping techniques, which are detailed both spatially and semantically, improve our spatial knowledge of forests. This has been made possible by the new Earth observation capabilities available since the launch of the European Copernicus programme. Unlike previous satellite missions, the Copernicus programme will run over the long term, ensuring the redundancy of the technology (several satellites) and open access. Using a continuous acquisition strategy with spatial resolutions of 10-20 m and temporal resolutions of 5-12 days, Sentinel satellites 1 and 2 are the new go-to instruments for regular long-term monitoring of forest ecosystems. In parallel, the increasing availability of Planet mosaics with very high spatial resolution, but of more variable quality, also constitutes a new source of data that is particularly well suited to the visual interpretation of samples distributed across the entire basin.

Within the framework of the Central African Forest Observatory (OFAC), a harmonized regional typology of forest types covering the 10 Central Africa Forest Commission (COMIFAC) countries was developed in 2018 through several regional workshops bringing together national experts. The 13 forest categories under this typology are defined using the ISO 19144-1 Land Cover Classification System (LCCS), as illustrated in Figure 1.4.

This regional mapping was undertaken as part of a collaboration between national experts and UCLouvain. It shows the spatial distribution of the different types of forest described on a physiognomic basis, based on variables such as the percentage of vegetation cover of the different vegetation strata, cover seasonality, the flood regime and altitude.

Thanks to the development of a new image correction method and an algorithm that improved cloud detection (see Figure 1.3), a coherent annual composite was produced using Sentinel-2 satellite data acquired in 2020 in the different spectral bands. The data on cloud zones were complemented by observations from 2018 and 2019. Observations from the Sentinel-1 radar satellites, which are not affected by atmospheric disturbance, were also used to classify forest types where the Sentinel-2 image time series was very cloudy.

At the classification stage, the classification algorithms are trained using data collected by the national experts applied to the spectro-temporal metrics from Sentinel-1 and Sentinel-2 data. The forest type map produced at a resolution of 20 m provides information on forest types at a level of spatial detail never before attained at this geographic scale. Figure 1.4 shows the regional map generated with the full range of forest classes identified and three zoomed in images of the Republic of the Congo.

The Congo Basin has three major moist forest complexes; the most typical is made up of edaphic forests and covers the centre of the basin. The maps show that edaphic forests include permanently flooded swamp forests (flooding > 9 months) (see Figure 1.5), periodically flooded swamp forests (4–9 months flooding) and riparian forests (see Figure 1.6). The tree layer covers more than 60% of periodically or permanently flooded swamp forests and 30%-60% of riparian forests. Riparian forests are found at the bottom of valleys or on shallow slopes along riverbanks. A large majority of the basin is covered by dense moist forests with an irregular age distribution (see Figure 1.7). This forest type is defined by a dense tree layer (> 60%), that is rich in species and markedly deciduous, with many emerging trees with imposing canopy. In the eastern half of the basin, dense moist forests with a regular age distribution (see Figure 1.8) – with fewer large crowns than forests with an irregular age distribution – seem to be gaining ground. Groves of monospecific evergreen dense

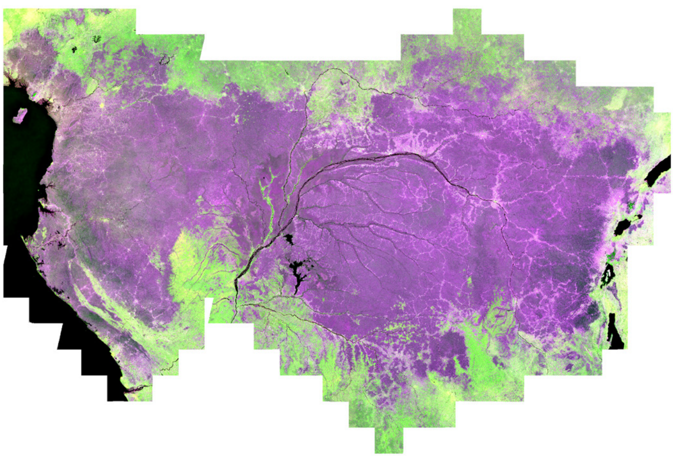


Figure 1.3: Cloudless Sentinel-2 mosaic of the Central African moist forest area, 2020. The innovative colour composite makes it possible to identify the functional types of the forest, which was not previously possible using satellite imagery.

moist forests (see Figure 1.10), most often of the species *Gilbertiodendron dewevrei*, punctuate these large blocks. Finally, mountane and sub-mountane forests border the great lakes region, where altitudes exceed 1100 m. Across the basin, open forests (see Figure 1.9), characterized by a density of 30% to 60%, are also identified, often on the margins of a degradation gradient.

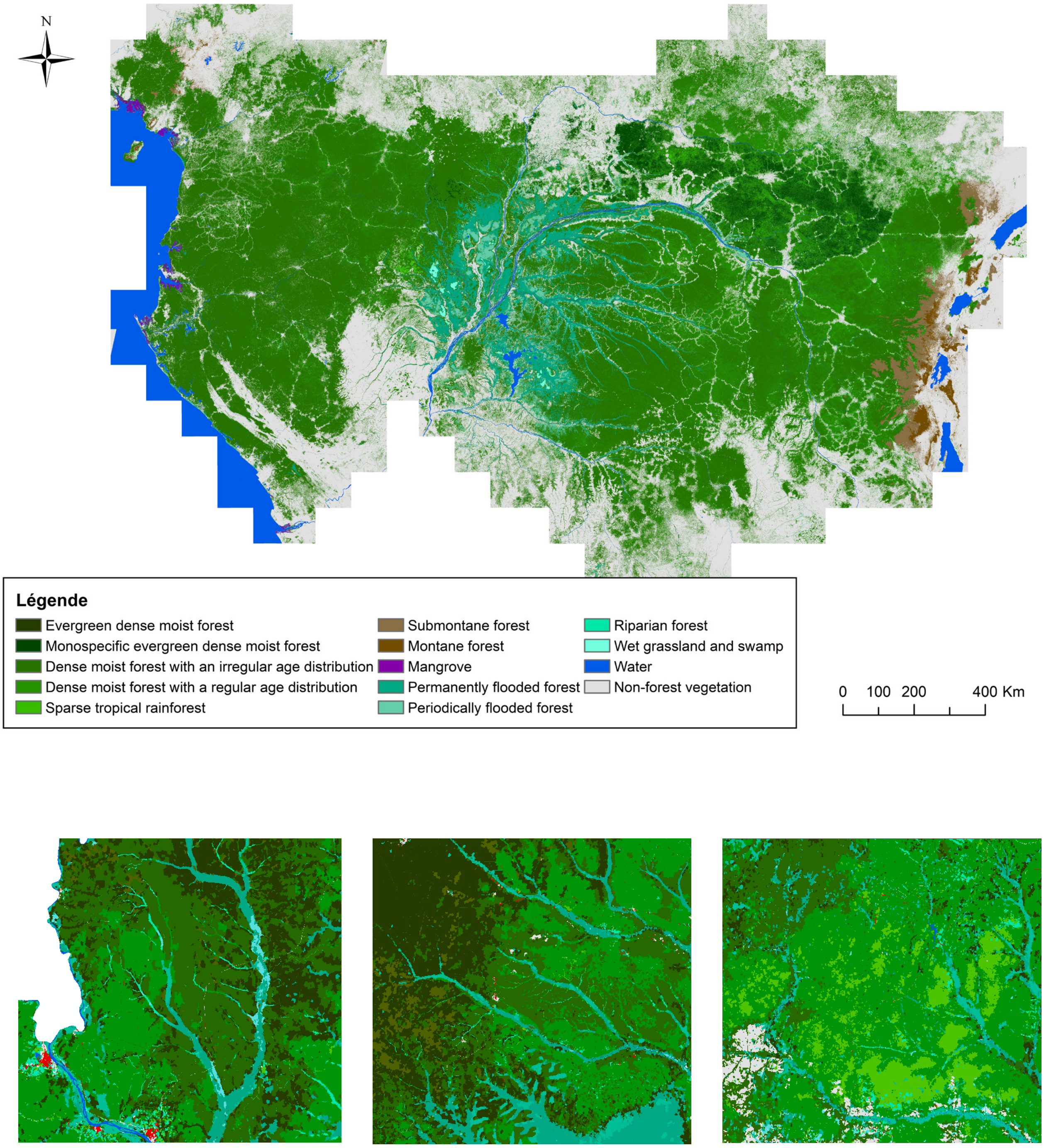


Figure 1.4: Map of forest types in the Congo Basin at 20 m resolution with the level of detail shown in three zoomed in images of the Republic of the Congo.

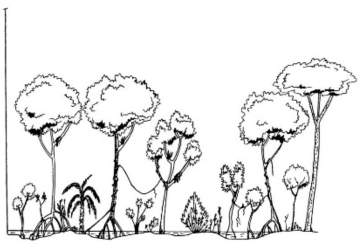


Figure 1.5: Permanently flooded forests.

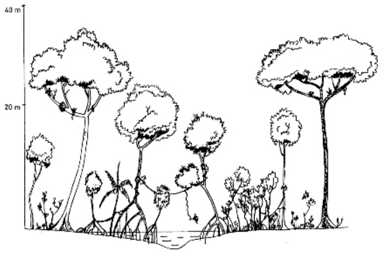


Figure 1.6: Riparian forests.

Figure 1.7: Dense moist forests with an irregular age distribution.

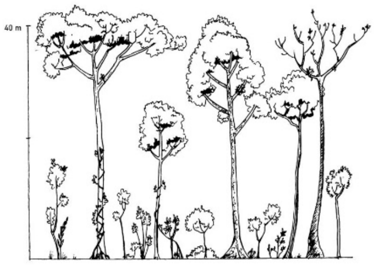


Figure 1.8: Dense moist forests with a regular age distribution.

Figure 1.9: Open forests.

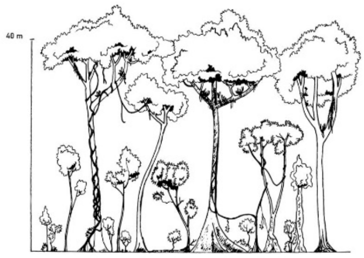


Figure 1.10: Evergreen dense moist forests.

1.1.3 Distribution of forest carbon stocks in Central Africa

Central African forests sequester about 40 Gt of carbon (Saatchi et al. 2011). These forests have structural characteristics that distinguish them from Amazonian forests: the density of trees per hectare is lower, but there are more large-diameter trees and trees at a similar diameter are larger. This results in a higher average level of carbon or biomass per hectare than that of Amazonian forests (Sullivan et al. 2017). Finally, while the atmospheric carbon absorption capacity of undisturbed Amazonian forests has been declining for around 30 years due to an increase in tree mortality attributed to climate change (Brienen et al. 2015), this trend has not yet been observed in Central Africa (Hubau et al. 2020). Currently, despite their comparatively smaller area, undisturbed forests in Africa are now absorbing more carbon than those in the Amazon. An increase in carbon loss after 2010 has however been observed (see 1.2.3 Estimation des taux de changements), which suggests the absorption capacity of intact forests in Central Africa will become saturated, despite the stability observed to date (Hubau et al. 2020).

