Land Use Policy 134 (2023) 106922

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Small scale agriculture continues to drive deforestation and degradation in fragmented forests in the Congo Basin (2015–2020)

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ARTICLE INFO

Keywords:
Forest
Deforestation
Degradation
Drivers
Agriculture
Climate change

ABSTRACT

The Central African region hosts the largest continuous tract of forest in Africa, regulating global climate while providing essential resources and livelihoods for millions of people and harbouring extensive biodiversity. Extractive industries, infrastructure development and industrial agriculture have often been cited as major threats to these forests and are expected to increase. A regional collaborative effort has produced the first systematically validated remote sensing assessment of deforestation and degradation drivers in six central African countries for the 2015–2020 time period. Multiple, overlapping drivers are assessed through visual interpretation and show that the rural complex, a combination of small-scale agriculture, villages, and roads contributes to the majority of observed deforestation and degradation. Industrial drivers such as mining and forestry are less common, although their impacts on carbon and biodiversity could be more permanent and significant than informal activities. Artisanal forestry is the only driver that is observed to be consistently increasing over the study period. Our assessment produces information relevant for climate change mitigation and land use planning which requires detailed information on multiple direct drivers to target specific activities and investments.

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https://doi.org/10.1016/j.landusepol.2023.106922
Received 28 January 2023; Received in revised form 31 August 2023; Accepted 18 September 2023
Available online 7 October 2023

1. Introduction

1.1. Forests and climate

Central African forests play a major role in mitigating anthropogenic climate change, acting as an important carbon sink (Harris et al., 2021; Houghton, 2005; Justice et al., 2001; Mitchard, 2018). Deforestation, through forest conversion to other land uses is the second largest source of global carbon emissions after fossil fuel combustion (IPCC, 2014; Le Quéré et al., 2016; Smith et al., 2014; van der Werf et al., 2009), while the emissions associated with forest degradation remain uncertain and mostly unaccounted for or underestimated (Pearson et al., 2017). These forests are also providing important natural resources to increasing populations, supporting food security and livelihoods for local communities, and are home to a large proportion of the world's terrestrial biodiversity (Oldekop et al., 2020). The ecosystem services provided by intact tropical forests when free from human influence and disturbance, are even larger (Maxwell et al., 2019). Despite the intrinsic link to human health and economies, forests remain under constant threat of disturbance and conversion to other land uses. Climate change further threatens the close relationships between humans and forests including traditional ones, affecting all stakeholders who continue to benefit from forests (Bele et al., 2015; Sonwa et al., 2012).

There have been many targeted efforts in the last decade to accurately estimate deforestation and forest degradation over time using earth observation data, to help countries meet their climate targets and engagements and protect their natural resources. In order to meet these objectives through decision-making at national or subnational scales and to implement appropriate land use policies, a clear understanding of the causes and drivers of forest change is essential.

This study assesses the direct drivers of deforestation and degradation in six countries supported by the Central African Forest Initiative (CAFI), a coalition of donor and partner nations aiming to reduce forest loss while promoting sustainable development in a globally important carbon sink (Crezee et al., 2022; Dargie et al., 2017). Despite being such an important resource for the planet, the Congo Basin is relatively understudied and receives significantly less funding than countries on other continents (Eba'a Atyi et al., 2019; White et al., 2021). A number of carbon finance opportunities can help fill these gaps, such as those targeting High Forest Low Deforestation (HFLD) countries, results-based payments, bilateral agreements and other results-based mechanisms. Robust spatial information on the drivers of forest disturbance is needed to focus specific interventions, investments and activities.

1.2. Direct Drivers of Forest Disturbance

Monitoring deforestation and disturbance is one aspect of monitoring, whereas the understanding of the direct drivers of forest change is critically important for implementing required mitigation practices and policies. For example, addressing the impacts of activities of large companies will be different than working with individual smallholders concerned with local subsistence activities (Jayathilake et al., 2021; Minang and van Noordwijk, 2013; Moonen et al., 2016). There are many claims of large potential threats to Central African forests from infrastructure development (Kleinschroth et al., 2019; Laurance et al., 2017, 2015; Lhoest et al., 2020; Mosnier et al., 2014), industrial mining and extractive industries (Edwards et al., 2014; Tegegne et al., 2016; Weng et al., 2013), industrial agriculture (Feintrenie, 2014; Ordway et al., 2019) and large-scale forestry (Justice et al., 2001; Laurance et al., 2006). More recently, oil exploration is expected to begin in the heart of the Congo basin's vast swamp forests (Crezee et al., 2022; Delvaux and Fernandez-Alonso, 2015; Maclean and Searcey, 2022). These threats may have yet to realize, while most studies identify expanding small-scale agriculture as the primary cause of forest loss (Branthomme et al., 2023; Curtis et al., 2018; Kissinger et al., 2012; Tegegne et al., 2016; Tyukavina et al., 2018). Some cite forestry activities as having the greatest impact on forests (Justice et al., 2001) or little to no effect (Chervier et al., 2024). It is important to understand and assess all potential drivers because of their different impact on carbon stocks and emissions (Houghton, 2012), biodiversity (Kissinger et al., 2012; Shapiro et al., 2021a) or local communities (Caradang et al., 2013; Rademaekers et al., 2010). Industrial drivers (agriculture, mining) can have more permanent and long-lasting environmental and social impacts compared to small-scale or artisanal activities (Reed et al., 2013; Tchatchou et al., 2015). In contrast, small-scale agriculture may be restored or regenerate naturally and may quickly recover biomass and biodiversity (Mangaza et al., 2022).

This study addresses the proximate or direct drivers of Deforestation and Degradation (DD), defined as the immediate human actions that directly affect forest cover and biomass (Geist and Lambin, 2002; Kissinger et al., 2012; Meyfroidt, 2016) which is different from post-deforestation land use. As explained above, we assess the presence of multiple overlapping direct drivers on both deforestation and degradation as this reflects the realities of local processes, stakeholders and decisions that result in DD (Moonen et al., 2016). Additionally, as this is a remote sensing study, we are unable to determine the extent and impact of indirect or underlying drivers, such as population growth, external demand for resources, which are addressed in more detail in the discussion.

For this research, we uniquely address drivers at a relevant local scale. Many studies only identify one possible direct driver (Curtis et al., 2018; De Sy et al., 2019; Tyukavina et al., 2018), whereas multiple, overlapping drivers have been found to be better correlated with changes in forest cover at smaller scales (Ferrer Velasco et al., 2020). This provides important contextual information to properly define and focus interventions and mitigations, for example, agriculture associated with industrial activities such as mining or forestry in contrast to isolated, rural, subsistence agriculture.

1.3. Operational definitions of deforestation and degradation

The Food and Agriculture Organization of the United Nations (FAO) provides a generally accepted definition of deforestation as "a conversion of forest to other land use, or a permanent reduction in tree cover below an established forest definition threshold" (FAO, 2016). Meanwhile, forest degradation definitions vary widely, so there is an urgent need for standard operational definitions to support monitoring, decision making and restoration efforts (Sasaki and Putz, 2009). Several definitions for degradation, such as the reduction of ecosystem services delivery, are very broad and difficult to quantify. We define forest degradation for the purposes of this research, and in contrast to deforestation, as "a permanent or temporary change in forest cover that does not fall below the established forest definition threshold" – which are disturbances in areas that remain forest. These operational definitions enable the assessment of deforestation separately from degradation through remote sensing and visual interpretation.

1.4. Objectives

This goal of this research is to develop an open-source, statistically validated assessment of deforestation and degradation (DD) and the associated direct drivers at regional scale covering six countries of Central Africa over the 2015–2020 study period. The identification of distinct forest classes, types of change and the presence of direct drivers is visually interpreted by a team of regional experts over a stratified random sample of points. The relative contribution of drivers and their combinations are assessed by forest types, fragmentation classes and their associated biomass. The methodology is globally applicable, replicable, and open access to support decision making activities such as land use planning and prioritization as well as for validating other satellite sources of data for monitoring forest ecosystems.

2. Methods

The methodological approach includes analysis of dense time series of satellite imagery to identify potential areas of deforestation and degradation in the study area, followed by a validation of a representative sample of points through visual interpretation to follow the best practices for sample-based area estimation (Olofsson et al., 2014) and the identification of direct drivers. Given the release of freely available satellite data and the need for comprehensive forest monitoring, there has been an associated increase in interoperable, open source and cloud-based platforms to provide toolkits for remote sensing, land cover mapping and forest monitoring (Tenneson et al., 2018), including Google Earth Engine (GEE) and FAO's SEPAL (https://sepal.io), enabling countries to produce their own monitoring data. The methods use entirely open-source software, as described in Fig. 1.

