Trees, Forests and People 23 (2026) 101126

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Dynamics and determinants of forest cover changes in the inner Congo basin

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ARTICLE INFO

Keywords:
Central Africa
Deforestation and forest degradation
Crop
Small-scale agriculture
Tropical forest
Remote sensing
Demography

ABSTRACT

Massive deforestation and forest degradation have been observed in the inner Congo basin in the last decades. While agricultural expansion onto forest land is widely recognized as the main driver of deforestation, local dynamics and social drivers remain understudied. This study investigates both the forest cover dynamics monitored from satellite products and the agricultural practices from household interviews across the Tshopo, the largest province of the Democratic Republic of the Congo (DRC). We combined satellite-based forest cover data (Tropical Moist Forest dataset, 1990–2023) with household surveys ($n = 850$) around Kisangani, the provincial capital, and up to 150 km along the six main road axes. Between 1990 and 2023, 9.7 % of mature tropical moist forest — corresponding to 1905,800 ha — was lost across the Tshopo province, being deforested, degraded, or disturbed. Deforestation accelerated since 2010, and the spatial pattern indicates urban expansion, and agricultural encroachment into forests. Household interviews confirm that small-scale farming is the dominant agricultural system in the region (94 % of respondents), with fields mostly installed on fallow land. The food crops such as cassava, rice, maize and bananas are predominant and perennial crops such as oil palms, cocoa and coffee are less common. Geographical and production factors, namely proximity to Kisangani city and household economic capital, are the main determinants of agricultural practices in the Tshopo. Although individual small-scale farming has a limited impact on forest cover (only 11 % of food crop fields and 8 % of perennial crop plantations are established on mature forest lands), the cumulative effect of seasonal land conversion is substantial. Household-level deforestation (349 ha per cropping season for 850 households) extrapolated to approximately 195,000 ha of mature forest cleared annually across the province. Given the high level of human impact and poverty in the region, it is crucial to promote sustainable agricultural practices that increase productivity without encroaching on mature forests, considering the diversity of producer profiles, in a context of high instability.

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https://doi.org/10.1016/j.tfp.2025.101126

Available online 13 December 2025

1. Introduction

Each year, 10 million ha of forest are lost worldwide due to deforestation (FAO, 2020a) and about 500 million ha of forest land are degraded (Sasaki et al., 2016). Africa recently became the continent with the highest annual deforestation rate, with 3.9 million ha of net forest loss per year between 2010 and 2020 (FAO, 2020b). The Congo basin, which is the second largest contiguous block of tropical forests in the world (Marquant et al., 2015), has become the most threatened, and the situation is projected to worsen in the future (Abernethy et al., 2016). Since 2010, massive deforestation and forest degradation have been specifically observed in the Democratic Republic of the Congo (DRC) (Vancutsem et al., 2021), with an annual deforestation rate estimated between 500,000 and up to 1.1 million ha between 2010 and 2020, according to WRI and FAO, respectively. The DRC has become the second country in the world after Brazil, with the largest area of forest lost (FAO, 2020a; WRI, 2025).

Deforestation is the conversion of forest to other land uses, regardless of whether it is human-induced (FAO, 2020b), while forest degradation is the reduction of the capacity of a forest to produce goods and services (ITTO, 2002). Several drivers of deforestation vary according to geographic, economic, and demographic conditions, development history, and current policy and institutional factors (Gillet et al., 2016; Tyukavina et al., 2018). In the DRC, the main direct drivers are, in decreasing order of importance, small-scale agriculture, artisanal wood logging, harvesting of fuelwood and charcoal production, mining, and bush fires (Ickowitz et al., 2015; Molinario et al., 2015; Ladewig et al., 2024). Small-scale agriculture for agricultural commodities is estimated to account for 92 % of forest loss in the country (Tyukavina et al., 2018; Vancutsem et al., 2021; Feng et al., 2022). Indirect drivers such as demographic growth are also involved, given that the DRC is the most populous country in central Africa, with 105 million people currently (The World Bank Group, 2023), 218 million people expected by 2050 and 430 million projected for 2100 (United Nations, Department of Economic and Social Affairs, Population Division, 2024). Deforestation in the DRC occurs mainly around urban centers, like Kisangani city in the inner Congo basin (Akkermans et al., 2013; Molinario et al., 2015; Harris et al., 2017; Balandi et al., 2024), and along road axes and rivers (Potapov et al., 2012; Mayaux et al., 2013; Shapiro et al., 2023). This induce a spatial pattern of mixed land uses that has been labeled as the rural complex, consisting of mosaics of productive food crop fields and perennial crop plantations, fallows, patches of regrowing secondary forest and, to a lesser extent, settlements (Molinario et al., 2015; Shapiro et al., 2023).