However, the spatial distribution of forest carbon stocks across Central Africa remains largely unknown, mainly due to the lack of field observations – especially in the eastern half of the region (www.afritron.org) – and the difficulties of extrapolating carbon stocks using remote sensing.

There are no satellite sensors able to "measure" carbon or forest biomass directly. Maps produced using remote sensing are therefore generated based on the indirect relationships identified between what the sensors actually measure (for example, forest stand reflectance) and reference biomass estimates, often derived from forest inventories. However, the vast majority of satellite signals are currently very insensitive to variations in biomass if they exceed 100 to 200 t/ha^{-1} (called signal

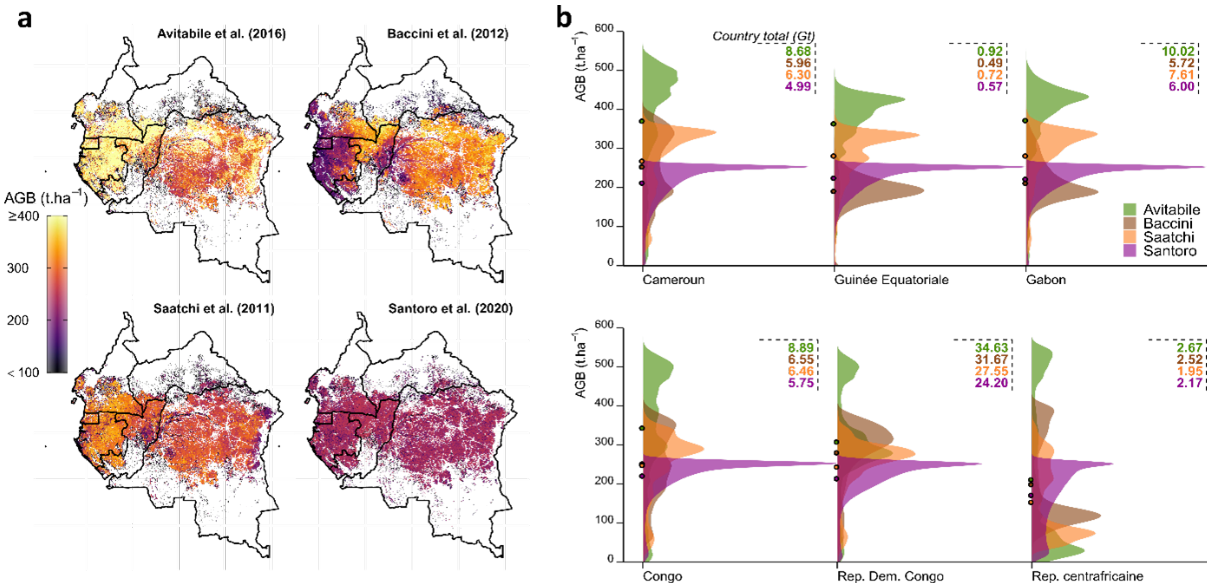


Figure 1.11: Comparison of above-ground biomass (t/ha-1) of Central African moist forests from maps produced by Avitabile et al. (2016), Baccini et al. (2012), Saatchi et al. (2011) et Santoro et al. (2020). a. Spatial distribution of biomass. b. Density histograms representing aerial biomass values per hectare by country (X axis) and map (colour code). The average of each distribution is represented by a coloured dot and the cumulative biomass (in Gt) across all the moist forests in each country is given (upper-right quadrant).

"saturation"), which characterizes a large majority of forests in Central Africa. Moreover, the Atlantic coast of Central Africa is characterized by high cloud cover that interferes with optical satellite signals and further complicates large-scale biomass mapping.

These difficulties have not been overcome by the studies currently available on the spatial distribution of forest biomass in the region. These studies use satellite remote sensing data to extrapolate reference biomass measurements estimated in the field, except for Santoro et al. (2020), which did not use reference measurements and instead used purely physical models. Despite taking similar approaches, the various maps produced show very different types of distribution (see Figure 1.11-a), which led to radically different country estimates (see Figure 1.11-b). In Gabon, for example, the average above-ground biomass per hectare for moist forests is about 375 t/ha^{-1} according to the map produced by Avitabile et al. (2016), compared with only 210 t/ha^{-1} according to Baccini et al. (2012), with estimates of total biomass ranging from single to double digits (10 Gt for one, 5.7 Gt for the other, see Figure 1.11-b). Highly accurate local biomass maps, based on aerial LiDAR, showed that all these maps provided only very poor predictions of observed biomass variations (Réjou-Méchain et al. 2019). These regional maps also fail to reflect changes in biomass obtained from forest inventory data (Ploton et al. 2020). These maps should therefore be regarded with an appropriate level of caution.

In the absence of adequate satellite data to extrapolate forest biomass, only approaches that rely on representative statistical sampling of different forest types are currently able to provide reliable estimates with the associated level of uncertainty. Aerial LiDAR can also provide reliable biomass estimates. Based on a large random sample, Xu et al. (2017) were able to use LiDAR data to map the distribution of carbon in DRC at the national level. They also used LiDAR data collected in DRC for the Central African area, in combination with other samples at the global level, from a range of studies, to monitor global above-ground biomass between 2000 and 2019. The quality of these different biomass estimates will likely increase through the use of large samples and LiDAR data. Together, these approaches, based on representative statistical sampling of different forest types and the use of LiDAR data, show that biomass maps based solely on optical data can, despite their large systemic errors, substantially improve the accuracy of average height and above-ground biomass estimates at the local level (for example, Næsset et al. 2020). Moreover, a global map of forest canopy heights was produced at 30 m resolution using the GEDI and Landsat satellites (Potapov et al. 2021).

The reliability of large-scale above-ground biomass maps should improve significantly with NASA's GEDI space mission (2020-2022) and the expected launch of the ESA's Biomass radar satellite (P-band) in 2022. Unlike previous satellite data, these new sensors were specifically designed to map forest biomass. They are particularly sensitive to biomass even in the highest values (Minh et al. 2016). GEDI LiDAR data, which are currently being collected and analysed, provide, among other things, measurements of canopy heights across the tropics, with a sampling density that should provide several measurements per square kilometre (Patterson et al. 2019). The strong relationship between forest height and biomass will make it possible to produce biomass mapping models that will very likely outperform regional models.

To make the best use of these new satellite data, Central African countries will face the major challenge of setting up measurement “supersites”, where highly accurate forest biomass estimations are made (Chave et al. 2019). This will make it easier to adjust and evaluate the maps produced at the local level.

1.1.4 Complementarity of the different approaches

The three approaches to characterizing forests, namely using floristic characteristics, currently at 10 x 10 km, physiognomic characteristics, at 20 x 20 m, and carbon characteristics, should be gradually combined given their clear complementarity.

For example, in the centre of the Republic of the Congo, floristic class 7 (central evergreen) corresponds to the class “open dense moist forest” on the detailed physiognomic map. Forests with a cover density of 30–60% appear to correspond to taxa with a low potential maximum diameter, but with a high wood density. By combining these two products we can identify a degraded forest, composed of species with high wood density suggestive of slow growth and high carbon stock in the remaining trees.

Similarly, in northern Congo, floristic class 6 (semi-deciduous) aligns with the classes “dense moist forest with a regular age distribution” and “dense moist forest with an irregular age distribution” on the detailed physiognomic map. Class 6 is defined by species with a medium wood density, an average maximum diameter and a mixture of deciduous and evergreen species. The constituent species of this class are split between fast-growing taxa with lower wood densities and high potential volumes, and slow-growing taxa with the opposite characteristics. The physiognomic approach is consistent with this description, but distinguishes between two classes in this region based on the higher presence of trees with large crowns in forests with an irregular age distribution compared with forests with a regular age distribution.

The wealth of information produced at the different scales demonstrates the importance and complementarity of using different approaches to manage local land use and forest conservation in the face of regional and global challenges. The vulnerability of forest communities to change can be predicted by combining climate change scenarios, human pressure projections and the detailed spatial distribution of the forest. Such predictions can then inform conservation strategies. In this way, by preserving the evolving functional potential of existing forests, or at least maintaining their connectivity, it might be possible to limit the regional and global impacts of expected changes.

1.2 Dynamics of dense moist forests

Beyond the characterization of each forest type, it is essential to regularly monitor forest cover to quantify and pinpoint the location of the change processes observed, including deforestation, degradation and reforestation. Below, we discuss the relative influence of the change factors affecting these different dynamics and analyse the impact of land use on them.

Through a comprehensive wall-to-wall mapping of tropical moist forest (TMF) covering the last three decades (from year 1990 to year 2020) at fine spatial resolution, new information on TMF are provided (see Figure 1.12). TMF extent and the related disturbances (deforestation and degradation), and post-disturbances recovery are documented on an annual basis (Vancutsem et al. 2021). TMF product and Global Forest Watch data (Hansen et al. 2013) available since 2013, are the only consistent and up to date products for monitoring deforestation of Central African forests from the year 2000. The consistency of the method is a key point for forest monitoring and the annual worldwide product is GFW and JRC's major advantage. The TMF product of Vancutsem et al. (2021) is very detailed on the thematic aspect; it documents deforestation in Central Africa in an unprecedented manner by including deforestation after degradation and deforestation followed by a regrowth, by identifying specific forest conversion to commodities or water, and by including changes within the mangroves. This has been achieved thanks to the analysis of each individual valid observation of the Landsat satellite archive allowing to capture short-term disturbances such as selective logging and severe weather events. Today, TMF products and GFW data are the main sources that alert us regarding deforestation activities and are used to stratify a sampling design in the field. The major advantage of a sampling approach is the opportunity to quantify uncertainties in estimates.

1.2.1 Stages of forest development in the Congo Basin

Although no ecosystem may be considered truly undisturbed, because some degree of human impact is present everywhere (Sanderson et al. 2002), the **undisturbed moist forests** in the TMF product are defined as undisturbed (degradation or deforestation) tropical moist forest coverage observed over the Landsat historical record since 1983.

A **deforested land** is defined as a permanent conversion from moist forest cover to another land cover whereas a **degraded forest** is defined as a moist forest cover where disturbances (canopy opening in a 0.9 ha Landsat pixel) were observed over a short period of time. Here the duration of the disturbance (and consequently the period over which the disturbance is detected with satellite imagery) is assumed as a proxy of the disturbance impact, i.e. the higher the duration of the detected disturbance, the higher the impact on the forest cover, and the higher the risk to have a permanent conversion of the TMF. All disturbances for which the impacts were observed over more than 2.5 years (or 900 days) were considered as deforestation processes. Short-term disturbances include logging activities, fires and natural damaging phenomena such as wind storms and extreme drought. This definition is close to the definition of forest degradation adopted by Thompson et al. (2013) that consider the following criteria: a loss of productivity, depletion of biodiversity, unusual disturbances (droughts, windfalls), and a reduction of carbon sinks.