2.1. Study area: Central Africa

The six countries of Central Africa (Fig. 2) are home to the largest continuous tract of tropical forest in Africa, a crucial biome supporting global climate, rainfall and water cycles (de Wasseige et al., 2015; Washington et al., 2013). The region is known for its largely intact forests (Grantham et al., 2020; Shapiro et al., 2021b) globally significant carbon stocks (Dargie et al., 2017; Harris et al., 2021; Pan et al., 2011) and unique biodiversity (WWF, 2006). Low access to infrastructure, notably electricity (International Energy Agency, 2022), a high reliance on natural resources and rapid population growth, coupled with vulnerability to climate change are expected to place additional pressures on these forests. The countries in the region score relatively low on the human development index (UNDP, 2022), signalling the potential for rapid economic growth that can significantly compound existing pressures on natural ecosystems (Megevand, 2013; Tchatchou et al., 2015) – creating a complex situation to meet the needs for sustainable development investments, global climate targets all while ensuring food security (Mosnier et al., 2014).

2.2. Image composites

Best pixel image composites were developed to provide cloud-free imagery for the 2015 baseline year. In some locations, up to three years of data (as early as 2012) were needed to fill gaps from clouds. The SEPAL optical mosaic module was used to develop medoid composites from all Landsat satellites, applying BRDF correction and excluding pixels in the 50% percentile of NDVI values. A radar composite was created from ALOS PALSAR 2015 backscatter data, with a layover/shadow mask applied, with a Quegan filter (Quegan and Yu, 2001) and an additional band for the radar forest deforestation index (RFDI, Mitchard et al., 2012).

2.3. Percent tree cover

For the integration of national forest definitions, a percent tree cover product (0–100% at 30 m resolution) for the year 2015 was created by classifying selected samples of cloud-free PlanetScope images (5 m resolution) from 2015 in each country using 824 manually digitised points and a Random Forest classifier in Google Earth Engine (Gorelick et al., 2017). These sample forest/non-forest masks were upscaled to percent tree cover at 30 m resolution, from which 5139 random tree cover samples were collected as training data for a Random Forest regression model applied to an image stack of Landsat, Sentinel-1 and ALOS PALSAR composites and an additional 19 derived spectral indices, and further refined using available canopy height data available canopy height data (Potapov et al., 2021).

2.4. Regional land cover

We developed a regional land cover map to define 12 types of forest cover, and 7 types of non-forest (Table 1), synthesized from vegetation classifications from each of the six countries and harmonising them using the universal Land Cover Classification System (LCCS) framework (Di Gregorio, 2005).

Landsat satellite image composites for the baseline year, along with auxiliary information on elevation (Farr and Kobrick, 2000), the percent tree cover dataset, and water sources (Pekel et al., 2016), were classified. A supervised training algorithm was executed in SEPAL using the random forest machine learning approach, calibrated with 2190 training points provided by partners and derived from visual interpretation of 5 m resolution image mosaics for 2015–2020 provided by Planet, through a program financed by the Norwegian Government (NICFI), along with other high-resolution images using Collect Earth Online, a tool provided by the Open Foris Initiative of the FAO (Saah et al., 2019). Additional cleaning steps were applied, including defining montane and

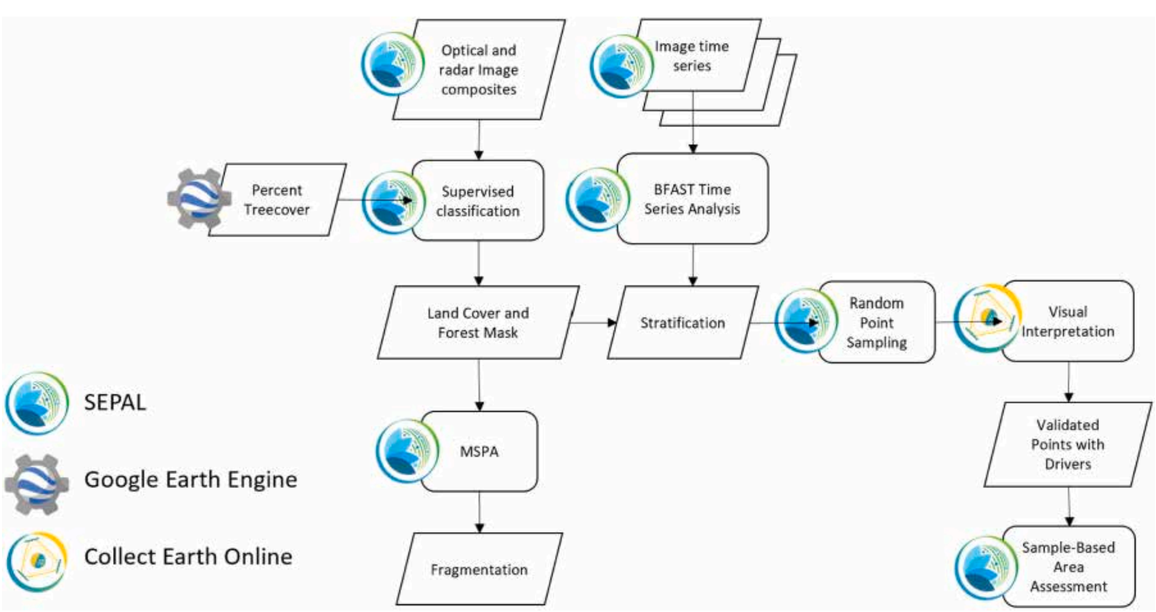


Fig. 1. Methodological approach for image processing and validation for sample-based area assessment using open source tools.