Deforestation and degradation studies often cover large areas, which is one of the most significant advantages of remote sensing approaches (Bourgoin et al., 2021; Guidance et al., 2021). Such studies can encompass the global tropics (Achard et al., 2014; Hansen et al., 2020) or focus on a specific region such as central Africa (Ernst et al., 2013; Tyukavina et al., 2018; Ross et al., 2021), though forests of the inner Congo basin, remain understudied (Verbeeck et al., 2011; Dupuis et al., 2020). Agricultural activities have been identified as the main driver of deforestation (e.g., Mayaux et al., 2013; Hansen et al., 2013; Harris et al., 2017; Molinario et al., 2015, 2020; Shapiro et al., 2023); however, the link between the spatial patterns in the landscape monitored with remote sensing, such as land and forest cover dynamics (Vancutsem et al., 2021), and the agricultural practices in the field is barely explored. Notably, the variations in farming practices are rarely considered (Masha et al., 2024).

To develop sustainable land use strategies that are urgently needed in the DRC (Molinario et al., 2015), it is crucial to bridge the gap between the routinely monitored forest/land cover dynamics (Vancutsem et al., 2021; Bourgoin et al., 2024) and the local agricultural practices, notably their spatial variations and determinants. In this study, we investigated both the forest cover dynamics (deforestation and forest degradation) and their determinants in the Tshopo, the largest province of the DRC. We specifically (i) assessed the dynamics of forest cover changes over the 1990–2023 period using the Tropical Moist Forest (TMF) products (Vancutsem et al., 2021), (ii) identified the dominant agricultural practices in the region using household interviews, (iii) examined their variations and determinants, and (iv) identified different stakeholder profiles. We assumed that the urban center, and specifically Kisangani city, the capital of the province, is the epicenter of deforestation and forest degradation, as the consumption basin of the province for food products (Bolakonga, 2013; Akkermans et al., 2013; Molinario et al., 2015; Van Vliet et al., 2015; Balandi et al., 2024), wood energy (Imani and Moore-Delate, 2021) and timber (Benneker et al., 2012).

2. Material and methods

2.1. Study area

This study was carried out in the inner Congo basin, in the Tshopo province (Fig. 1), which is the largest province of the DRC, covering 200,240 km^2, and 8.5 % of the country area (Moonen et al., 2016). The climate is equatorial continental, belonging to the Af type of Köppen's classification, with annual rainfall varying between 1600 and 1800 mm and mean annual temperature between 24 and 25 °C (Bolakonga, 2013). Tropical moist forest is the main land cover (87 %, Vancutsem et al., 2021), with agricultural areas (~10 %) located mainly along roads, rivers, and in the surroundings of large cities such as Kisangani, the capital of the province (Omasombo et al., 2020; Balandi et al., 2024). Agriculture is the primary source of income (Moonen et al., 2019) involving approximately 83 % of households (INS, 2021) and focusing primarily on food crops such as cassava, rice, banana, maize, and peanut (Van Hoof, 2011; Moonen et al., 2016, 2017). Perennial crops, mainly cocoa and oil palm plantations, and to a lesser extent coffee and rubber, are also cultivated in the area (Bolakonga et al., 2017). The population is estimated at 2.6 million inhabitants (INS, 2021), of which circa 20 % live in the city of Kisangani (Moloba et al., 2019; Sonwa et al., 2020). The population density varies from >400 inhabitants/km^2 in Kisangani to three inhabitants/km^2 in the most remote rural areas (FONAREDD, 2016).

2.2. Data collection

2.2.1. Forest cover changes

Yearly data on forest cover and forest cover changes — including deforestation, degradation, and regrowth — for the 1990–2023 period across the Tshopo province were extracted from the "Tropical Moist Forest" (TMF) dataset (Vancutsem et al., 2021) developed by the Joint Research Centre (JRC) and available online (https://forobs.jrc.ec.europa.eu/TMF). This prodcut is based on Landsat 7, 8 and 9 Collection 2 imagery, with a 0.09 ha resolution (30 m). For each pixel, we extracted from the TMF dataset the deforestation year and the yearly change. We did not use the yearly transition classes in this study, because they capture short-duration disturbances that may not represent real land use change. We therefore used the aggregated multi-year TMF forest-cover classes, which are more robust for long-term forest-cover analysis. Settlements data were collected from the GRID3 COD - Settlement Extents v2.0, available online (https://data.grid3.org/datasets/GRID3::grid3-cod-settlement-extents-v2-0/about).