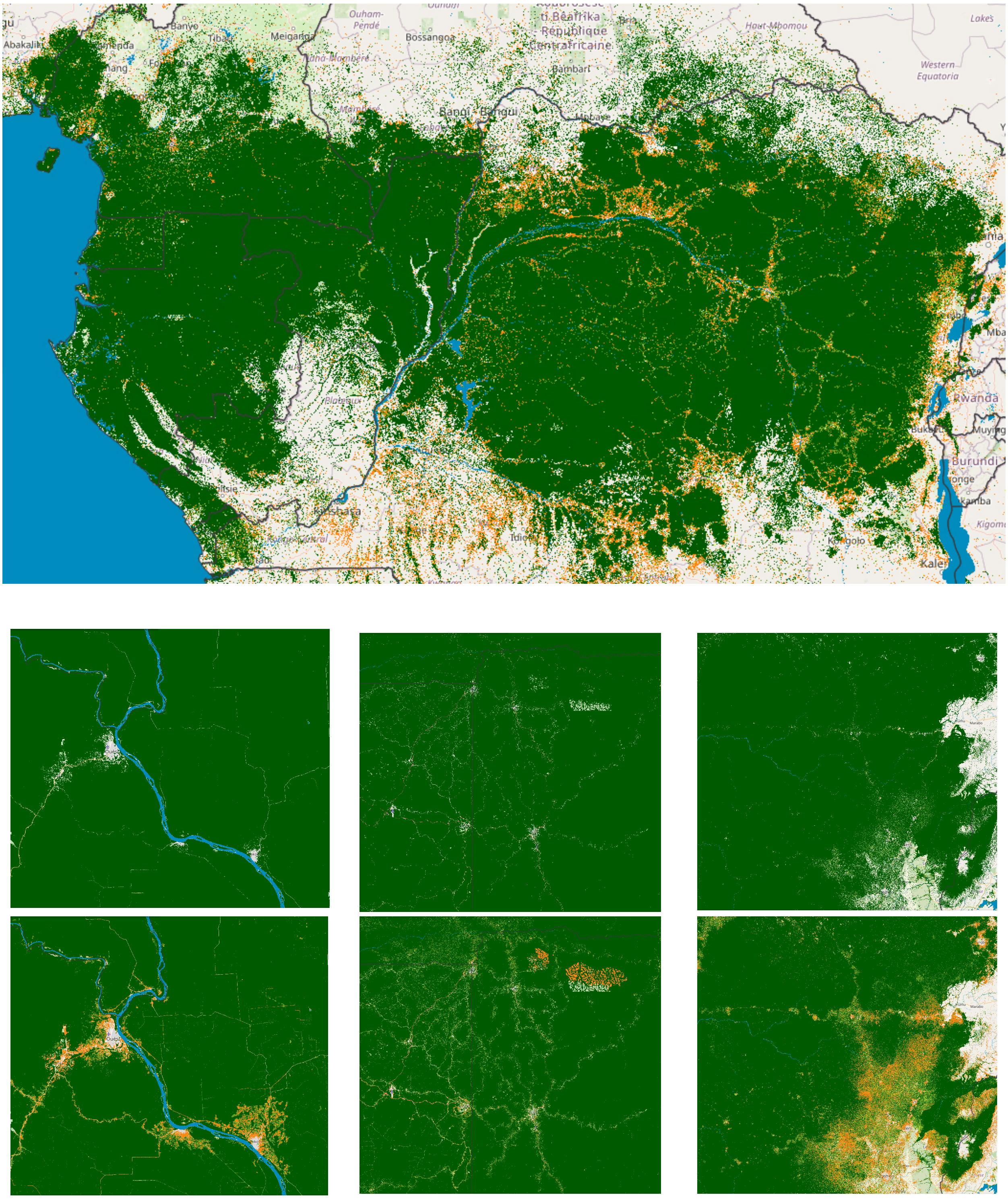


Figure 1.12: Map of undisturbed tropical moist forests in Central Africa (top) with three zoomed in images: northern Republic of the Congo (left), Equatorial Guinea/Gabon (middle) and eastern DRC (right), for 1990 (top) and 2019 (bottom).

Two levels of degradation were empirically identified: **degradation with short-term impacts** (observed within a 1-year maximum duration), which includes the majority of logging activities, and **degradation with long-term impacts** (between one and 2.5 years) which mainly corresponds to strong fires (forest fires). 50 percent of the degradation are observed over less than six-months. For disturbances for which the impacts were observed over more than 2.5 years and that were therefore considered as deforestation processes, 68 percent of such deforestations were observed over more than five years.

A **forest regeneration** is a two-phase transition from moist forest to (i) deforested land and then (ii) vegetative regrowth. A minimum 3-years duration of permanent moist forest cover presence is needed to classify a pixel as forest regeneration (to avoid confusion with farms).

The collection of 30 maps derived from Landsat data provides the surface area of the TMF and disturbance categories fo each year, from 1990 to 2020 (Figure 1.12). These maps are used to document annual disturbances over the whole period, with ten transition categories for each annual statistic: (i) degradation that occurs before deforestation, (ii) short-term degradation not followed by deforestation, (iii) short-term degradation not followed by deforestation, (iv) long-term degradation not followed by deforestation, (v) direct deforestation (without prior degradation) not followed by forest regeneration, (vi) direct deforestation followed by forest regeneration, (vii) deforestation after degradation followed by forest regeneration, (viii) deforestation after degradation not followed by regrowth, (ix) forest conversion to water bodies and (x) forest conversion to tree plantations.

1.2.2 Method for monitoring forest dynamics

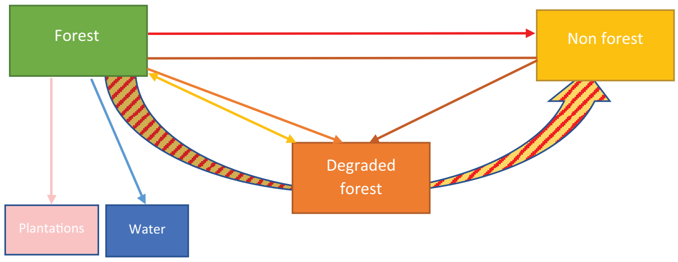
In order to deal with geographic and temporal breaks of the Landsat archive and the persistent presence of clouds in some areas like the Gulf of Guinea, (i) a reference initial period (baseline) for mapping the initial TMF surface area and (ii) a monitoring period for detecting the changes are determined at the pixel level. In addition, thanks to additional datasets, commission errors in the baseline map of tropical moist forests are reduced by taking into account possible confusion with commodities, wetlands, bamboos, and deciduous forest.

The disturbances are monitored on a single-date basis with a classification on each image of the Landsat archive. This allows (i) to capture the disturbances that are visible from space only over a short period, such as logging activities, and (ii) to record the time and number of disturbances observed. A disturbance observed refers to lack of tree foliage cover within a Landsat pixel. The number of disturbances observed constitutes an indicator of disturbance intensity.

Finally, in order to produce a more conservative map of undisturbed forests by excluding areas impacted by logging activities and possibly undetected, disturbance buffer zones using a threshold distance of 120 m around disturbed pixels are created. This distance corresponds to the average observed distance between two lumber yards and is consistent with the distances used in previous studies for assessing intact forests (Qie et al. 2017).

1.2.3 Estimating rates of change

The surface area of evergreen and semi-deciduous forests of Central Africa is estimated at about 200 million ha in January 2020 including 184.7 million ha with no visible sign of disturbances (Vancutsem et al. 2020). Overall close to 9 percent of the tropical moist forest area of Central Africa have disappeared since 2000, i.e. 18 million ha.



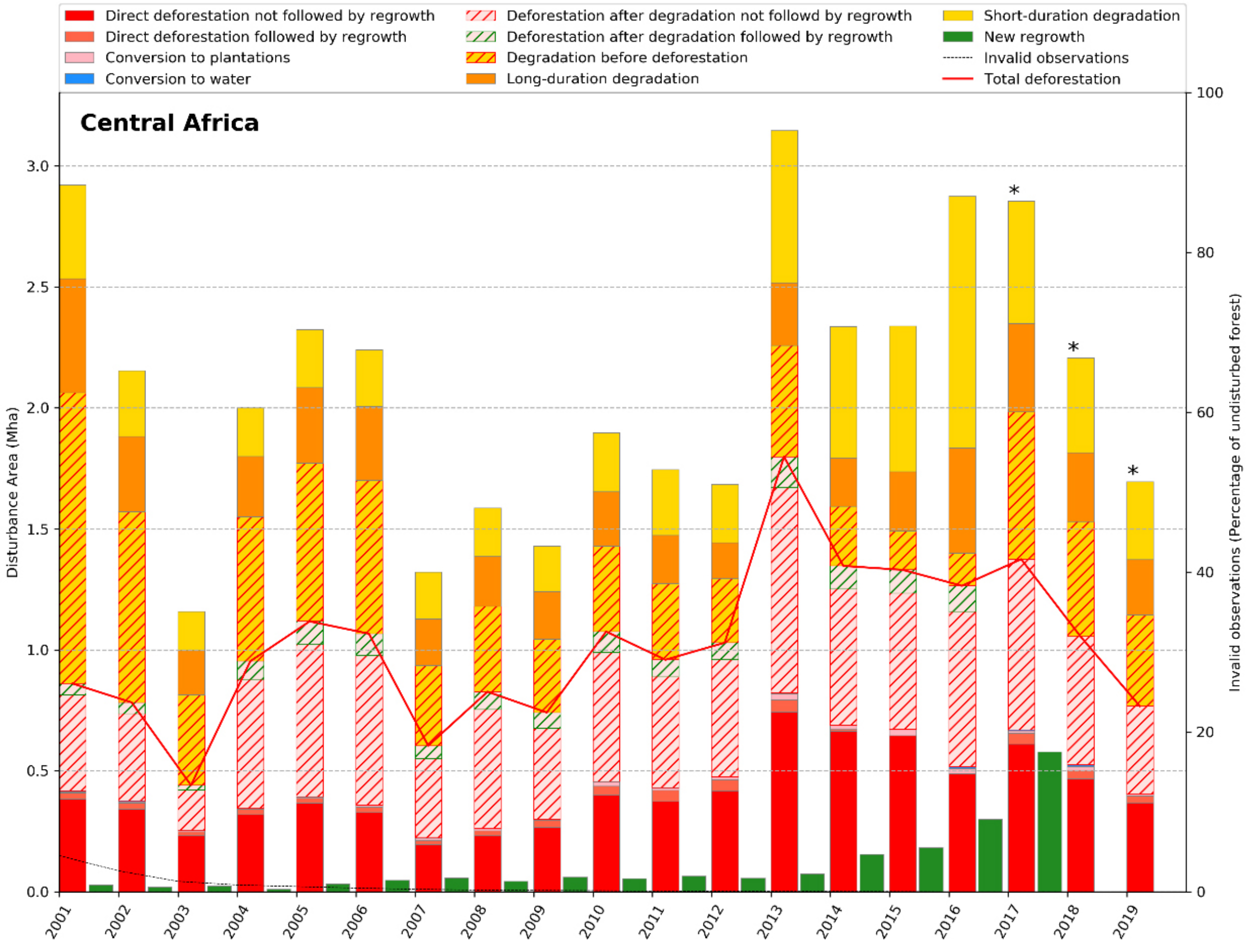


Figure 1.13: Annual change in deforestation (red bar) and degradation (yellow bar) in Central African tropical moist forests, 2001–2019.