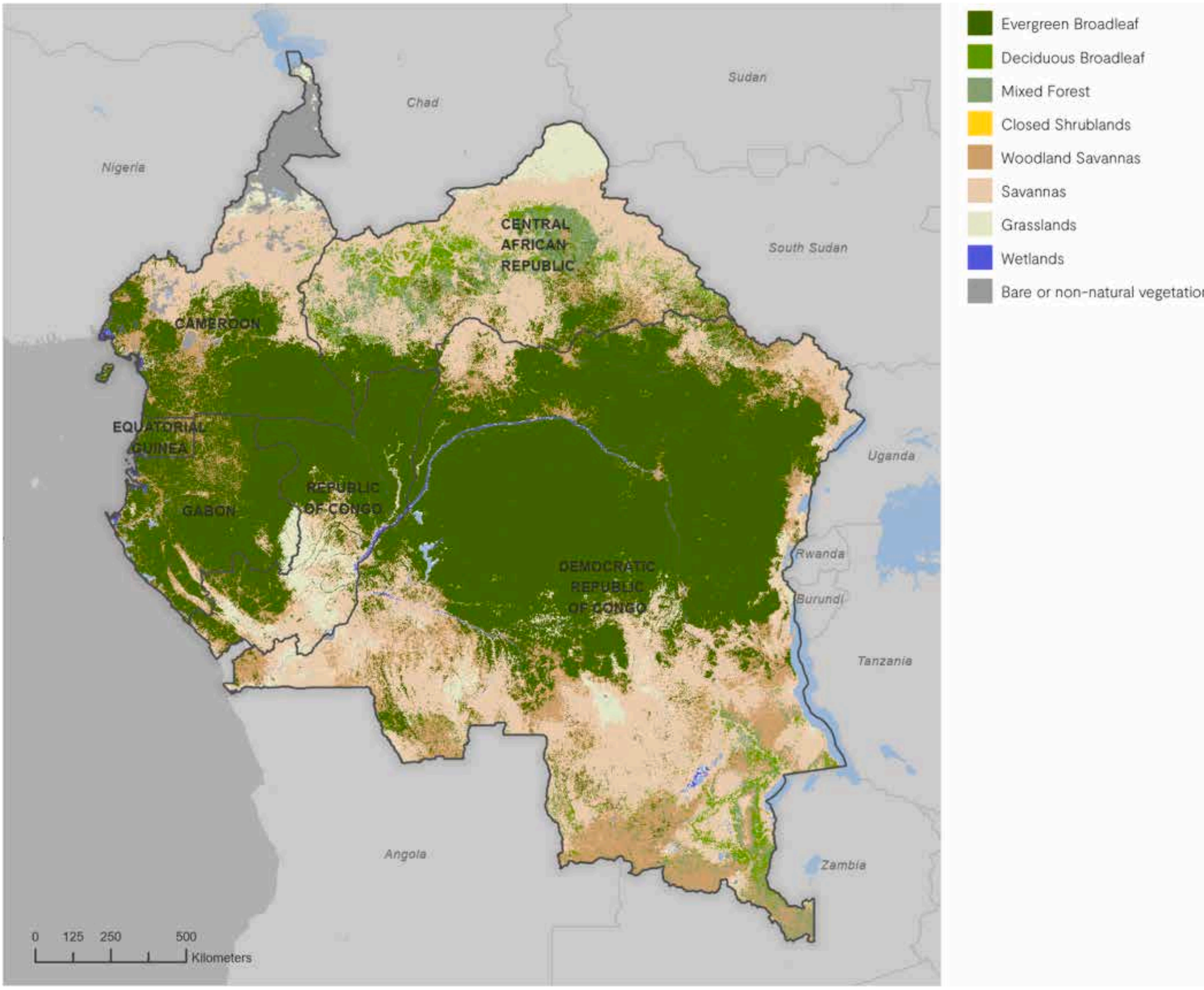


Fig. 2. The study area covers six countries of Central Africa (Cameroon, Central African Republic, Equatorial Guinea, Gabon, Republic of Congo and The Democratic Republic of Congo) encompassing more than 4.04 million km^2 in Central Africa comprising various forest types and savannas (data Source: MODIS MCD12Q1 Land Cover (Friedl and Sulla-Menashe, 2019)).

sub-montane forests according to elevation criteria; removing mangroves that were mapped inland or above 35 m elevation; data on seasonal and permanent water areas (Pekel et al., 2016) were used to identify aquatic grasslands and water bodies, while the Global Human Settlement Layer (GHSL; Pesaresi et al., 2016) was used to correct the developed areas class. We integrated the official 2015 national land cover data for Gabon (Boucka et al., 2021). These classes were recoded into a forest/non-forest map based on the appropriate national forest definition (% tree cover, canopy height) to effectively mask and target the analysis area.

2.5. Change detection

We primarily used the Breaks for Additive Seasonal and Trend (BFAST) dense time series change detection algorithm to identify forest disturbances (Verbesselt et al., 2010) and create the stratification for sample based area assessment and selection of samples to validate and identify drivers. BFAST is an iterative process which estimates the timing, magnitude, and direction of change of an index or a decimal value over a monitoring period compared to a historical time period. The normalised difference forest index (NDFI) was selected for assessment in BFAST, as it is a composite of fraction images which are sensitive to canopy disturbance in tropical forests (Souza et al., 2005). Landsat time series were compiled from January 1, 2012, to December 31, 2020, to encompass a 3 year historical time period to calibrate seasonal dynamics, and a monitoring period from January 1, 2015 to December 31, 2020. It should be noted that the detection of small-scale disturbances is challenging due to the spatial resolution of Landsat, therefore the detection of degradation in particular is limited (Lima et al., 2019).

2.6. Fragmentation

We apply the Multi-Spatial Pattern Analysis (MSPA) tool from the GuidosToolbox (GTB; Vogt and Riitters, 2017) to the forest mask to define core, inner and outer edge, corridor and patch forests (Table 2), using an edge size of 9 pixels (Shapiro et al., 2016). The process was executed in Guidos Toolbox Workbench (GWB; Vogt et al., 2022) version 1.8.8 on Ubuntu 22.04 LTS.

Table 1
Regional Land cover classification system. * In Central African Republic and Cameroon, shrub savannas with > 10% shrub cover with height greater than 5 and 3 m respectively were identified as forest, in adherence to the national forest definitions.

Code DDD	Forest/non-Forest	Name	Description
1	Forest	Dense Forest	Dense humid primary evergreen forest on terra firme, >60% tree cover
2	Forest	Dense Dry Forest	Dense dry forest, >60% tree cover, with dry seasons
3	Forest	Secondary Forest	Open forest, 30-60% tree cover, degraded or secondary
4	Forest	Dry Open Forest	Dry open forest, 30-60% tree cover, with dry seasons
5	Forest	Sub-Montane Forest	Forest >30% tree cover, 1100-1750m altitude
6	Forest	Montane Forest	Forest >30% tree cover >1750m altitude
7	Forest	Mangrove	Forest >30% tree cover on saline waterlogged soils
8	Forest	Swamp Forest	Swamp mixed forest, >30% tree cover, flooded > 9 months
9	Forest	Gallery Forest	Riparian forest in valleys or along river edges
10	Forest	Mature Forest Plantation	Tree cover >15%, cultivated or managed
11	Forest	Woodland Savanna	Woodland savanna 15-30%, tree cover > national forest definition
12	Forest*	Shrubland Savanna	Shrubland savanna >10% shrub cover > national forest definition
13	Non-Forest	Herbaceous Savanna	Grassland savanna <15% tree cover
14	Non-Forest	Aquatic grassland	Grassland regularly flooded
15	Non-Forest	Bare Land	<15% vegetation cover
16	Non-Forest	Cultivated Areas	Cultivated vegetation >15% vegetation cover
17	Non-Forest	Developed Areas	Human dominated and artificial surfaces
18	Non-Forest	Water	Water > 50%
19	Non-Forest	Shrubland Savanna	Shrubland savanna >10% tree cover < national forest definition

2.7. *Biomass assessment*

We calculate the average and standard deviation of 2010 above-ground biomass from the ESA BIOMASS mission (Santoro and Cartus, 2021) for each vegetation type and fragmentation class using the zonal statistics tool in a GIS.

2.8. *Visual interpretation*

Validation data points were selected for visual interpretation to identify forest type, presence of change, type of change (deforestation, degradation), date of change and presence of one or more direct drivers. A stratified random sampling scheme was developed to select spatially balanced samples proportional to the size of the map classes of forest type and change (Pagliarella et al., 2018). At least 150 random points per change class were selected, with more points for larger map classes (N = 11,078), along with a random sample of stable points from all land cover classes (N = 1,192). Visual interpretation of all points was performed using the Open Foris tool Collect Earth Online, using available the high-resolution optical image mosaics from Planet.

Samples were uploaded to Collect Earth Online for visual interpretation by a group of 60 experts from the project technical committee developed guidelines and agreed definitions and who were then trained in the use of the tool. The form which was iteratively tested and amended before proceeding to the validation phase which extended over a period of 5 months, owing to the fact that each point was validated by three independent users to avoid user bias. The final labelling of each point was determined by the agreement of 2 or more users (McRoberts et al., 2018); for differences in the identified date of change, the median value between users was selected.

Table 2
Forest fragmentation classes ordered from intact to most fragmented from MSPA (Soille and Vogt, 2009).

Class	description	fragmentation
core	interior forest area: pixels surrounded by other forest	low
inner edge	forest bordering non-forest perforation inside core forest	
outer edge	forest bordering exterior non-forest	
corridor	forest pixels (without core) connected to different core areas as either end	
patch	forest islands too small to contain core forest	
		high

2.9. Direct drivers

We first evaluate the location of disturbances with respect to roads and settlements, using available vector road data (Kleinschroth et al., 2019) converted to raster with the same resolution as the forest cover and change products (30 m). Best available settlement data (Santoro et al., 2021) were scaled to the same resolution combined with the roads to create a combined layer. Euclidean distance was calculated in QGIS (version 3.22.7; QGIS.org, 2022) and classified into 500 m buffer rings, and the area of deforestation and degradation for each year was summed in each distance class.

The identification of multiple drivers allows the understanding of the local context. We quantify the presence of one or more direct drivers in 2 km plots located around areas of observed DD. Eight observable drivers were defined according to their visibility in high resolution satellite imagery available In Collect Earth Online. One or more drivers were observed within a 2 km plot around all sample points. Drivers that could not be categorised into the defined categories (flooding, natural fires, or no visible cause) were labelled "other."

The unique drivers associated with deforestation or degradation were identified through their characteristics in high resolution satellite imagery and are described in Table 3. These elements were integrated into a classification guide and implemented through trainings of interpreters.

All validation points with observed drivers were also assessed according to forest type, fragmentation class and assessed according to their relative contribution to annual deforestation or degradation. Drivers were also grouped into common archetypes, which are further described in the Results.

3. Results

The outcomes of the analysis include the mapping and quantification of forest and land cover types, an assessment of fragmentation, and the associated drivers in each of these classes. Furthermore, we evaluate the presence of drivers in relation to roads and developed areas, and the analysis of the overlap of drivers, grouped into archetypes. The relative contribution of driver groups over time provides an understanding of the influence of each direct driver in time and space.