2.2.2. Household interviews

Information on agricultural practices was obtained from farmer interviews in villages scattered across the province, through household survey methods, using a structured questionnaire. The survey was carried out between June and December 2022, following a multilevel stratified sampling strategy (Moonen et al., 2016), and households were selected randomly after checking their voluntary consent to participate. A total of 850 households were interviewed with 17 households per village, and 50 villages sampled. The sampling design captured the

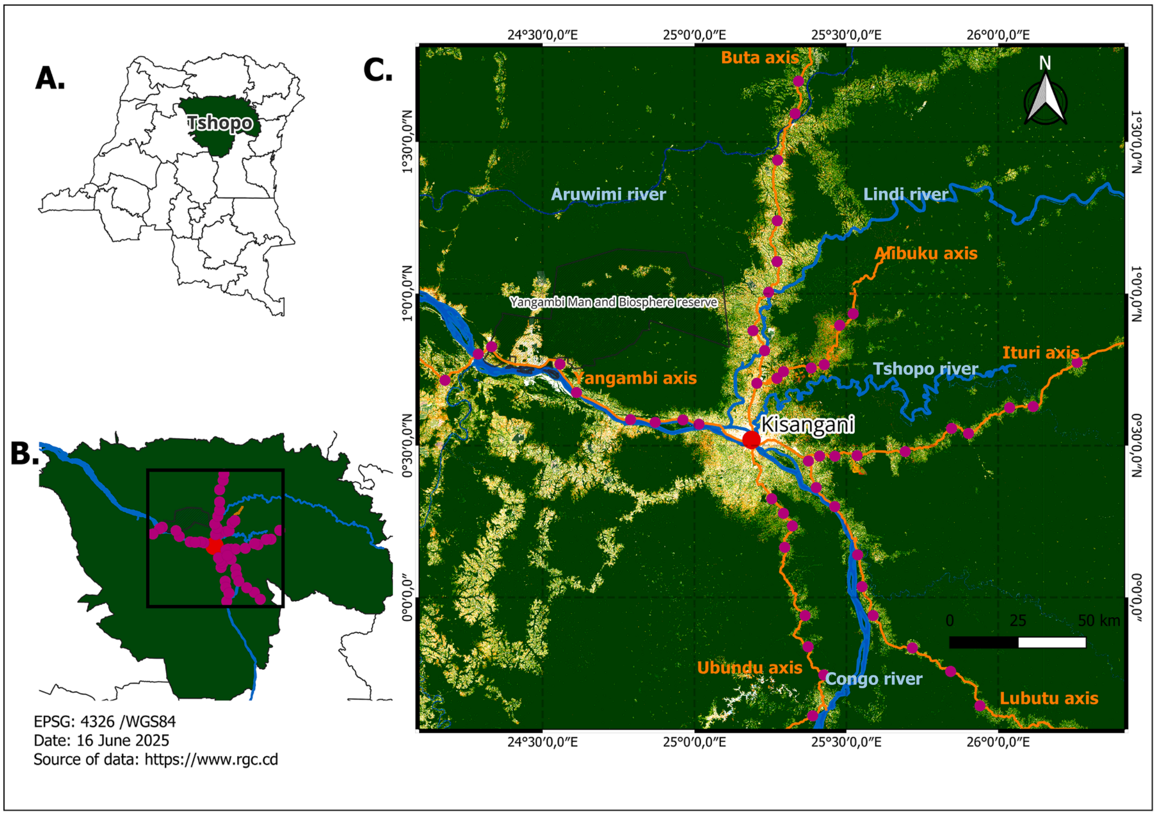

Fig. 1. Location of the study area in the DRC (A), in the Tshopo province (B) and around the city of Kisangani (C). The colors correspond to the land cover in the TMF dataset for the year 2021 (Vancutsem et al., 2021) with undisturbed tropical moist forest (dark green), degraded tropical moist forest (green), deforested land (orange), and tropical moist forest regrowth (light green). The main rivers (blue), the road axes used for sampling (orange), and the surveyed villages (pink dots) are also indicated.