Source: Vancutsem et al. 2020

The results underline the importance of the degradation process in these ecosystems with two key outcomes: degraded forests represent in Central Africa about 7 percent of the remaining surface area of TMFs (up to 30 percent when considering disturbance-edge-affected forests), and about 40 percent of all forest disturbances (deforestation, regeneration and degradation).

The analysis of changes shows a considerable increase of the annual disturbance rate in tropical moist forests of Central Africa during the last 5 years (2015-2020) that has reached 1.79 million ha per year compared to 1.36 million ha per year during the previous decade (2005-2015) (see Figure 1.13).

Table 1.1: Annual rates of undisturbed forest loss over 5 year timeframes by country, according to the TMF product, 2000–2020 (annual rates in %). Rates from other countries are not available in the study.

Study	Timeframe	Cameroon	CAR	Republic of the Congo	DRC	Gabon
TMF Vancutsem et al. 2021 (undisturbed tropical moist forests)	2000–2005	-0.25	-1.63	-0.25	-1.05	-0.12
	2005–2010	-0.08	-0.93	-0.25	-1	-0.08
	2010–2015	-0.12	-0.98	-0.56	-1.3	-0.13
	2015–2020	-0.21	-2.1	-0.71	-1.46	-0.21

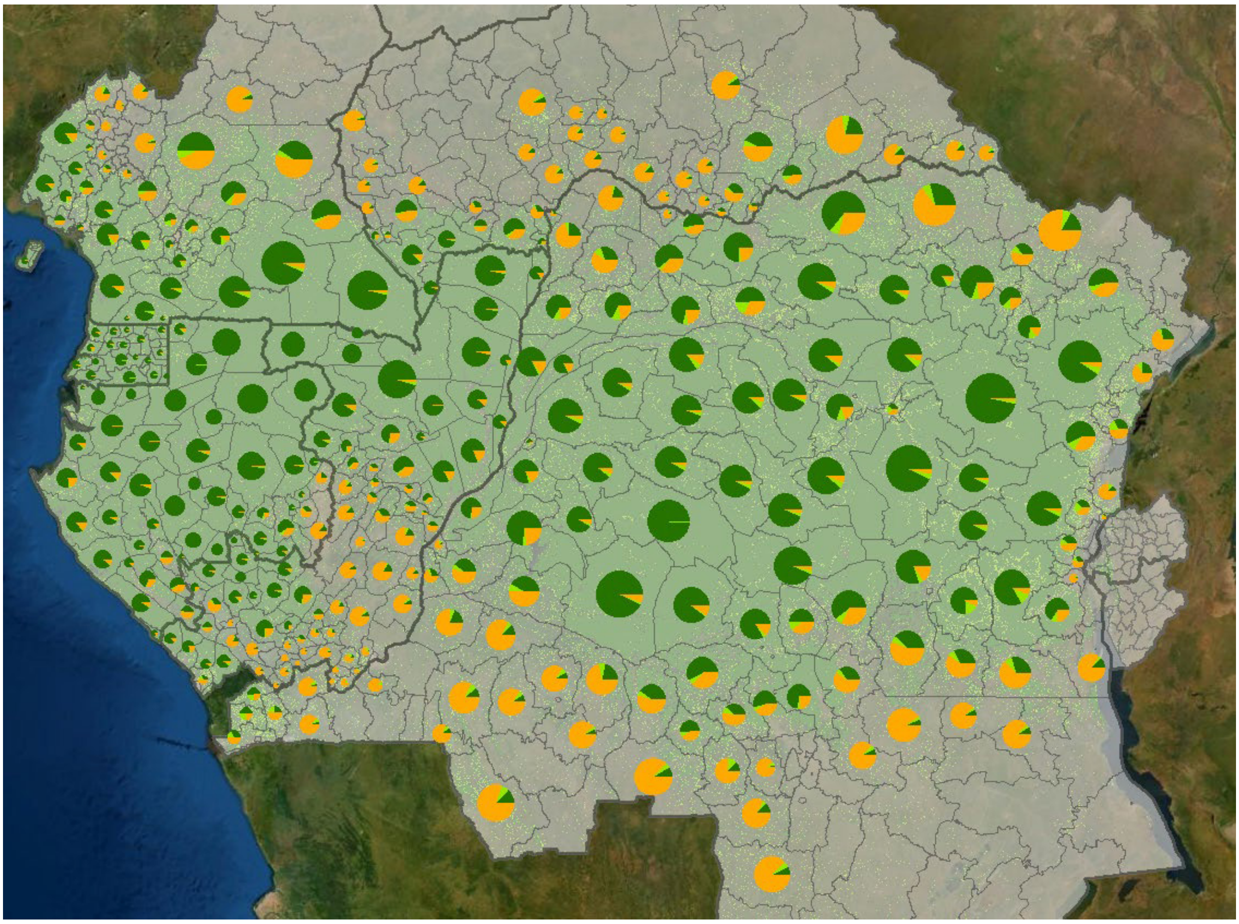


Figure 1.14: Proportion of intact forests (dark green), degraded forests (light green) and non-forests (orange) at the second administrative level (districts, sub-prefectures, departments or communes), according to the TMF product for 2019. In the figure, areas deforested before 2019 are classed as non-forest.

The Democratic Republic of the Congo is the African country with the largest remaining expanse of undisturbed moist forest with 105.8 million ha, and it is the second largest in the tropical world behind Brazil and before Indonesia. Gabon, Cameroon and the Republic of Congo have similar areas of remaining intact forests (between 19.8 and 23.4 million ha in 2019). The Republic of Congo and Gabon show very low rates of decline for the period 2000–2019 (0.03-0.1 million ha/year) compared to the DRC (1.4 million ha/year) (Vancutsem et al. 2020). In all Central African countries, there has been an increase in annual rates of disturbances since 2009. Without a slowdown in the present

Table 1.2: Annual rates of forest loss by country according to different sources (annual rates in % and confidence interval in brackets).

Study	Timeframe	Burundi	Cameroon	CAR	Chad	Republic of the Congo	DRC	Equ. Guinea	Gabon	Rwanda	Sao Tome and Principe
GFC by Hansen et al 2013 (forest cover)	2001–2019	-0.27	-0.22	-0.089	-0.6	-0.16	-0.38	-0.23	-0.093	-0.36	-0.029
(primary forest)		/	-0.17	-0.11	/	-0.079	-0.24	-0.14	-0.058	-0.032	/
FAO. (2015). FAO Forestry Paper No. 1. Global forest resources assessment 2015.	2000–2005	-1.78	-1.02	-0.07	-0.59	-0.08	-0.2	-0.67	0	2.28	0
	2005–2010	6.93	-1.07	-0.07	-2.15	-0.05	-0.2	-0.71	0	2.99	-0.87
	2010–2015	1.76	-1.13	-0.07	-2.41	-0.07	-0.2	-0.72	-0.89	1.48	0
National studies (Tritsch et al. 2020)	2000–2010		-0.176	-0.273		-0.082			-0.022		
National studies (de Wasseige et al. 2014)	2000–2005			-0.175		-0.052			-0.01		
	2005–2010			-0.175		-0.096			-0.01		
de Wasseige et al. 2014 (Tropical moist forest)	2000–2010		-0.06 (±0.04)	-0.05 (±0.02)		-0.07 (±0.02)	-0.19 (±0.04)	0.01 (±0.02)	-0.01 (±0.01)		
Tyukavina et al. 2018 (All forest types)	2000–2014		-0.53	-0.39		-0.43	-0.52	-0.46	-0.25		
Potapov et al., 2012. (HTP+HTS**)	2000–2005						-0.25				
	2005–2010						-0.272				
Tyukavina et al. 2013 (HTP+HTS**)	2000–2010						-0.47 (±0.4)				

HTP**: Humid Tropical Primary Forest
HTS**: Humid Tropical Secondary Forest

(last 10 years) disturbance rates, the Democratic Republic of the Congo would lose 22 percent of its moist forests by year 2050 (from 116.9 million ha in 2020 to 91 million ha in 2050) and 33 percent of its undisturbed moist forests by same year (from 105.8 to 71.4 million ha).

For all major sources, annual deforestation rates vary significantly from one study to another (Table 1.2). TMF is chosen as the reference because it is the only consistent and up-to-date study that differentiates deforestation and degradation since the year 2000 (Table 1.1). On the one hand, country data reported for the FAO-FRA corresponds to official national statistics. On the other hand, the GFC and TMF are sources of global data based on a standardized method. GFC and TMF publish annual rates from remote-sensing approaches, while FRA collects national statistic evaluating forest surface areas every 5 years and then gets forest loss surfaces at national scale. Table 1.1 provides information on annual loss rate of undisturbed tropical moist forest from 2000 to 2020 per country. Other national remote sensing studies provide results of forest loss assessment. However, because of disparaging methods, unrepeatable measurements, different forest cover considered and different forest definitions, a careful strategy is required for comparing results over time and between countries.

Figure 1.14 presents the proportion of undisturbed forest, degraded forest and non-forest area at the sub-national level. Administrative territories with a smaller proportion of undisturbed forests usually have a larger proportion of degraded forests, highlighting the fragility of these areas.

Finally, most of the forest area converted to tree plantations over the last 30 years in Africa are located in DRC, Cameroon and Gabon (80,000 ha, 70,000 ha and 40,000 ha respectively).

1.2.4 Drivers of deforestation

Unlike other tropical regions, small-scale processes rather than large-scale agriculture mainly cause deforestation and forest degradation in Africa. Deforestation here is more closely related to subsistence agriculture, small-scale charcoal production and gathering of wood for fuel. According to Curtis et al. (2018), shifting cultivation is a widespread driver of forest disturbance in sub-Saharan Africa. About 60 percent of new farmlands came from intact forests in the 1980s and 1990s, and was mainly used for small-scale and subsistence farming and breeding (Gibbs et al. 2010). Forest degradation is not always a precursor of deforestation, in particular in many woodland areas of Africa where the main drivers of forest degradation are wood gathering for fuel and charcoal production (Brink et al. 2014).

The expansion of farmland areas, a growing population and the expansion of urban infrastructure bring African moist forest areas closer to urban areas, which increases human pressure on them – in fact, all three factors are key drivers of deforestation (Mayaux et al. 2013). Deforestation increases dramatically when rural population density exceeds 8.5 people per km2, and declines as time to get to cities increase.