3.1. Regional forest cover

Land cover and forest types were mapped for the initial year of the study to provide baseline information on the study area and limit change detection analysis to nationally defined forest areas. The resulting forest mask (Fig. 3) includes all forest types (including woodland savannas, dry open types) derived from supervised classification, validated with 12,260 visually interpreted points and an estimated overall area-weighted accuracy of 71.14%. The classification tends to overestimate forest area (commission errors 28.6%), particularly in the woodland and shrubland savannas in northern Cameroon.

The sample-based area estimates a total of 247.8 ± 3.65 million ha of forest cover over the Congo Basin, or about 61.2% of total land area. Of these, 52% are core, intact forests, while 4.2% and 13% are inner and outer edge respectively, 27.4% corridor forests and 3.4% in small patches or islands (Fig. 4). A large intact forest block extends throughout the tropical forest zone in southeast Cameroon, Gabon, Republic of Congo and Democratic Republic of Congo, with several large contact patches in central Cameroon and the Central African Republic.

3.2. Disturbances by forest type

According to visually validated data, we see an overall decrease in disturbances since 2017. We evaluate the trends of annual DD associated with each type of forest and its estimated above-ground biomass (Fig. 5). DD are largely occurring in dense forests, which are also the most common, followed by dry open and secondary forests. While most forest types are dense tropical evergreen (59% of the region's forests), we observe a relatively lower proportion of disturbances in this class (<30%), meaning DD is less likely to occur in these types and tend to be focused in other forest types. For example, dry open and secondary forests comprise a relatively small proportion of forest area (10.3% and 6.4% respectively) yet make up a relatively larger proportion of annual disturbances (>15% and >10% respectively) indicating a much greater likelihood of deforestation or degradation, although these forests store relatively low above ground biomass. Higher carbon density ecosystems make up a lower proportion of annual changes.

3.3. Forest disturbance and fragmentation

Forest disturbances are disproportionately occurring in corridor forests (Fig. 6), which are about 27% of all forest area but comprise over 60% of annual deforestation and degradation. These forests have relatively low above-ground biomass compared to intact core forests. While over half of the region's forests are intact, only a small percentage of disturbances are occurring in these areas. Both deforestation and degradation are increasing in small patch forests, the most fragmented class with the least biomass.

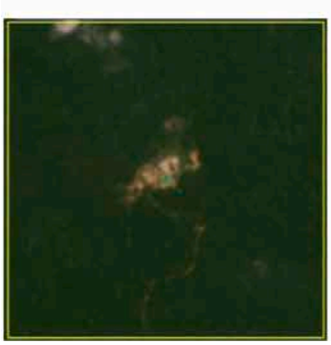
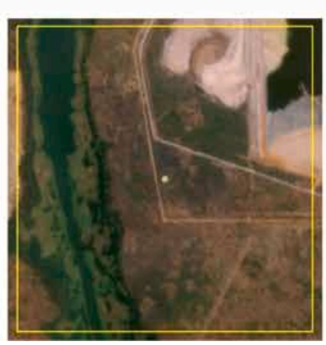
3.4. Direct drivers of disturbance

We confirm that most of our detections of DD are anthropogenic by assessing forest disturbances with respect to human presence and infrastructure. We observe that about 80% of all deforestation is located within 3 km of the nearest road or settlement (Fig. 7). In contrast, degradation generally extends slightly further, with 80% of degradation occurring within 4 km of the nearest road or settlement.

Next, we assess the presence of direct drivers from visually interpreted sample plots. Of all plots with the presence of an identified forest disturbance (N = 3811), the most commonly observed driver was artisanal agriculture, followed by infrastructure, artisanal forestry and settlements (Fig. 8). A majority of plots have more than one driver observed, with only 20% of all change plots with a single driver identified. The most common number of drivers is 2 (N = 1018), followed closely by 3 (N = 1006).

The four most common drivers are also commonly observed together, while certain drivers never overlap, for example industrial mining is only found with few of the other drivers and is never found with industrial agriculture.

Table 3
A total of eight direct drivers were defined by their specific characteristics identifiable in high resolution satellite imagery.

Artisanal Agriculture: Small irregular fields, generally less than 5 ha	Industrial Agriculture: Large regular fields of homogenous crops
	
Infrastructure: Roads or paths suitable for vehicular traffic	Settlements: Presence of houses, buildings, huts or other built-up features
	
Artisanal forestry: Forest with small canopy gaps or perforations and felled trees, more often without logging roads	Industrial forestry: Large consistent cuts (>5ha) and felled trees, presence of logging roads, skid trails
	
Artisanal mine: Small muddy clearings, often along waterways with turbid water	Industrial mine: Extensive infrastructure, open pits and exposed soils
	

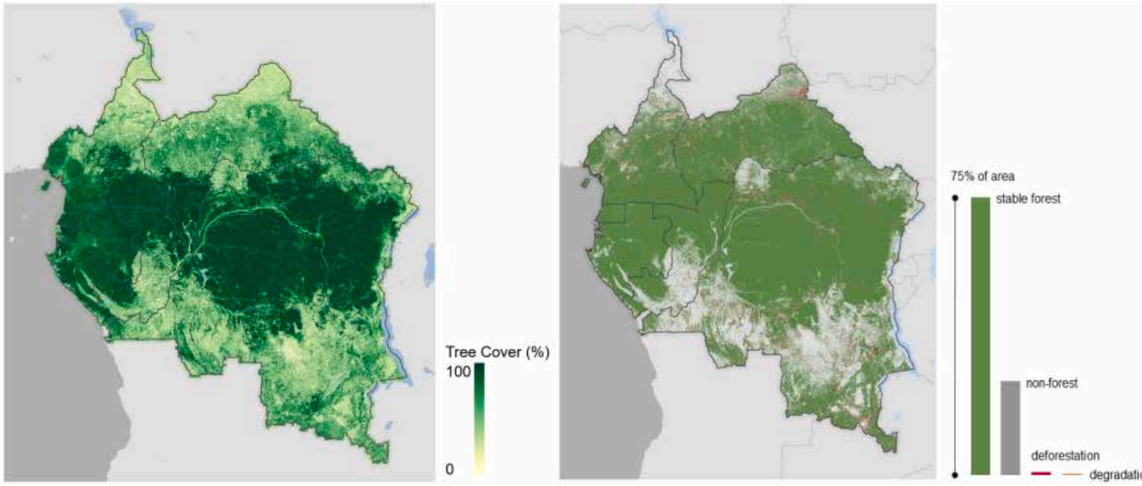


Fig. 3. Percent tree cover (left) shows percent tree cover per 1 ha pixel. Forest cover (right) in the Congo Basin countries integrates four different national definitions, which may result in border effects, notably between the Democratic Republic of Congo and Central African Republic.

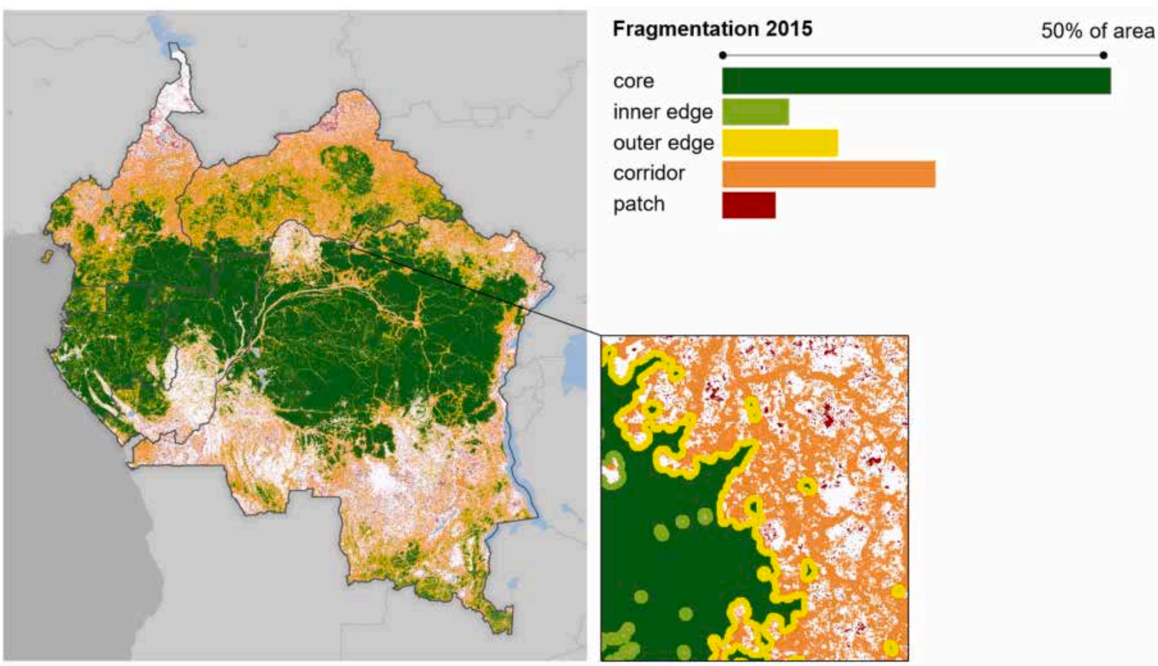


Fig. 4. Forest fragmentation (2015) derived from Morphological Spatial Pattern Analysis (MSPA) shows large areas of core forest in the central forest belt with some large patches in the Central African Republic. The inset shows how core forest can be perforated, creating inner edges, outer edges transition to fragmented corridor forests and small isolated patches.