disturbance gradient expected with the proximity to Kisangani city. We sampled three villages at 50 km intervals from Kisangani, i.e., 0 to 50 km, 50 to 100 km, and 100 to 150 km, and along the six main road axes from Kisangani (Fig. 1): the Buta axis to the north ($n = 9$ villages), the Alibuku axis to the northeast ($n = 6$), the Ituri axis to the east ($n = 9$), the Lubutu axis to the southeast ($n = 9$), the Ubundu axis to the south ($n = 8$), and the Yangambi axis to the west ($n = 9$). The interview lasted 15 to 20 min per household, and questions were administered in Lingala and/or Swahili, as the two languages are widely spoken in the study area compared to dialects (Omasombo et al., 2020), and investigators were fluent in both languages. In most cases, interviews were conducted with the farmers on-site. A few interviews were organized in Kisangani with owners that were not present in the village during the field mission.

Qualitative and quantitative data were collected from farmers who had at least one food crop field and/or a perennial crop plantation and who were heads of households. The same survey questionnaire was used for all households with information collected on both (i) household characteristics and (ii) agricultural practices. (i) The household characteristics included information on socio-economic factors (gender, age, household size, level of education, access to inputs, time spent in the village, year of mature forest clearing where the food crop field or the perennial crop plantation is located, land tenure, number of sources of income, main source of income and year of perennial crop plantation installation), production factors (land acquisition method, main activity, and workforce used in the food crop field or the perennial crop plantation), geographical factors (road axis, proximity to Kisangani city and distance from the village to the field) and cultural factors (ethnic group). (ii) The agricultural practices included information on the number of food crop fields and/or the perennial crop plantations, the main crop, the size of food crop field or perennial crop plantation, the previous land use before the installation of the food crop field or the perennial crop plantation, the duration of fallow and the number of rotations undergone by the food crop field.

2.3. Data analysis

To understand the dynamics and determinants of forest cover changes in the Tshopo, we first produced the land and forest cover map for the year 1990 and 2023 to illustrate the spatial patterns of undisturbed and degraded tropical moist forests, deforested land, and forest regrowth across the province. The analysis was based on the Tropical Moist Forest (TMF) dataset (Vancutsem et al., 2021), which is a fully processed and validated product based on a Landsat time series. All pre-processing steps, including geometric and radiometric correction, cloud and shadow masking, and temporal segmentation, were performed by the JRC as part of the TMF production workflow. The TMF product has an overall accuracy of 91.4 %, with yearly disturbance trajectories (from 1990 to 2023) specifically validated using >5000 reference samples. 'Degraded forest' was defined as closed evergreen or semi-evergreen forest that has experienced short-duration disturbance events ($\leq$2.5 years), while 'deforested land' reflected permanent canopy loss with no forest regrowth detected in the last 3 years. Then, before area calculations, the TMF layers were reprojected to the UTM 35 N coordinate system (EPSG:32,635) using the function terra::projet with nearest-neighbor resampling option (Hijmans, 2024). Second, we quantified the temporal trends by calculating the cumulative annual changes in forest cover between 1990 and 2023. These changes were expressed in area (in km^2) of deforested land, degraded forest and forest regrowth. These results were then compared to a bar plot of deforestation years to identify general trends and any acceleration period. Third, we conducted a spatial analysis using a 10 km $\times$ 10 km grid applied across the province. We calculated disturbance rates (% per year) between 2020 and 2023, including annual deforestation rates, and also combining degradation and deforestation rates. Finally, we examined several remote sensing products to identify potential determinants of forest cover changes, paying particular attention to proximity to settlements. A linear regression model was used to assess the relationship between disturbance rates and accessibility, using travel time to cities as a proxy (Nelson et al., 2019). The four grid cells corresponding to the city of Kisangani were excluded from the latter analysis.