1.2.5 Analysis of changes in forest cover by land use, at the country and regional level.

Land-use policies are a valuable tool for managing human pressure on forest resources. They can be used to create protected areas, establish forestry concessions, convert such concessions into conservation concessions and designate community forests. Given the limited resources available and the importance of Central African forests to biodiversity conservation, there is an urgent need to prioritize the protection of the most important areas and to focus conservation efforts by studying landscapes locally and analysing their strengths and weaknesses. In their study, Grantham et al. (2020) applied a method for identifying priority conservation areas to maximize the biodiversity return on investment. Despite the greater resilience of intact forests compared with degraded forests, it is important to consider factors other than the "intactness" of the forests when identifying priority conservation areas to avoid overlooking vital ecosystems. The biodiversity present in an ecosystem should also be considered where determining how an ecosystem is prioritized for conservation, as should patch size and connectivity. According to their findings, DRC has the highest number of priority areas in the region, followed by Gabon, the Republic of the Congo and Cameroon. Community participation in conservation efforts is a necessary condition for success, not just for joint efforts to combat illegal logging, the expansion of subsistence agriculture and forest clearing for housing, but also for raising awareness of the need for forest conservation. The expansion of conservation areas will, moreover, reduce the resources available to local populations. It is therefore essential to ensure they benefit from the introduction of conservation measures. Ensuring local people are invested in the management of the forests around their villages, that they receive funds from the sale of carbon credits and that they have exclusive use of forests and access to non-timber forest products is one way to achieve a win-win for forest conservation and the economic development of remote villages (Djomo et al. 2018).

Community forests have existed in Central Africa since the late 1990s and were first introduced in Cameroon. Recognising the customary rights of forest communities, including their land rights, is considered one of the best ways to effectively protect forests while reducing poverty (Rainforest Foundation UK 2019). Unfortunately, the results in Cameroon are not very convincing, in particular due to the level of bureaucracy and the difficulty of organizing collective action within Cameroonian villages. Gabon, which authorized the assignment of community forests a few years ago, has faced similar challenges. DRC passed its own legislation on community forests in 2016 to allow communities to manage their forests according to their ancestral customs in perpetuity, which, according to Ewango et al. (2019), ensured better forest management. In CAR, the first community forest was created in 2019 and covered an area of about 15,000 ha. Equatorial Guinea has its own specific tenure categories, but because they do not grant the holder the right to use specific resources, they are not considered community forests. The Republic of the Congo, for its part, has still not authorized community forests. However, "Community Development Areas" have been set up around remote villages in concession areas to allow local people to farm, hunt and collect timber for local needs (Karsenty and Vermeulen 2016). Companies can still log in these areas if they pay the communities for the privilege.

Many protected areas have been created in Central Africa over the past two decades in an effort to reduce pressure on forests, preserve ecosystems rich in fauna and flora and benefit local communities (Bowker et al. 2016). However, a lack of financial, technical and human resources, alongside the political instability, corruption and conflicts present in many countries in the region, make it difficult to properly manage these protected areas. The question of whether protected areas effectively reduce deforestation is at the heart discourse in this area (Aubréville 1957; Troupin 1966; White 1986; Bowker et al. 2016; Vancutsem et al. 2020). It is difficult to make firm conclusions about the role protected areas play in forest conservation. Some studies (Joppa and Pfaff 2011; Bowker et al. 2016; Bruggeman et al. 2018) show that they are generally located in areas at low risk of conversion to another land use and that they are therefore at low risk of deforestation due to their characteristics. Bowker et al. (2016) argue that the effectiveness of forest protection measures differs enormously between protected areas in the same country. While good governance does play an important role in the management of these protected areas, it is not the only factor that determines the effectiveness of forest protection measures. Size and accessibility are other decisive features. Larger parks are more effective than smaller ones, likely due to their lower perimeter-to-area ratio. Indeed, the likelihood of the perimeter being breached is lower than for a protected area the same size. In DRC in particular, more remote parks have greater conservation potential. Some protected areas perform well mainly because of their difficult terrain, while others are particularly threatened and hard to protect because they are easy to access and closer to inhabited areas (Joppa and Pfaff 2011). These findings underscore the need to optimize which areas are subject to protection, taking into account the risk of degradation and the cost of protecting them (Joppa and Pfaff 2011).

Designating certified or uncertified forestry concessions makes it possible to delineate logging areas and curb illegal logging. If they are sustainably managed and established outside the boundaries of high conservation value areas, production forests can play a crucial role in biodiversity conservation (Duveiller et al. 2008). Selective logging has also been shown to have a low impact on biodiversity loss and, at an FSC-certified harvesting intensity, the majority of taxonomic groups have shown resilience (Lhoest et al. 2020). However, local disturbances (logging, hunting, poaching), made easier by the increased accessibility of remote areas, can impact conservation.

Mining, the last land use type we discuss here does not seek to conserve biodiversity or protect forest resources at all; to the contrary, mining concessions – prone to radically transform the landscape – are a major threat to forests.

The total area figures for the different land use classifications at the national level (see Figure 1.15) were calculated based on data from the 2020 IUCN World Database on Protected Areas (WDPA) for protected areas and from the 2019 survey for forestry concessions. The data on Cameroon's

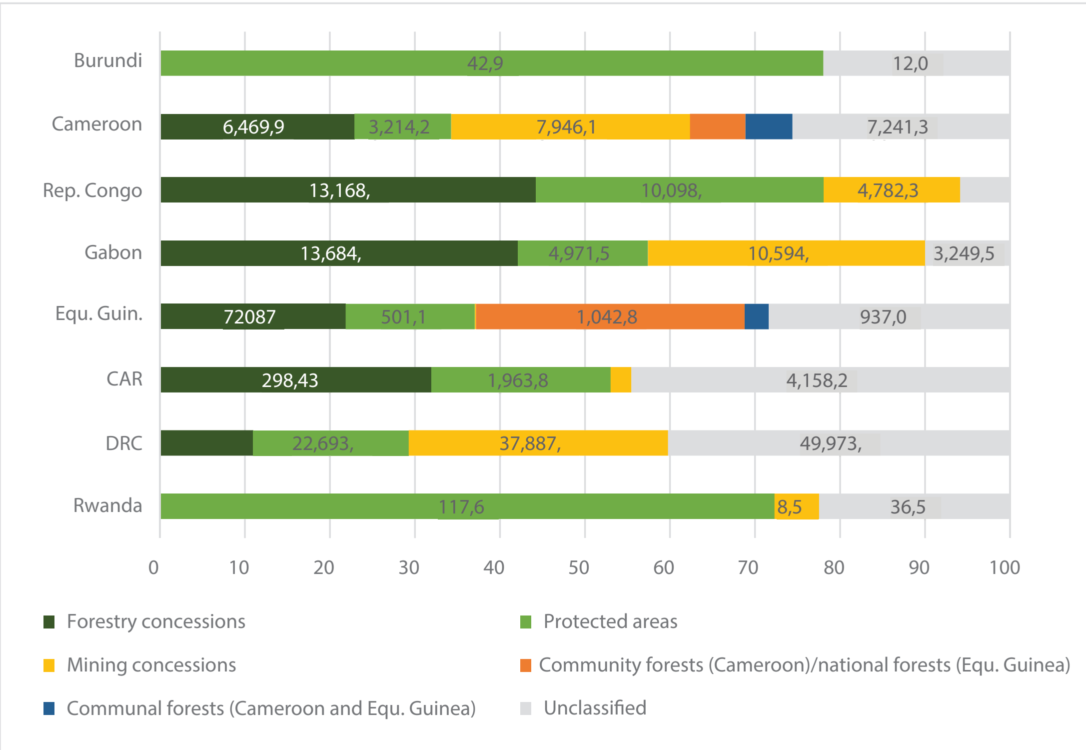


Figure 1.15: Forest cover (intact and degraded) by land-use classification by country (ha).

NB: Some countries have a total forest cover higher than 100 percent because there was forest regrowth between some land uses.

community and communal forests and that on Equatorial Guinea's national and communal forests come from the World Resources Institute (WRI). Mining permit data come from the SNL Metals & Mining database (accessed 2 December 2020). The level of forest disturbance in the different land-use classifications was calculated using the Joint Research Centre's TMF product (Vancutsem et al. 2021), which maps intact tropical moist forests, forests that have never been degraded over the observation period (2000–2019), degraded tropical moist forests and forests that have suffered visible degradation for up to 2.5 consecutive years over the timeframe studied.

The figures on forest disturbances by type of land use and by country (see Tables 1.3 to 1.6) highlight the magnitude of forest degradation and deforestation in forestry concessions in DRC and CAR compared with those observed in Cameroon or Gabon. Differences between countries are partly explained by different demographic contexts. In DRC, for instance, high population density near concessions leads to the blurring of the boundaries between the industrial and informal logging areas in a concession (Karsenty 2016). Concessions in DRC are usually very large, making them difficult to manage and leading to the gradual encroachment of smallholder farmers, illegal loggers and charcoal producers into the forest (Karsenty 2016). How areas are delimited may, in some cases, be another reason for differences between countries. For example, unlike DRC, Cameroon has a policy of excluding areas close to settlements from concessions. The most recent findings presented

Table 1.3: National annual rates of deforestation, degradation and regrowth in forestry concessions in dense forest areas in Central Africa, 2000–2010 and 2010–2020.

Country	2000–2010			2010–2020		
	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)
Cameroon	0.02	0.05	0.00	0.04	0.16	0.01
Congo	0.04	0.11	0.00	0.13	0.30	0.01
Gabon	0.01	0.06	0.00	0.02	0.07	0.00
Equ. Guinea	0.01	0.10	0.00	0.06	0.24	0.01
CAR	0.25	0.17	0.00	0.27	0.33	0.03
DRC	0.19	0.32	0.00	0.46	0.54	0.05

Table 1.4: National annual rates of deforestation, degradation and regrowth in protected dense forest areas in Central Africa, 2000–2010 and 2010–2020.

Country	2000–2010			2010–2020		
	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)
Cameroon	0.01	0.03	0.00	0.04	0.08	0.01
Congo	0.04	0.06	0.00	0.08	0.00	0.13
Gabon	0.01	0.04	0.00	0.01	0.06	0.00
Equ. Guinea	0.02	0.06	0.00	0.03	0.08	0.01
CAR	0.27	0.22	0.02	0.28	0.43	0.06
DRC	0.17	0.13	0.03	0.18	0.25	0.07

Table 1.5: National annual rates of deforestation, degradation and regrowth in mining concessions in dense forest areas in Central Africa, 2000–2010 and 2010–2020.

Country	2000–2010			2010–2020		
	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)
Cameroon	0.11	0.22	0.00	0.19	0.45	0.03
Congo	0.04	0.20	0.00	0.19	0.44	0.01
Gabon	0.01	0.09	0.00	0.03	0.12	0.00
Equ. Guinea	0.02	0.25	0.00	0.14	0.74	0.02
CAR	0.39	0.46	0.02	0.32	0.65	0.08
DRC	0.65	0.60	0.04	0.70	0.93	0.23

Table 1.6: National annual rates of deforestation, degradation and regrowth in unclassified dense forest areas in Central Africa, 2000–2010 and 2010–2020.