3.5. Representative driver archetypes

To address the overlap of drivers and derive local context, we identify archetypes, or common driver combinations which represent realities and processes on the ground. Common driver combinations were grouped according to drivers with the most permanent potential impact (for example, industrial activities such as mining), and frequent occurrence with other drivers (e.g., mining activities are associated with infrastructure and agriculture for local workers). The overlapping drivers were grouped according to their combinations shown in Table 4. Due to the wide definition of the "other" driver category, it was not included in the grouping (and it was never observed alone).

The most common archetype consists of at least three drivers, which include artisanal agriculture, roads and settlements, and is representative of the agricultural mosaic, or so-called "rural complex" which is a particular feature of the study region (Molinario et al., 2020, 2017, 2015; Verhegghen et al., 2012).

We assess these archetypes in space and time (Fig. 9). The rural complex has the largest contribution to DD in all years and is decreasing before increasing in relation to deforestation, and relatively stable with regards to degradation. The presence of artisanal forestry (observed alone), and agriculture associated with infrastructure are increasing over time. There are similar trends for degradation, of which artisanal forestry has a greater contribution than for deforestation. Industrial drivers related to forestry, agriculture and mining are generally observed to be stable or decrease.

Each archetype was observed in relation to fragmentation class. Fig. 10 shows the overall distribution of fragmentation classes over the entire study region, and the proportion of each class associated with each archetype. Although most forests are in the intact core class, and

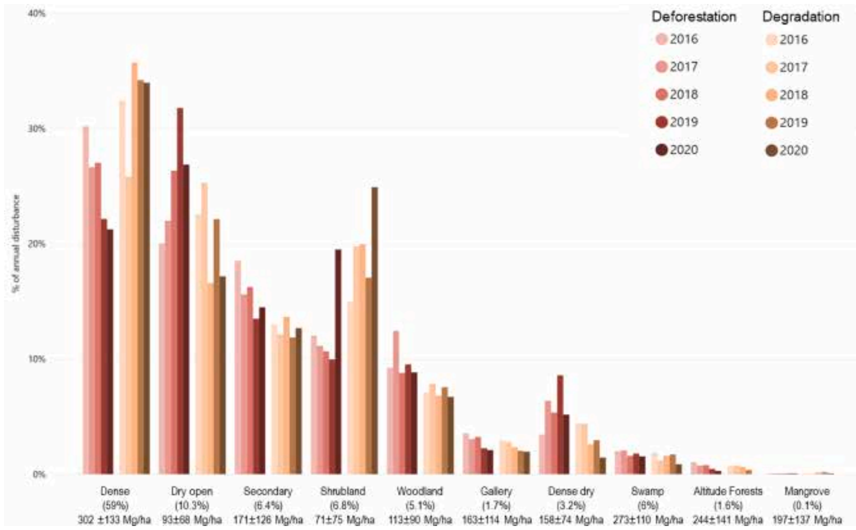


Fig. 5. Proportion of annual deforestation (left bars in red) and degradation (right bars in orange) by forest type. The proportion of each forest type as a percentage of regional forest area is shown in parentheses, and the mean and standard deviation of above-ground biomass derived from the ESA Biomass product (Santoro and Cartus, 2021) for 2010 is shown in Mg/ha.

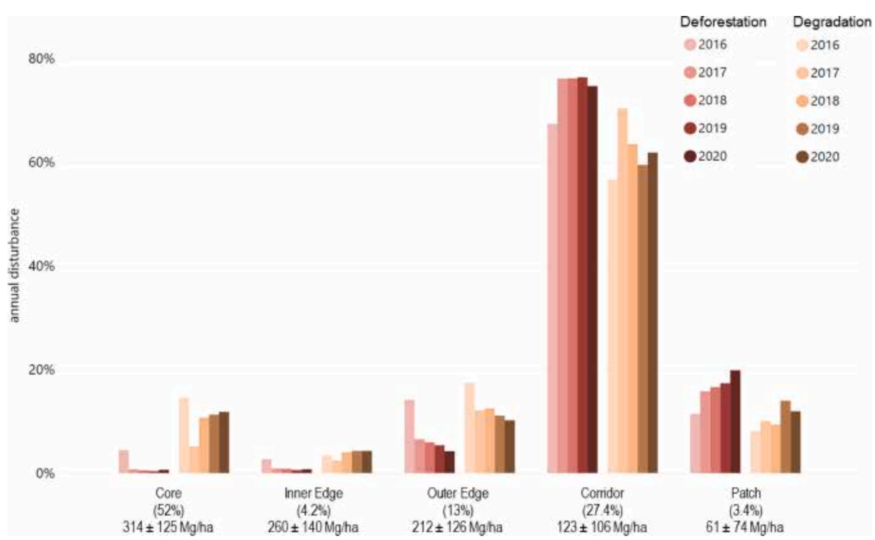


Fig. 6. The proportion of annual disturbance by fragmentation class, shown with the proportion of regional forest in each class and average biomass estimated from ESA Biomass 2010 (Santoro and Cartus, 2021). While core forests are the most common, with highest biomass, changes are mostly occurring in fragmented corridor forests, which store less biomass.

over a quarter are corridors, drivers are disproportionately affecting fragmented forests albeit differently. Industrial activities such as forestry, forestry and agriculture affect core forests more than other drivers, along with artisanal mining and forestry.

4. Discussion

4.1. Mapping all of Central Africa's Forests

We assess forest cover over the entire area of the study region, integrating four unique forest definitions for a comprehensive forest monitoring of tropical and seasonal dry forests. The wide diversity of vegetation types in Central Africa presents significant challenges for mapping forest with EO due to interannual dynamics and heterogeneity, and as a result many efforts are often focused on tropical dense forest despite being technically considered forest according to national definitions (Bastin et al., 2017). The ecosystems outside the tropical zone are nevertheless widely present in Africa, important to global carbon cycles, local livelihoods and biodiversity hotspots (Grace et al., 2006; Janzen, 1988) and expected to rapidly expand as a result of climate change making them important to currently assess (Huang et al., 2016). We overcome the obstacles to mapping dry and open forest via the application of specific national forest definitions applied to high-resolution imagery with visual interpretation, and sensor fusion classification approaches to produce the percent tree cover map.

4.2. Fragmented forests

The fragmentation analysis identified more than half of the region's forest as intact, including swamp forests which are also known store the largest carbon stocks (Lewis et al., 2009). We identify several large patches of core forests observed in the Central African Republic and central Cameroon which are not identified as Intact Forest Landscapes (IFLs; Potapov et al., 2017, 2008) but nevertheless are large, continuous and not significantly affected by anthropogenic activities (Grantham et al., 2020). We observe disturbances to occur mostly in already

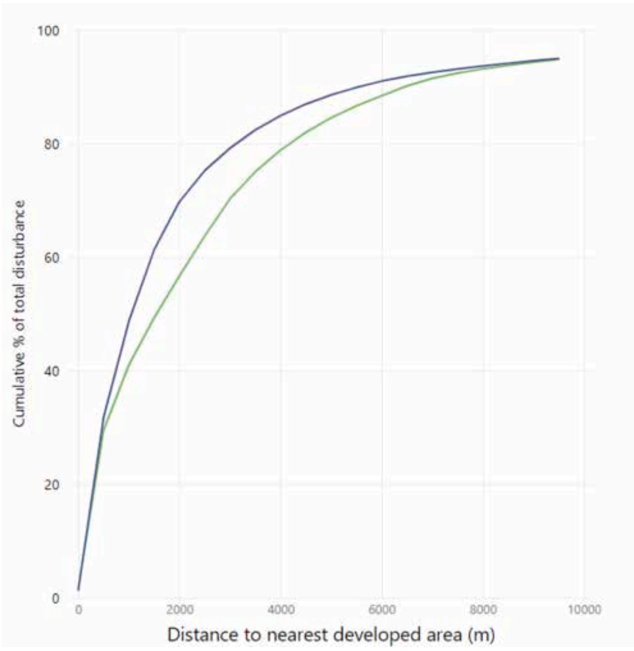


Fig. 7. Cumulative proportion of deforestation and degradation relative to distance to nearest road or settlement shows that half of all deforestation occurs within 1.5 km of developed areas while degradation tends to be observed at greater distances.