To determine the general pattern in agricultural practices across the Tshopo province, we first used a descriptive analysis based on barplots, showing the frequency of all variables, separately for food crop fields and for perennial crop plantations. Household characteristics were then tested as potential determinants of agricultural practices, including socio-economic, production, geographical, and cultural factors. The chi-square test was used to determine the strength of the relationship between categorical variables describing agricultural practices and household characteristics. An ANOVA was used to test the effect of categorical household variables on quantitative agricultural practices. The normality and homoscedasticity of residuals were verified with Shapiro and Bartlett tests, respectively, and the non-parametric Kruskal-Wallis test was used when the two conditions were not met ($p < 0.05$). Simple linear models were adopted to establish a relationship between quantitative variables describing agricultural practices and household characteristics. Logistic regressions were also used to assess the effect of quantitative household characteristics on each agricultural practice modality. For each significant quantitative variable explaining the perception of a practice modality, we confirmed its importance by developing Pearson correlation tests. The Multiple Correspondence Analysis (MCA) implemented in the ade4 package in R (Dray and Dufour, 2007) was used to visualize the correspondence between agricultural practices and their determinants, including socio-economic, production, geographic, and cultural factors. Finally, to better understand the diversity of stakeholders, we conducted another MCA, followed by an unsupervised clustering of individual MCA scores to identify groups of farmers sharing similar patterns of land acquisition methods, labour use and economic capital.

All analyses were conducted using R software version R 4.2.3, under its interface RStudio version 2.1. The ggplot2 package was used for graph presentation (Wickham, 2016).

3. Results

3.1. Changes in forest cover in the Tshopo province

The Tshopo province was covered by mature tropical moist forest in 1990 which represented 98.1 % of the area (Fig. 2A), while only 88.4 % in 2023 (Fig. 2B). Thus, between 1990 and 2023, 9.7 % of mature tropical moist forest was lost across the Tshopo province, corresponding to a total of 1905,800 ha (19,058 km^2) of forest-cover being deforested, degraded, or disturbed, according to the TMF dataset. Non-forested areas almost doubled in 33 years, with a spatial pattern linked to urbanisation and agricultural expansion. Specifically, a strong spatial variation in forest cover loss was revealed depending on proximity to the city of Kisangani. Deforestation rates within the TMF indicated that deforestation is notably higher in the 0–100 km zone than in the 100–150 km zone. While massive deforestation occurred between 2010 and 2020, forest regrowth was also observed, and contributed to a slight increase in mature tropical moist forest (undisturbed tropical moist forest that has maintained a closed canopy, with no detectable signs of disturbance, such as degradation or deforestation, throughout the monitoring period) in the province (Fig. 2C). Annual forest cover loss remained relatively low and stable between 1990 and 2010, averaging 12,325 ha/year (0.06 %/year). In contrast, between 2010 and 2020, the mean annual forest loss increased by >7.6-fold, reaching 93,868 ha/