Country	2000–2010			2010–2020		
	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)	Deforestation rate (%)	Degradation rate (%)	Regrowth rate (%)
Cameroon	0.23	0.34	0.01	0.53	0.95	0.05
Congo	0.22	0.00	0.00	0.35	0.48	0.04
Gabon	0.05	0.00	0.00	0.12	0.00	0.27
Equ. Guinea	0.05	0.28	0.00	0.16	0.49	0.01
CAR	0.64	0.61	0.06	0.65	0.13	1.22
DRC	0.51	0.42	0.02	0.61	0.65	0.15

here are based on a 30 m resolution and are consistent with the study by Davis et al. (2020). This study concludes that forestry concessions benefit forest conservation in the majority of Central African countries with forests, with the possible exception of CAR and the Republic of the Congo (Davis et al. 2020). Panlasigui et al. (2018) have shown how the presence of forest concessions has significantly reduced forest loss on the Cameroonian coast where forests are under high pressure due to their proximity to the port city of Douala. Conversely, Karsenty and Hardin (2017) note that in regions where population pressure on forests is already high, the presence of forestry concessions can worsen forest loss. Moreover, when access to forests is improved as part of industrial activities, it becomes easier for subsistence farming, poaching or hunting to reach previously inaccessible areas (Karsenty and Hardin 2017; Tyukavina et al. 2018). It is therefore likely that hidden local factors influence whether forestry concessions have a positive or negative effect.

Deforestation and degradation rates in protected areas (see tableau 1.4) follow the same trends as rates in forestry concessions, i.e. there are more forest disturbances in CAR and DRC than in other forested countries. While deforestation rates in both types of area tended to increase between 2010 and 2020, deforestation rates in Equatorial Guinea and DRC are over twice as high in forestry concessions as in protected areas. In CAR deforestation rates remain very slightly higher in protected areas than in forestry concessions. Nevertheless, degradation rates are lower in protected areas than in forestry concessions (except in CAR) for the two timeframes studied.

The similarity of deforestation rates between protected areas and forestry concessions in some countries is surprising given that protected areas do not have logging routes, which are the main source of forest disturbances within the concessions. This suggests that some of the forests in protected areas have been degraded by illegal activities. In an effort to capture the diverse realities of protected areas, the Central Africa Forest Observatory (OFAC) analytical platform provides more detailed analyses of each protected area (https://www.observatoire-comifac.net/analytical_platform).

Across the whole Congo Basin, 5% of protected areas are overlapped by mining titles, of which 65% are occupied by forests (intact or degraded). Although currently prohibited in Cameroon, it was previously permitted for mining titles and conservation areas to overlap, which partly explains why mining concessions are found in 24% of the country's protected areas. In the Republic of the Congo, 7% of protected areas are overlapped by mining titles, with figures of 6% in Gabon and 3% in DRC.

For the two timeframes covered, the rates calculated here show that forest degradation and deforestation are greater in unclassified areas than in mining concessions for all forested countries, except in DRC, where the opposite is true. Forest regrowth rates follow an inverse trend and are higher in unclassified areas for all countries over both timeframes, except in DRC. In DRC, forest growth has been observed in mining concessions. However, in the absence of information on the mining activity carried out under the permits, it is difficult to quantify the impact of mining on forest disturbance. According to the 2018 WWF report, very few sites have entered the production stage. Therefore, the discovery of significant reserves could lead to major environmental damage (Grantham and Tibaldeschi 2018).

DRC and CAR have the highest rates of forest degradation and deforestation related to the mining sector (see Table 1.5). Excluding artisanal operations, 11.6% of DRC is covered by mining titles, of which 35% – almost 10 billion ha – cover forests. The impact of artisanal and small-scale mining is difficult to measure and monitor. Individual operations generally cause only minor damage, as they are short-term and affect very small local areas, but the cumulative effect of these negative impacts on the local area significantly increases the pressure on the forests. In addition to its impact on deforestation, artisanal mining also fuels conflicts in eastern DRC and feeds into the insecurity in that part of the country (Hund et al. 2017).

A 2017 WWF study on Cameroon, DRC, Gabon and the Republic of the Congo analysed the current state of mining and its impact on biodiversity conservation in the Congo Basin (Noiraud et al. 2017). Mining is more widespread in the forest region than oil and gas extraction (Hund et al. 2017). Countries in the subregion see mining as a key driver of their economic development. The direct and indirect risks of mining for the environment include deforestation – mainly due to the construction of the infrastructure required –, biodiversity loss and the pollution of aquatic environments. Large-scale mining operations tend to encourage the movement of large numbers of people seeking to benefit from the economic assets generated by mining. This situation leads, in turn, to a rise in poaching and subsistence agriculture (Hund et al. 2017; Noiraud et al. 2017). In Cameroon, the industrial mining sector is still in its infancy and mainly causes degradation through its exploration activities. Non-industrial operations, which also cause degradation, are however widespread.

Countries would benefit from drawing up national land use plans to enable different sectors to coordinate. This would help to avoid conflict over the use of the forest for production and conservation activities, mining and forestry concessions, the development of agribusiness and the protection of local populations' livelihoods.

1.3 Forest reference emission level of countries in the subregion

1.3.1 What is a forest reference emission level?

Context

The United Nations Framework Convention on Climate Change (UNFCCC) encourages countries to mitigate climate change by taking voluntary steps to reduce greenhouse gas emissions and increase the removal and long-term storage of greenhouse gases. The mechanism for reducing emissions from deforestation and forest degradation (REDD+) guides these efforts in the forest sector, targeting five activities in particular: (1) reducing emissions from deforestation, (2) reducing emissions from forest degradation, (3) conserving forest carbon stocks, (4) managing forests sustainably and (5) enhancing forest carbon stocks. Countries participating in REDD+ are also eligible to receive payments if they can demonstrate the effectiveness (or "results") of the REDD+ activities implemented.

Box 1.1: REDD+ and the Copernicus land monitoring service

Baudouin Desclée, Andreas Langner, Hugh Eva, Hervis Ghomsi, Christophe Sannier

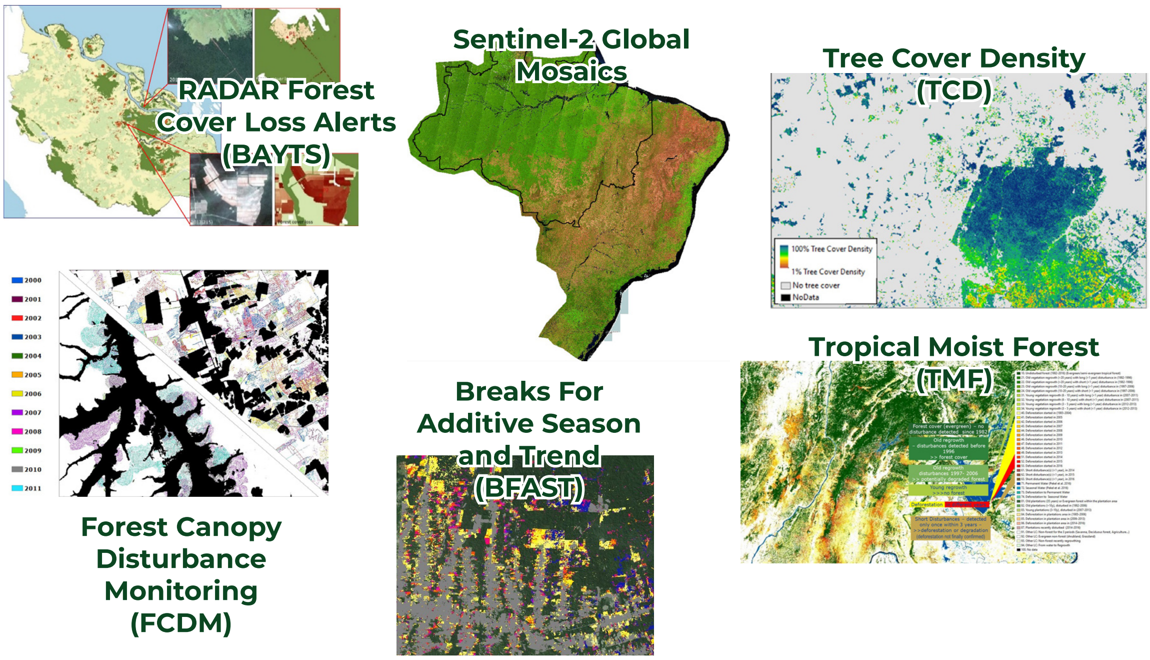
The REDDCopernicus project (https://www.reddcopernicus.info) was launched in 2019 to incorporate forest monitoring into the European Copernicus programme. It formed part of the EU Horizon 2020 programme. With a view to supporting REDD+ processes, this research and development project aims to coordinate and consolidate the EU's existing forest monitoring capacity, which relies on the Copernicus earth observation services.

The team has prepared a preliminary design for the planned Copernicus REDD+ services that incorporates the main technical and organizational components. A list of potential products, methods and data that might be suited to forest monitoring were subject to comparative assessment and nine products were selected covering four components: (1) analysis-ready satellite data (Sentinel-2 Global Mosaic 2 (S2GM-2) and JRC-L1C-S2 composites); (2) forest/tree cover status maps (tree cover density (TCD), Forest Type (FTY) and TMF products); (3) forest cover change maps((TMF) and Breaks for Additive Season and Trend (BFAST) products) and (4) forest disturbance and alert maps (Forest Canopy Disturbance Monitoring (FCDM) and BAYTS products). In addition to the above data components, the project also incorporates platform and service solutions for processing, downloading and analysing data.

Two online workshops were organized for users from the Congo Basin in September and October 2020 to further develop the initial design of the Copernicus REDD+ component and to collect feedback from users. Initially planned as face-to-face meetings, the workshops were successfully reorganized as webinars with interactive sessions using specialist online tools combining a geoportal and expert surveys. Participants included several national

Continued on next page

Box 1.1: continued



Data and products selected for the preliminary design and presented at REDDCopernicus workshops.

actors working in the field of forest monitoring and management (National Climate Change Observatory (ONACC), STREDD+, CNC, Gabonese Studies and Space Observations Agency (AGEOS), National Centre for Forest and Fauna Inventory (CNIAF), Marien Ngouabi University/Geomatic and Applied Tropical Ecology Laboratory (UMNG/LGETA), Directorate of Forest Inventories and Management (DIAF), Regional Post-Graduate Training School on Integrated Management of Tropical Forests and Lands (ERAIFT)) and regional or international institutions (OFAC/COMIFAC, FAO, WRI).

Case studies on example sites were presented at these workshops using a geoportal, developed specifically for the REDDCopernicus project. To evaluate how useful these products would be for monitoring and reporting on national REDD+ forests, feedback was collected from users using an online questionnaire.

Using the positive feedback collected from users during these online workshops, the products and services designed for the potential REDD+ component of the Copernicus land monitoring services will be refined to better meet national reporting needs.