fragmented forests, which are more likely to contain smaller trees, open canopies and lower biomass which are easier to access and clear and as a result may have lower species diversity (Chaplin-Kramer et al., 2015; Haddad et al., 2015). More specifically, the most affected forests are corridors which are significant functional components of the forest ecosystem spatial structure (Vogt et al., 2007) indicating the need to promote conservation activities outside of highest value, intact forests through what are known as "integrated landscape approaches" incorporating multiple land uses that balance human activities with conservation (Reed et al., 2015). Disturbances were also found to be increasing over time in small forest patches, which follows published observations of greater forest loss in small fragments with non-primary forest, as

Table 4
The observed combinations of drivers were grouped into thematic classes or archetypes based on specific criteria.

Archetype	Notes	# of plots
Rural complex	Artisanal agriculture with roads and settlements, with or without artisanal forestry, and no presence of industrial drivers	2607
Artisanal forestry	Artisanal forestry with or without "other" driver, or with settlements or roads without any artisanal agriculture	187
Industrial agriculture	Industrial agriculture and other non-industrial drivers	253
Industrial forestry	Industrial forestry and other non-industrial drivers	223
Industrial forestry and agriculture	Industrial forestry and industrial agriculture identified together	84
Industrial mining	Presence of industrial mining with or without other drivers	59
Artisanal mining	No more than 2 drivers, including artisanal mining, no industrial drivers present	37
Human infrastructure	Roads and settlements observed alone or together, no other drivers observed	56
Infrastructure related agriculture	Infrastructure and artisanal agriculture observed together	237

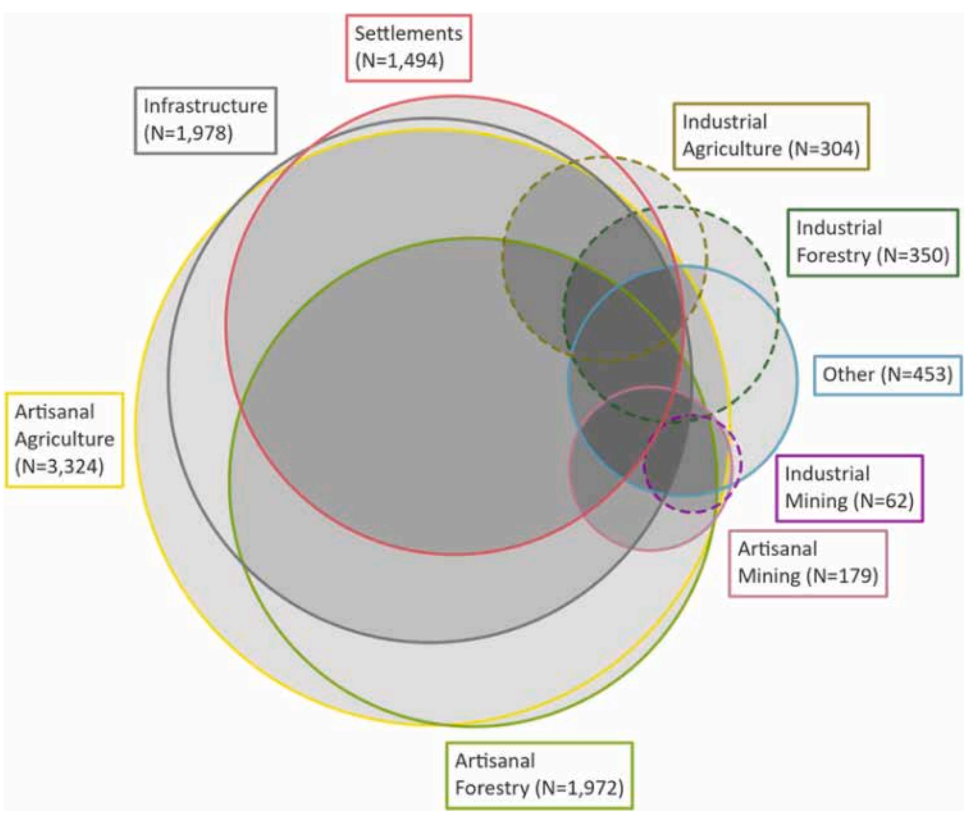


Fig. 8. Representation of overlapping drivers in the Congo Basin. The size of the circle indicates the observation frequency of each driver in the validation data set. Grey shading shows how many drivers are observed in one plot, and overlapping circles indicate which drivers are commonly found together while circles which don't overlap show the spatial divergence of some drivers.

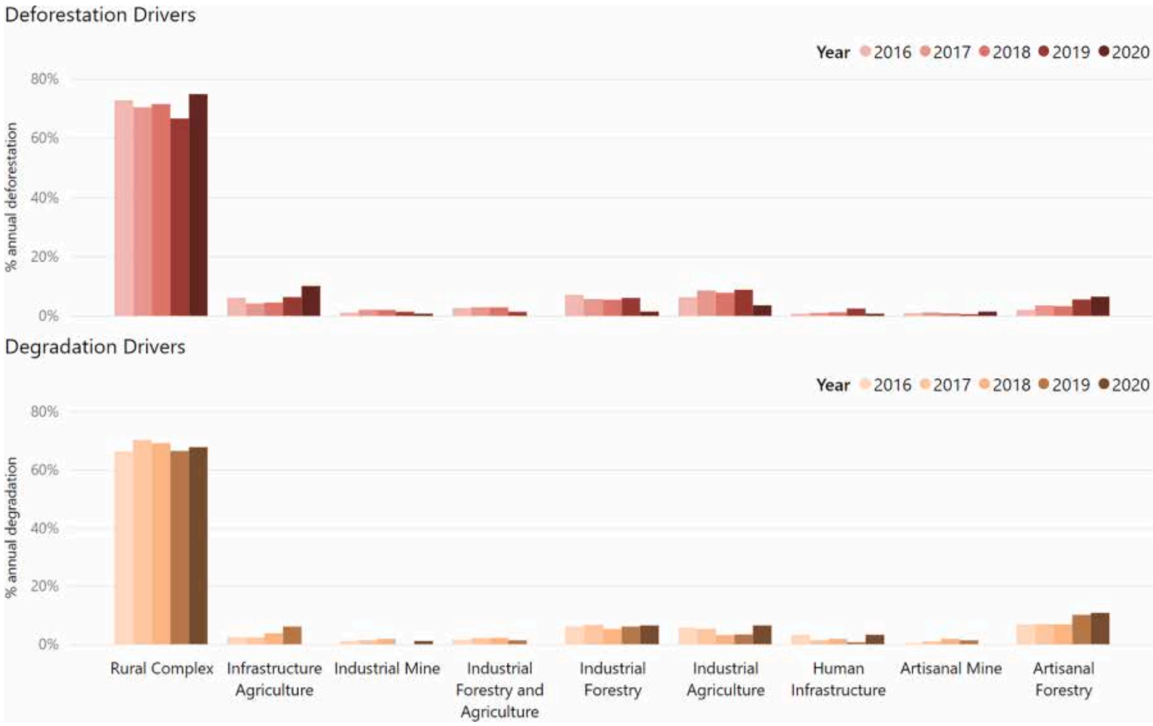


Fig. 9. Grouped drivers over time shown by proportion of annual deforestation and degradation (2015–2020). The greatest proportion of deforestation and degradation is associated with the rural complex which are not associated with any industrial drivers.