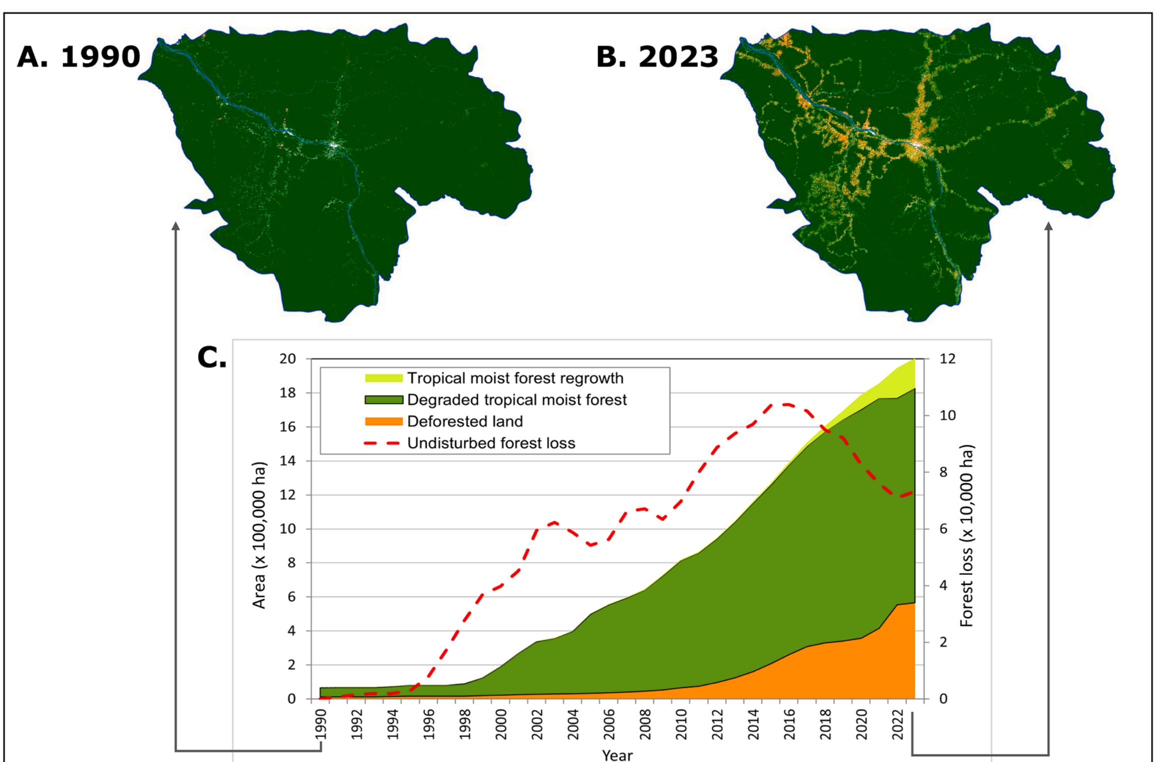

Fig. 2. Forest cover and forest cover changes across the Tshopo province in the DRC according to the TMF dataset. Land and forest covers were mapped for the year 1990 (A) and 2023 (B) with colors corresponding to undisturbed tropical moist forest (dark green), degraded tropical moist forest (green), deforested land (orange), tropical moist forest regrowth (light green). Permanent water bodies (blue) are also indicated. The yearly dynamics of cumulative area of deforested land, degraded and regrowth forests (C) is also shown over the 1990–2023 period.

year (0.52 %/year), and confirming a clear acceleration in forest cover change during the last decade (Fig. S1).

3.2. Agricultural practices in the Tshopo province

The 850 respondents included 697 males (82 %) and 153 females (18 %). The average age of respondents was 45, with a minimum of 19 and a maximum of 85 years. The average household size was 9 ± 5 people, with a maximum of 35 people. Natives of the province constituted the vast majority of respondents (85 %). Most respondents were farmers (89 %), but a few state employees were also interviewed (5 %), including village chiefs, teachers, and nurses, and, to a lesser extent, traders (1 %), fisherman (2 %) and others (3 %). The main source of income was agriculture (98 %), although some respondents combined agriculture with a state salary, or other incomes from trade in non-agricultural products, hunting, gathering, fishing, and livestock. The education level was relatively low, with only 2 % of respondents having a university degree, 56 % having a secondary school education, 37 % having only an elementary school education, and with 4 % having never attended school.

Small-scale farming was the most widespread agricultural system in the Tshopo. The agricultural practices generally focused on food crops cultivation (94 % of respondents). The most important crops, in decreasing order, were cassava (52 %), rice (30 %), maize (12 %), banana (3 %), and to a lesser extent, cowpea and peanut (Fig. 3A). Perennial crops were less widespread, with only 19 % of respondents growing them. The most common ones were oil palm (71 %), cocoa (24 %) and coffee (5 %, Fig. 3B). Of the 850 respondents, we recorded information for 1176 food crop fields and 174 perennial crop plantations. Respondents owned an average of one food crop field and/or one perennial crop plantation per household. Food crop fields were typically <2 ha (90 %) and perennial crop plantations <3 ha (79 %). On average, food crop fields measured 1.01 ± 0.41 ha, whereas perennial crop plantations showed greater variability, averaging 4.06 ± 12.57 ha likely due to a few very large plots skewing the mean. During the current cropping season, both food crop fields and perennial crop plantations were mainly located on fallow land, but a few of them were installed on cleared mature forest (11 % and 8 %, respectively, for food and perennial crops), thereby contributing directly to deforestation. Based on an average field size of 1.01 ha and the fact that 11 % of food crop fields were located in mature forests (representing around 129 fields), it was estimated that during the recent cropping season 130 ha of mature forest were converted into agricultural land by the 850 households surveyed. This highlighted the substantial impact of small-scale farming on forest cover change. In contrast, the sum of the areas of individual plantations in mature forests represented 219 ha. The average fallow duration was 4 years, with most of them falling within the range of 3 to 10 years (77 %). Plots commonly underwent one (52 %) or two (23 %) cultivation rotations before the next fallow cycle.