Objectives

The performance of REDD+ activities is assessed using a baseline called the forest reference emission level, which only takes account of greenhouse gas emissions, or the forest reference level, which takes account of both greenhouse gas emissions and removals. To conduct a REDD+ performance assessment it is therefore necessary to measure the difference between the forest carbon flows observed after the implementation of measures to reduce greenhouse gas emissions and the flows that would have occurred without these interventions (business-as-usual or status quo scenario). The forest reference emission level is used for this purpose and is therefore a key pillar of the REDD+ mechanism. Establishing its forest reference emission level enables a country to (1) measure its contribution to climate change mitigation through its interventions to limit the negative impact of human activity on forest resources, (2) present this contribution in the context of the UNFCCC, (3) evaluate the effectiveness of the policies and measures implemented, and (4) receive payments based on its greenhouse gas emissions reduction results (CO_2, CH_4, N_2O).

Technical overview

There are a number of technical aspects to consider when establishing forest reference emission levels. They vary in complexity and are often interrelated. Some very general aspects will be covered below (readers can refer to the literature on the subject for more detail, e.g. Sandker et al. 2016). Countries may decide how to establish their forest reference emission levels, but the method used must meet certain criteria: **transparency** (concerning, for example, the methods and data used); **accuracy** and **precision** (following Intergovernmental Panel on Climate Change (IPCC) good practices: IPCC 2003; IPCC 2006; GFOI 2016)); and **completeness** (to allow independent assessors to re-construct the reference level (see Sandker et al. 2016)). It is also imperative that the method used to construct the forest reference (emission) level includes information on its parameters, for example, on **how forests are defined**, **the scope** (e.g. which REDD+ activities or which carbon and gas reservoirs are considered), **the scale** (e.g. national, provincial or biome level), **the reference period** (or historical period) and the **accounting period**. This information provides a framework for developing a method for monitoring greenhouse gas flows (often limited to measuring CO_2 emissions). The method chosen is used to quantify "historical" emissions over the reference period (2000–2014 in the illustrative forest reference emission level in Figure 1.16), i.e. before interventions began to be implemented to reduce greenhouse gas emissions from the forest sector. Historical emissions are used as a benchmark to estimate what the level of emissions would have been over the accounting period – i.e. the period following the implementation of interventions – if these interventions had not occurred (the business-as-usual scenario). The level of emissions over the accounting period can be projected using the average of the historical emissions (as shown in Figure 1.16). If a country considers past greenhouse gas emissions to be a poor predictor of its future emissions from the forest sector, especially where emissions have been planned before the national forest reference level is established (e.g. forestry concessions, national and local development plans, etc.), an "adjustment" to the national reference level may be considered. National reference levels are deemed to have been "adjusted" when criteria other than historical emissions are taken into account.

The performance of REDD+ activities can then be assessed by comparing current emissions with the national forest reference level established for the accounting period, expressed in tonnes of CO_2 equivalent (tCO2e) per year.

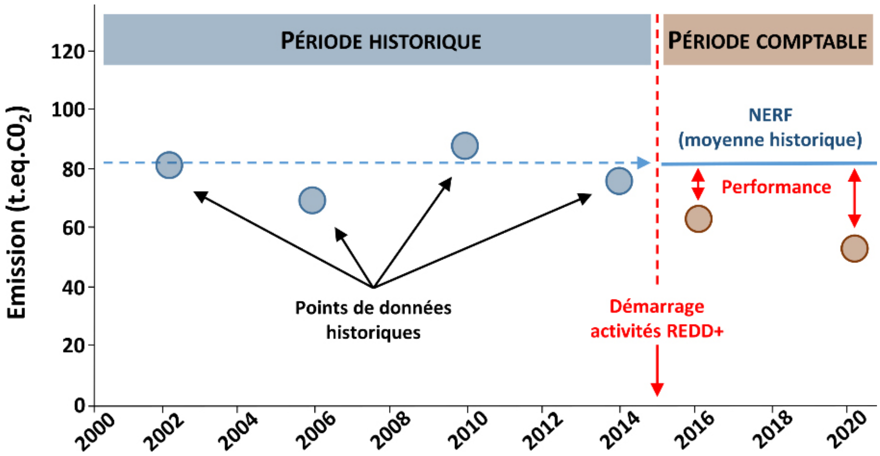


Figure 1.16: Example forest reference emission level

Calculating activity data and emission factors

How emissions are calculated to determine each historical data point (blue points in Figure 1.16) is a direct determinant of the reliability of national reference level estimates. The number of historical data points corresponds to the number of times a change was observed over the period studied. The calculation of emissions generally consists of two components: **activity data** and **emission factors**. Activity data relate to the spatial extent of a change in land use over a given time interval (for example, conversion from moist forest to cropland). Activity data are usually obtained by analysing satellite images to detect these changes and categorize them (e.g. from moist forest to cropland, in the example above) according to specified land use classes. Emission factors are an estimate of the difference between the carbon stock in forest biomass and the carbon stock in the land as used after conversion, and are typically estimated from inventory data (Sandker et al 2016). Multiplying activity data by the associated emission factor provides an estimate of the carbon flow over the time interval considered, which can be converted directly into CO_2 equivalent. A major challenge when establishing forest reference levels is minimizing uncertainties about activity data and emission factors, which together determine the accuracy of emission estimates.

1.3.2 Submission status of forest reference emission levels for Central Africa

At the time of writing, four Central African countries have submitted a forest reference emission level to the UNFCCC: the Republic of the Congo (2016), DRC (2018), Gabon (2021) and Equatorial Guinea (2020). CAR finalized its forest reference emission level in 2020, but has not yet submitted it to the UNFCCC. As the two most recent drafts have not yet undergone a technical evaluation, they are not commented on here, but do appear, for information, in Table 1.3. The forest reference emission levels of the Republic of the Congo, Gabon and DRC offer points of comparison, but also have salient differences in terms of the definitions, methods and data used.

Parameters of forest reference emission level submissions

While all three countries' forest reference emission levels cover their entire national territory, DRC's reference level is unique in that it is calculated by aggregating the estimated activity data for each of the country's 26 provinces. The calculation of activity data by province is justified in DRC by the country's large size and by the desire to be able to assess the impact of the various emission

Table 1.7: Overview of forest reference emission levels in Central Africa.

Country		Republic of the Congo	Gabon	Equatorial Guinea		Democratic Republic of the Congo		Central African Republic
Definition of forest		*Official & Technical*	*Official & Technical*	*Official*	*Technical*	*Official*	*Technical*	*Official & Technical*
	Area	0.5 ha	1 ha	0.5 ha	1 ha	0.5 ha	0.09 ha	0.81 ha
	Height	3 m	5 m	5 m	5 m	3 m	-	5 m
	Canopy cover	30%	30%	10%	30%	30%	50%	10%
Scope	**Activities**	Deforestation	Deforestation	Deforestation		Deforestation		Deforestation
		Degradation	Degradation	Degradation		-		Degradation
	Reservoirs	Above-ground biomass	Above-ground biomass	Above-ground biomass		Above-ground biomass		Above-ground biomass
		Below-ground biomass	Below-ground biomass	Below-ground biomass		Below-ground biomass		Below-ground biomass
		Deadwood biomass	Deadwood biomass	Deadwood biomass		-		Deadwood biomass
			Litter and soil organic carbon					Litter and soil organic carbon
								Harvested wood products
	Gases	CO_2	CO_2	CO_2		CO_2		CO_2, CH_4, N_2O
Scale		National	National	National		National		National
Periods	**Reference period**	2000–2012	2000–2009	2014–2018		2000–2014		2011–2018
	Accounting period	2015–2020	2010–2018	-		2015–2019		-
Activity Data	**Methodology**	*Sample-based (870 points)*	*Sample-based (665 points (primary sampling unit))*	*Sample-based (1,832 points)*		*Sample-based (21 323 points)*		*Sample-based (1,200 points)*
		& Bookkeeping (pixel archiving)						
	Data points	1	1	1		2		4
Emission Factors	**Source:**	National forest inventory	National forest inventory	IPCC (2006)		Pre-dating the national forest inventory		National forest inventory
	Number of strata	5	7	7		6		4
Forest reference emission levels	**Approach used**	Historical average	Historical average	Historical average		Linear projection		Historical average
	Adjustment	Yes	Yes	-		Yes		-

reduction policies and interventions implemented at the provincial level, in view of the local context. However, this choice has serious implications in terms of the work required to calculate activity data. Similarly, the Republic of the Congo and Gabon use the same official and technical definitions of forest, but DRC has introduced an "operational" definition that differs from the official definition of forest for technical reasons (see Table 1.3). This operational definition allows for the area of the reference samples to be adjusted to the spatial resolution of the map showing land use change (i.e. 30 x 30 m), given that this method uses the reference sample areas to describe the extent of the forest. Unlike the Republic of the Congo and Gabon, DRC does not consider forest degradation. However, the operational definition of forest in DRC means that emissions associated with tree cover loss that is much lower than that considered in the Republic of the Congo or Gabon will be taken into account. This should make it possible to more accurately quantify the country's forest-related emissions, which are often linked to small-scale land use changes (in particular, slash-and-burn agriculture). In addition to above-ground and below-ground biomass, the Republic of the Congo and Gabon include dead wood as a carbon reservoir when calculating their forest reference emission levels. Moreover, the Republic of the Congo and Gabon use the historical average to determine their forest reference emission levels, while DRC uses a linear projection. In line with the Forest Carbon Partnership Facility (FCPF) methodological framework, existing carbon stocks may be adjusted upward by up to 0.1% per year. The Republic of the Congo, Gabon and DRC all take advantage of this possibility.

Calculation of activity data

Two main methodological approaches can be used to calculate activity data. For the first method, considered state of the art, random reference samples from the whole territory are interpreted and stratified using the pixel change map (Olofsson et al. 2014). This sample-based approach was used to calculate the forest reference emission levels of the Republic of the Congo, Gabon, and DRC, with a respective 870, 665 and 21,323 samples interpreted using satellite images. The very high number of samples used in DRC is a direct result of the decision to quantify the activity data for each of the country's 26 provinces.

An alternative method, not adopted at the time, involves mapping changes in land use using satellite images to produce a map of changes. Activity data are then obtained by adding together the area of the pixels showing the transitions (from dense moist forest to cropland, for example). This *pixel-based* approach, based on data from Global Forest Watch, leads to seriously flawed results that underestimate cover loss in tropical moist forests in Africa by around 90% (Tyukavina et al. 2015).

Calculation of emission factors

All three countries use inventory data to calculate their forest reference emission levels. The Republic of the Congo uses data taken from the National Forest Inventory (NFI). This inventory, carried out between 2007 and 2015, covers the entire country, except the swamp areas in the east of the country. These data are converted to biomass estimates using a pan-tropical allometric equation that fails to account for variations in height-diameter allometry. This weakness is noted as a possible point of improvement in the forest reference emission level documentation. Gabon began collecting new inventory data in 2017 and in 2020 covered 104 non-mangrove forest sites. The pan-tropical allometric equation used converts tree diameter into above-ground biomass and takes account of variables like wood density and tree height. In DRC, the inventory data predate the national forest inventory, given that the first national inventory only started in 2018. While the country's emission factors were calculated using an allometric equation for estimating biomass that takes account of tree height, and therefore of variations in height-diameter allometry, using data from the first national forest inventory would significantly improve these estimates.