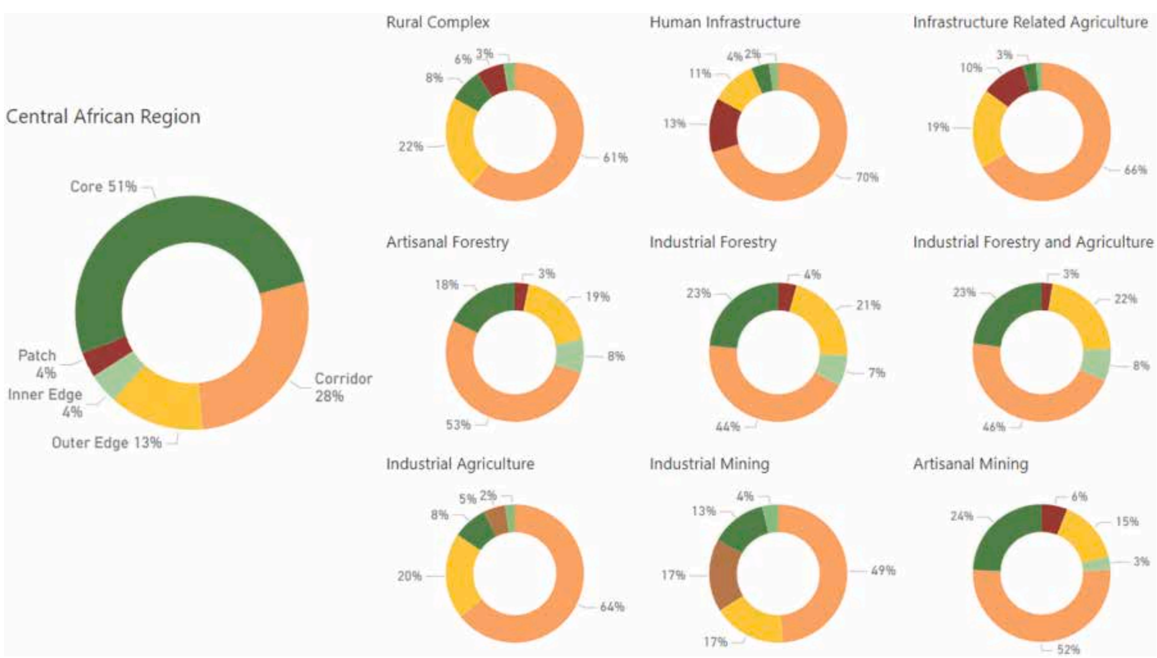


Fig. 10. Distribution of fragmentation classes in all forests of the study region (left); the proportion of fragmentation classes affected by disturbances associated with each driver archetype, estimated by the number visually interpreted points. Forestry and mining drivers are those most affecting core forests.

larger fragments are more difficult to clear (Hansen et al., 2020). From these assessments we can see how human encroachments on forests are typical of the agricultural frontier at forest edges, and we can identify several such fronts in the region (Pacheco et al., 2021).

Evaluation of carbon stock per fragmentation class and forest type indicate that open, secondary and shrub forests are twice as likely to have disturbances, representing a relatively small area of overall forests, and low carbon stocks. Dense tropical forest types, meanwhile, which contain the greatest above-ground carbon per hectare, and comprise 60% of all forests, but encompass less than 30% of all deforestation and degradation. This shows how the large intact and carbon rich ecosystems are potentially less affected by human disturbances, which can be a result of inaccessibility, lack of machinery required to clear dense forests with large trees, preference for secondary forests (Molinario et al., 2015), or management - most forest concessions in the region are located within these intact forest blocks. Effective and inclusive forest management could be a pathway to securing carbon in these commercially exploited forests (Tritsch et al., 2020).

4.3. Trends in forest disturbance (2015–2020)

In comparison with existing global datasets on forest disturbances, we observe similar trends in the 2015–2020 time period for all Congo Basin countries. Data from Global Forest Change (GFC; Hansen et al., 2013) and Tropical Moist Forests (TMF; Dalimier et al., 2022; Vancutsem et al., 2021) report higher rates of forest disturbance after 2015, which then decrease from 2017 until 2019. Estimated burned forest area has also been observed to be generally decreasing since 2001 (Andela et al., 2017). The FAO Forest Resources Assessment Remote Sensing survey also observed an overall slowing of deforestation in 2010–2018 in comparison to 2000–2010, which diverges from the Global Forest Resources Assessment (2020) which identifies an increase in rates of loss between 1990 and 2020 (FAO, 2001) which demonstrates how different methodologies may not reach consensus, and that assessments should be tailored to regional or national scales.

While forest disturbances are observed to be declining during the study period, it is important to also evaluate the trends in the context of a longer time period, as we could be potentially be seeing a return to 2015 levels of disturbance after a significant spike in 2017. Several studies report relatively stable trends of deforestation before and after 2015, but an overall higher rate of deforestation in the region after 2015 (Dalimier et al., 2022; Vancutsem et al., 2021). The estimation of deforestation trends before and after 2015 may be unreliable due to updated algorithms applied by global analyses, and biases due to an increased data availability since 2015 (Palahí et al., 2021). One hypothesis for the increase in forest disturbance in 2017 is the unusually warm year after an El Niño in 2016, incurring additional deforestation and degradation from forest fires, storms, climate-related mortality or associated further deforestation (Allen et al., 2010). Extreme heat and drought can increase deforestation associated with slash and burn practices (Staal et al., 2020) or cause an expansion of agriculture as a result of reduced yields (Djiongo et al., 2019). An assessment of cropland extent in the region using available data (Potapov et al., 2022) has indicated that cropland is in fact increasing overall, however this expansion is mostly occurring primarily outside of the forest domain; cropland activities are increasing in regenerating, or secondary forests which are outside the area of this study. Further validation and assessments are being conducting to validate these observations.

4.4. Direct drivers of forest change

We provide the first assessment of direct drivers in Central Africa which addresses deforestation and degradation separately, and also over time – essential for targeting management and interventions (Rudel et al., 2009). It is important to distinguish artisanal and industrial drivers, as this influences the policy responses which can be related to the level of private investment and production systems associated with forest change (Branthomme et al., 2023). A majority of DD are found within walking distance of settlements or roads, which is expected as accessible forests are easier and more available to clear (Hansen et al., 2020; Wilkie et al., 1998), while being planned as rural development zones (Chervier et al., 2024). Other studies have explored the role of roads and settlements on deforestation inside forest concessions, an effect which can be counteracted with effective management plans (Tritsch et al., 2020).

The dominant direct driver associated with deforestation and degradation is observed to be artisanal agriculture, more specifically subsistence activities which have a long history and tradition (Geist and Lambin, 2002; Tegegne et al., 2016; Tyukavina et al., 2018). The rural complex archetype, which is a combination of artisanal agriculture, roads and settlements without the presence of industrial activities is also the most commonly reported in other studies (Ickowitz et al., 2015) is targeting fragmented forests. Industrial forestry and agricultural activities are more present in core forests, and with industrial mining, are observed in fewer locations, and do not appear to be increasing, despite numerous reports and predictions (Tegegne et al., 2016). While the rural complex archetype is the most common throughout the region, its potential impacts on carbon, biodiversity are likely much lower and less permanent due to fallow periods which can allow for natural regeneration of vegetation (Karthik et al., 2009) and its presence in corridor and already fragmented forests.

Subsistence agricultural activities tend to be localized around settlements and existing clearings (Chervier et al., 2024; Molinario et al., 2015), and in already fragmented forests, limiting the spatial extent of impact in intact, carbon rich forests. Furthermore, we observe a larger increase in the area of cropland extent between 2015 and 2019 (Potapov et al., 2022) in areas that are non-forest, demonstrating that non-forest or regenerating areas are preferred for establishment of agriculture than forested areas. The dominance of the rural complex is not surprising given the significant dependency of rural populations on agriculture and its long history, and links to culture and economy (Arthur-Josué et al., 2020; Sonwa et al., 2010). In contrast, we find that industrial drivers tend to be more present in core, carbon rich forest types. Furthermore, industrial activities, for example mining, even when small-scale may have more permanent and significant impacts on human health, carbon and biodiversity (Edwards et al., 2014). These areas can be more difficult and costly to restore than natural regeneration of areas of small-scale agricultural areas (Stanturf et al., 2019). The contribution of the rural complex archetype to forest disturbance is however potentially increasing with unsustainable agricultural practices, and expected to expand with increasing population which can lead to reduced fallow times and land degradation (Ickowitz et al., 2015). There is a need for the improvement of rural agricultural practices, which are particularly vulnerable to climate change which can subsequently affect food security, health and livelihoods (Arthur-Josué et al., 2020; Challinor et al., 2007; Connolly-Boutin and Smit, 2016).