3.3. Determinants of agricultural practices

Agricultural practices for food crops in the Tshopo province varied according to geographical, cultural, socio-economic and production factors. Of these factors, proximity to Kisangani city was found to influence field size, crop type, fallow duration, previous land use, the number of fields per household and the number of rotations per food crop field. This results was confirmed by the MCA with the first axis revealing two distinct groups based on proximity to Kisangani (Fig. 4). In areas within 100 km of the city, farming systems were characterised by larger fields (over 1 ha), short fallow durations (1–2 years), a high number of crop rotations per plot and the frequent establishment of fields in mature forest, which contributed directly to deforestation. Households often managed several fields simultaneously. In contrast, areas beyond 100 km had smaller fields (≤1 ha) which were often established on land that had been left fallow for a long time (sometimes exceeding 10 years). Both areas grew cash crops such as cassava, rice, maize and bananas, although peanuts and cowpeas were grown in areas far from the city.

Crop types also varied across road axes (Table 1). Cassava predominated on the Yangambi, Ubundu, Ituri and Lubutu axes, while rice predominated on the Buta and Alibuku axes (Table S1). On the Alibuku axis, the field size was larger and the proportion of fields installed on mature forest was the highest, whereas on the Buta axis, plot rotation was frequent and fallow periods were short. Ethnicity also influenced crop selection, field size and fallow duration. In addition, the use of hired labour was associated with larger field sizes compared to reliance on family labour. Finally, household size influenced the number of fields and the type of crops.

Agricultural practices for perennial crop plantations varied, in decreasing order of importance, according to production, cultural, geographical, and socio-economic factors (Table 2). Land acquisition rights influenced the main perennial crop, the size of the plantation, and the previous land use, with most plantations acquired by purchase being

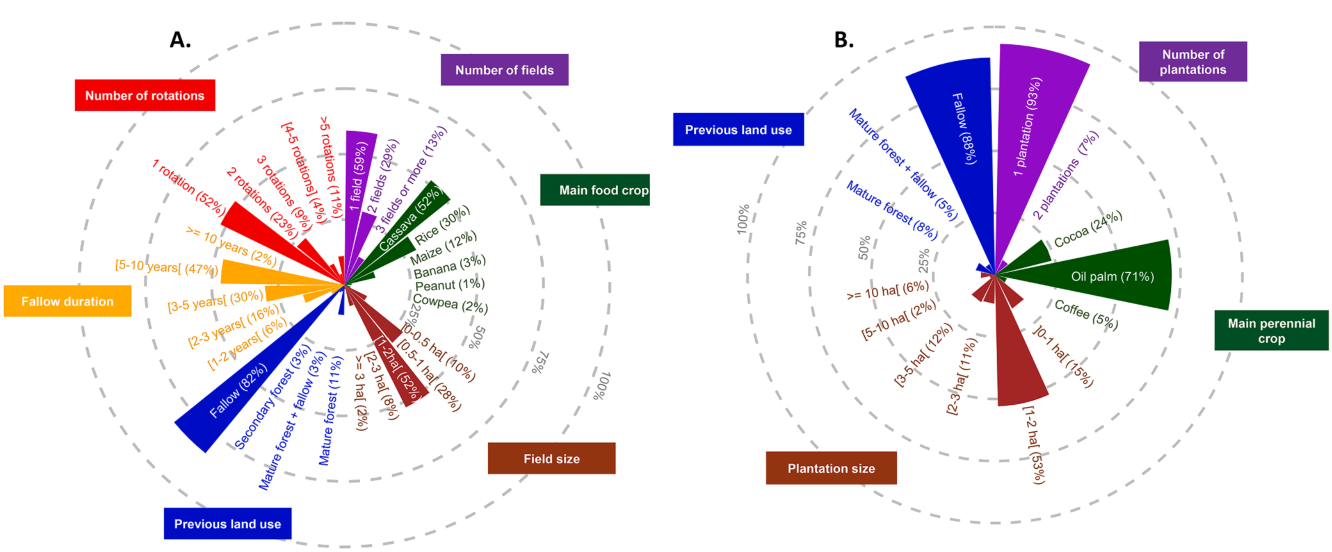

Fig. 3. Agricultural practices in food crop fields (A) and in perennial crop plantations (B) in the Tshopo province. Each color represents a specific variable group: number of fields or plantations (purple), main food or perennial crops (green), field or plantation size (dark brown), previous land use (blue), fallow duration (yellow–orange) and number of rotations (red). The percentages for each agricultural practice indicate the proportion of respondents who mentioned that practice.