1.3.3 Forest reference emission levels at the provincial level: Case study of Maï-Ndombe province in the Democratic Republic of the Congo

Activity data and the associated emissions were estimated for Mai-Ndombe province in DRC for a 2005–2014 reference period and for an initial 2018–2019 accounting period in line with DRC's Programme Document and the Emission Reductions Payment Agreement (ERPA). The end date of the reference period aligns with that of the national forest reference emission level, but the start date is set at 2005 because the Carbon Facility's methodological framework requires a duration of around 10 years. The method used was based on good practices recommended by the IPCC. Such approaches use statistically unbiased estimators with known uncertainty. Strata were established using maps produced from remote-sensing data, making it possible to take a stratified random sample for the probabilistic analysis of Landsat and Google Earth time series reference data. The maps produced showed relevant forest cover transitions, in particular the dynamics of dense moist forest loss and the dynamics of secondary forest loss and gain. Landsat imagery was used to map the province. The reference data interpreted were used to calculate net activity data in relation to forest change with a target margin of error of ± 20 percentage points at the 90% confidence level for each activity class, which was achieved using 2,000 reference samples. The resulting area estimates were combined with national emission and removal factors to estimate emissions and removals at the province level. A reference level was calculated for emissions and another for removals to account for the inherent effects of removals.

The reference emission level was derived from the averages for shorter periods, 2005–2009 and 2010–2014, and was calculated based on annual emissions of 28,917,393 tCO_2/year and annual removals of -1,680,533 tCO_2/year, resulting in an average of 27,236,859 tCO_2/year. To this total, 5,788,886 tCO_2/year were added following the 0.1% adjustment (see *Contours des soumissions NERF*) giving a total of 33,025,746 tCO_2/year (see Tables 1.4 to 1.7 and Figure 17 for all figures). Over the reference period, there was a significant upward trend in emissions, with the 2005–2009 emission level of 18,092,216 tCO_2/year doubling to 36,971,610 tCO_2/year in 2010–2014. This situation justifies the inclusion of an alternative reference emission level based on a business-as-usual scenario. Although many business-as-usual adjustments are possible, a scenario that is conservative compared with other options was established by projecting a straight line between the first and last years of the reference period using the average emissions in the sub-period. Any other line between the two periods would be less conservative.

Estimated net emissions for the first two years of the accounting period, 2018–2019, were calculated based on emissions of 42,854,387 tCO_2/year and removals of -2,855,028 tCO_2/year, the latter calculated on the basis of projected rates of forest gain. This calculation results in net emissions of 39,999,359 tCO_2/year, well above the FCPF reference level, but below the conservative business-as-usual adjustment of 44,523,368 tCO_2/year for the same period. The business-as-usual scenario therefore shows an emission reduction of more than 4 million tCO_2/year over the 2018–2019 accounting period. This suggests that an upward trend in emissions over the reference period could justify a business-as-usual adjustment when assessing the performance of the emission reduction programme in Mayi-Ndombe province in DRC.

Table 1.8: Revised activity data from the University of Maryland for the reference period (2005–2014).

Land use change	Activity data (ha)	90% confidence interval (+/- ha)	Uncertainty
Deforestation, primary forest	154,643	18,685	12.1%
Deforestation, secondary forest	381,344	47,602	12.5%
Degradation	144,756	23,176	16.0%
Regrowth, primary forest	N/A	N/A	N/A
Regrowth, secondary forest	239,234	31,151	13.0%

Table 1.9: National emission factors (submission to UNFCCC).

Land use change	Emission factors (tCO_2/ha) Removal factors (tCO_2/ha/year)	90% confidence interval (+/- tCO_2/ha)	Uncertainty
Deforestation, primary forest	688.30	58.74	8.5%
Deforestation, secondary forest	351.23	104.14	29.6%
Degradation	337.07	61.64	18.3%
Regrowth, primary forest	N/A	N/A	N/A
Regrowth, secondary forest	-17.56	5.21	29.6%

Table 1.10: Revised reference emission level based on University of Maryland activity data and national emission factors.

Land-use change	Emissions / Removals (tCO_2/year)	90% confidence interval (+/- tCO_2/year)	Uncertainty
Deforestation, primary forest	10,644,095	1,574,557	14.8%
Deforestation, secondary forest	13,394,055	4,308,914	32.2%
Degradation	4,879,243	1,185,873	24.3%
Regrowth, primary forest	N/A	N/A	N/A
Regrowth, secondary forest	-1,680,533	524,297	-31.2%
Forest reference level	**27,236,859**	4,767,300	17.5%
Adjustment	**5,788,886**	569,825	9.84%
Adjusted forest reference level	**33,025,746**	4,801,234	14.54%

Table 1.11: Results of the emission reduction programme for the first reporting period.

Forest reference (emission) levels and emissions, 1st reporting period	Emissions / Removals (tCO_2/year)	90% confidence interval (+/- tCO_2/year)	Uncertainty
FCPF forest reference level - emissions	34,706,279	4,801,234	14.5%
FCPF - Baseline removals, 1st accounting period (2018–2019)	-1,680,533	524,297	31.2%
FCPF forest reference level	33,025,746	4,829,776	14.6%
Emissions, 1st accounting period (2018–2019)	42,854,387	18,814,673	43.9%
Removals 1st accounting period (2018–2019)	-2,855,028	738,285	-25.9%
Net emissions, 1st accounting period (2018–2019)	**39,999,359**	18,829,152	47.1%
Business-as-usual (BAU) emissions (2018–2019)	**44,523,368**		
Emission reductions, 1st accounting period (2018–2019) with FCPF adjustment	**-6,973,613**		
Emission reductions, 1st accounting period (21 Sep 2018 - 30 Jul 2019) with FCPF adjustment	**-5,977,382**		
Emission reductions, 1st accounting period (2018–2019) with BAU adjustment	**4,524,009**		
Emission reductions, 1st accounting period (21 Sep 2018 - 30 Jul 2019) with BAU adjustment	**3,877,723**		

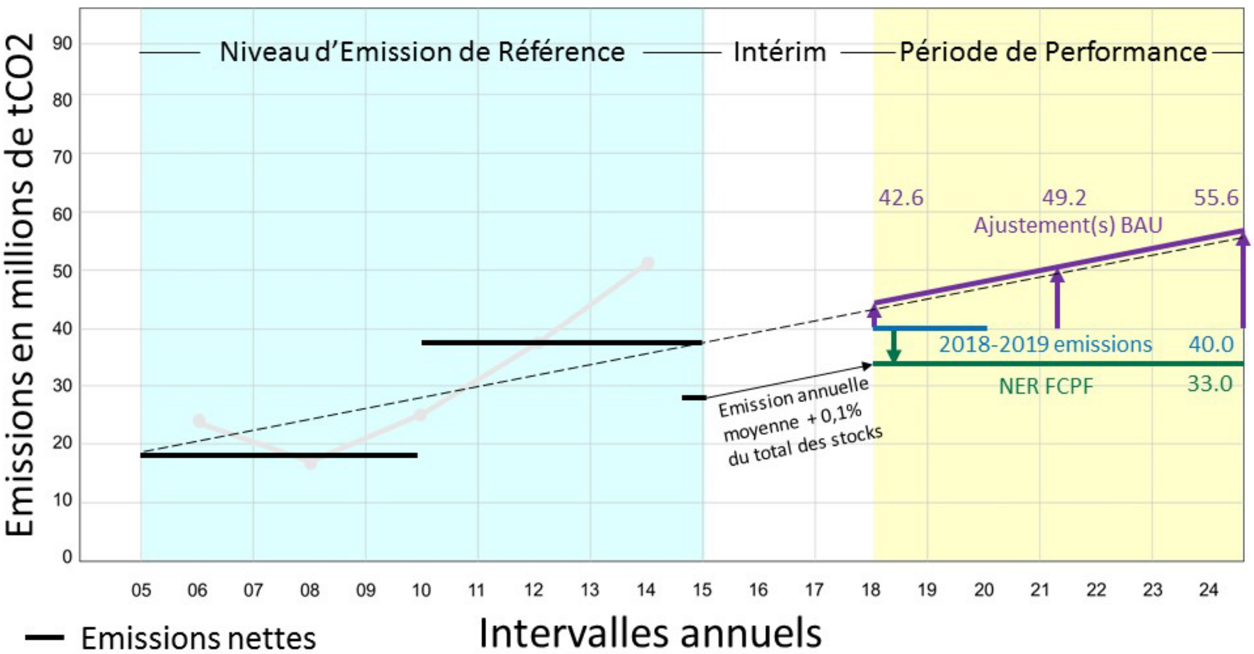


Figure 1.17: Graph showing the reference emission levels and accounting period for Mai-Ndombe province, DRC. Reference emission levels are shown as black lines, estimated emissions in the accounting period are shown in blue, and FCPF and business-as-usual adjusted reference emission levels are shown in green and purple, respectively. Gross annual emissions are shown in grey in two-year intervals and mirror the increasing emissions rate over the reference period.

Conclusions and outlook for forest monitoring in the Congo Basin

Since 2000, the loss of intact forests has accelerated in all Central African countries, with deforestation rates reaching highs over the past five years. If the current pace of deforestation and forest degradation continues, 27% of the undisturbed moist forest in Central Africa (including Angola and Uganda) that existed in 2020 will have disappeared by 2050.

Land-use policies are a valuable tool in the fight against deforestation and forest degradation. Protected areas, forestry concessions and community forests can significantly reduce forest loss and engage local people in the conservation of forests, while securing their livelihoods.

When it comes to monitoring deforestation and degradation at the national or sub-national level, methods for monitoring forest cover and the associated biodiversity will undoubtedly improve. New opportunities for monitoring forest ecosystems have opened up thanks to the launch of the Sentinel-1 and Sentinel-2 satellites in recent years and the availability of free Planet data through Norway's International Climate and Forest Initiative (NICFI). The spatial and temporal resolution of these data makes it possible to accurately monitor Central Africa’s tropical forests. The redundancy of the observation system and the long-term nature of the Sentinel satellite mission mean that remote sensing is likely to be the main operational source of information for monitoring forest change in the coming decades.

The GEDI and Biomass satellites will improve the quality of biomass mapping, which still has many weaknesses. The development of networks for the collection of field data will continue to be essential for the adjustment and evaluation of the relationships between sensor measurements and biomass reference estimates made on the ground.

Finally, it is important to significantly increase the transparency and traceability of monitoring systems and to ensure the independence of national authorities when they produce their reports. The disconnect between the people monitoring the forests and the countries conserving them negatively affects the legitimacy, effectiveness and dissemination the information generated. It is therefore important to hand over the leadership of forest monitoring efforts in the Congo Basin to national experts from COMIFAC member countries, while also harmonizing the methods and forest type definitions used in the region.