The central premise of our approach is the identification of multiple overlapping drivers, which is representative of DD occurring at national and sub-national scales (Butsic et al., 2015; Carr and McCusker, 2009; Ferrer Velasco et al., 2020; Shapiro et al., 2021a) and the result of the actions of multiple actors, multiple processes and motivations (Moonen et al., 2016; Rudel and Roper, 1997; Rudel et al., 2009). Global assessments, or post-disturbance land use cannot adequately discern multiple drivers (Ferrer Velasco et al., 2020; Rudel et al., 2009) and are not relevant for decision making which requires national context (Tegegne et al., 2016). Furthermore, drivers need to be considered beyond their spatial footprint: any direct driver of forest disturbance does not solely affect the direct area it covers, but inevitably influences what is around it which is particularly true for linear infrastructure such as roads (Ibisch et al., 2016; Kleinschroth et al., 2019), or industrial activities which inevitably incur changes outside permit boundaries, through connecting infrastructure or land clearing to support the livelihoods of local communities drawn to these areas (Molinario et al., 2020). Agriculture that is not associated with infrastructure will tend to be subsistence activities whereas agriculture along roads is better connected to markets, which increases the potential to produce for sale (Ickowitz et al., 2015).

One specific driver absent from our conclusions is the extraction of fuelwood and harvesting for charcoal, which is being reported as a significant cause of deforestation and degradation in Congo Basin countries and has the potential to increase (Behrendt et al., 2013; Bilonda, 2020; Lescuyer et al., 2014; Schure et al., 2012). Access to electrical infrastructure is very limited in the study region, making populations entirely dependent on charcoal for preparing food (Behrendt et al., 2013; Schure et al., 2011). Large-scale harvesting of fuelwood is mostly driven by demand from urban centres, and is mostly informal and uncontrolled, although more industrial forms of fuelwood collection is being developed in some countries of the region (Schure et al., 2012). Within our methodology we lack specific information to be able identify the scope and impact of such practices (Molinario et al., 2020). The artisanal forestry driver definition includes the harvesting of such forest products, and we observe a consistent increase of this driver over the time period, particularly associated with degradation. Given the increasing scale of these activities, they could in fact be large enough to produce on the scale of industrial forestry (Lescuyer et al., 2014; Uhm et al., 2022). Higher resolution imagery (<1 m) could provide more robust evidence to identify charcoal production such as the presence of kilns. Additional research, including socio-economic surveys, which are currently underway are necessary to understand the scale of this driver in more detail.

4.5. Implications for forest governance

Although deforestation and degradation rates are typically low in the Central African region, the potential environmental and socio-economic impacts from continued uncontrolled exploitation and conversion have been recognized by national governments. As a result, efforts to manage forest resources through sustainable management initiatives, international cooperations and agreements have been implemented. The cooperation of Central African member states through international and regional initiatives such as COMIFAC (Commission des Forêts d'Afrique Centrale), the Congo Basin Forest Partnership (CBFP), the UN-REDD programme to reduce emissions from deforestation and degradation), CAFI's results-based payment agreements and various bilateral initiatives are some examples of these efforts, backed by significant investments to provide harmonized, strategic policies and cooperation for better forest management. New international climate financing mechanisms (e.g. the public-private LEAF Coalition, and similar bilateral agreements) are generating further incentives and momentum to implement deforestation reduction programmes, which should be used to address the major obstacles to effective forest management: the need for increased involvement and inclusion of local populations within land management and decisions; the implementation of successful community forestry initiatives; the clarification of local land tenure, rights and ownership of forest resources; the development of technical capacity within national institutions; and the need for better forest monitoring and carbon accounting (Djomo et al., 2017). With robust and reliable data and outputs, the proposed approach provides a straightforward pathway to understand better status and trends of deforestation and degradation drivers. Only through the provision of this type of information on drivers and trends can existing pilot efforts be sustained and further developed to have a wider and longer-term impact on poverty and food security.

4.6. Food security and climate change mitigation

In Sub-Saharan Africa and more specifically in Central Africa, an overwhelming majority of the predominantly rural communities depend on agricultural and forest-related activities for their basic needs (Bele et al., 2015; de Wasseige et al., 2009) and meeting the requirements for food and livelihoods are inevitably associated with forest disturbance. A large majority of crops in the region are rainfed, with citizens largely employed in agriculture, making the population particularly vulnerable to the impacts of climate change, which is already reducing yields and slowing growth of the agricultural sector (Pörtner et al., 2022). The information provided in this study on direct drivers is directly relevant to improving policies and implementing activities that meet the needs of local communities through sustainable development, land use and agricultural planning, which can be supported by international climate mitigation efforts (Branthomme et al., 2023). By identifying small-scale agriculture and related activities as the main drivers of deforestation in Central Africa, the study highlights the importance of decarbonizing food systems, uncoupling development from deforestation and the urgency of improving agricultural practices and promoting climate-smart agriculture which can reduce the carbon footprint of agricultural activities while promoting a resilient and more productive farming system (Mangaza et al., 2021). Other activities include targeting small-scale agriculture activities through rural development initiatives implemented by local communities. New innovations in agricultural practices need to be implemented to increase productivity, improve livelihoods, and reduce pressure to convert additional forests into agriculture. These approaches include providing new crop varieties which are adapted to local conditions and improve yield, disseminating information on available new practices, better post-harvest handling, mechanisms to promote products in local markets, and promotion of agroforestry where possible (Kotto-Same et al., 2000; Sonwa and Hanna, 2017). It is also essential to tailor solutions to the local context and properly respond to specific climate-related risks, outcomes, and adaptation and integrate the roles of policy contexts, culture to inform adaptation policies, strategies, and measures (Sonwa et al., 2016).

5. Conclusions

For public and private finance to be successful, resources need to target relevant direct drivers of deforestation, particularly when they are multiple and overlapping. This research provides a better understanding of the drivers of recent forest loss, degradation, and the dynamics, interactions of direct drivers on carbon stocks to help countries fulfil their commitments to meeting climate change mitigation targets (Sonwa et al., 2022). We show that low impact drivers such as artisanal agriculture and forestry associated with the rural complex are primarily driving forest deforestation and degradation, while industrial drivers with potentially more significant impacts are spatially limited. This research indicates that more resources need to be invested towards sustainable, climate smart agriculture, to meet the needs of local populations, while conserving forest resources.

The approach presented here is the first to address a wide variety of unique and overlapping drivers in the spatial and temporal dimension, executed through a collaborative international partnership. This is useful to support crucial institutional capacity development of partner nations to derive specific information for mitigation activities, responding to specific drivers of change, and defining development pathways to avoid further environmental degradation. The methodology is adaptable to any geography, uses open-source tools encouraging replication and uptake, can be updated for new time periods. This aspect is important, as five years is likely too short to realistically observe post-disturbance dynamics, the establishment of new land uses, and the potential impacts of recent investments and initiatives. Therefore, an update incorporating a longer study period is being conducted to validate these assessments. Over a longer time span, we could validate the observed trends while also potentially observe forest regrowth or regeneration, which is not yet considered here. In addition, the evaluation of potential impacts on biodiversity and standing carbon stocks are important to determine relative emissions and will complement this effort to focus conservation activities and guide land use planning efforts.

CRediT authorship contribution statement

Bourgoin Clément: Validation, Writing – original draft, Writing – review & editing, Methodology. **Ouissika Chérubins Brice:** Methodology, Validation, Supervision. **Kipute Daddy:** Validation. **Sonwa Denis Jean:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Shapiro Aurélie Camille:** Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing, Software, Supervision. **Mertens Benoît:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **d'Annunzio Rémi:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Software, Supervision. **Tchana Elisée:** Conceptualization, Data curation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Desclée Baudouin:** Validation, Writing – original draft, Writing – review & editing, Methodology. **Khasa Damase:** Conceptualization, Writing – original draft, Writing – review & editing. **Jungers Quentin:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Nana Tatiana:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Obame Conan Vassily:** Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Milandou Carine:** Methodology, Validation. **Rambaud Pierrick:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Kondjo Héritier Koy:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Iyanga Josefina Mbulito:** Methodology, Validation, Writing – original draft, Writing – review & editing. **Gangyo Francis Inicko:** Methodology, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All spatial and tabular data developed by the project, along with relevant auxilliary data are accessible via the online database: https://data.congo.dddafrica.info.

Acknowledgements

The authors wish to acknowledge the financial support of the Central African Forest Initiative (CAFI). We also thank Peter Vogt for processing MSPA to produce the fragmentation map using Guidos Workbench and Joint Research Centre (JRC) server resources.

Disclaimer

The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of FAO or CAFI.

Code Availability

All modules used and developed in SEPAL are available via https://sepal.io, additional scripts are in the GitHub repository: https://github.com/aurelgrooves/sepal_DDD

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