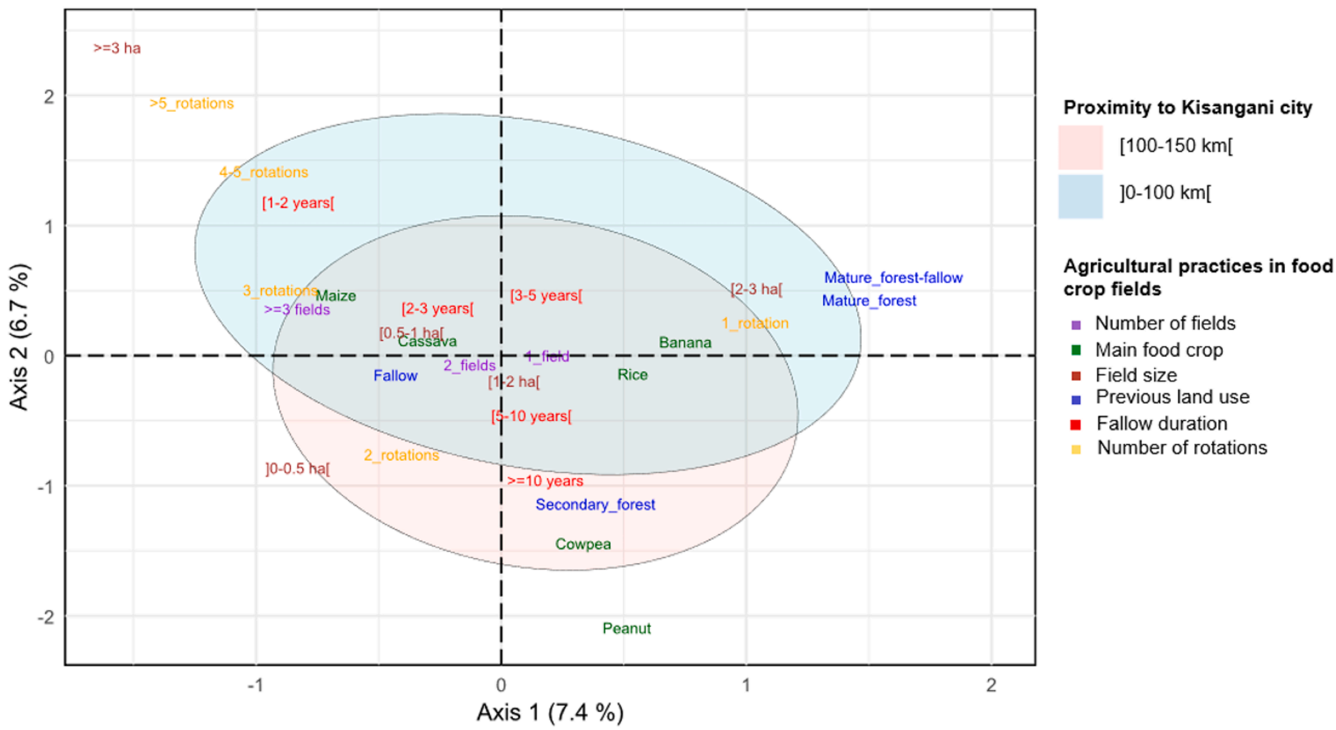

Fig. 4. Multivariate relationships between agricultural practices for food crop fields and proximity to Kisangani city.

Table 1
Determinants of agricultural practices in food crop fields ($n = 850$ respondents). The significance level of the relationships is indicated with * for $p < 0.05$, ** for $p < 0.01$ and *** for $p < 0.001$.

	Main crop	Field size	Previous land use	Number of rotations	Fallow duration	Number of fields
Socio-economic factors						
Gender						
Age	**			**		
Household size	**	***				*
Level of education						
Access to inputs				***		**
Time in the village			**	**		
Year of mature forest clearing	***	*	***	***		
Field acquisition year	***		***			
Land tenure			*	***		*
Plantation ownership	**			***		*
Number of sources of income	*					*
Sources of income			**			
Production factors						
Land acquisition method		*	***			
Main activity	*		*			
Workforce		**	***	*		
Geographical factors						
Road axis	***	***	***	***		***
Proximity to Kisangani city	***	*		***	*	
Distance village – field	**	***	**		*	
Cultural factor						
Ethnic group	*	*			*	*

mainly for cocoa and established on mature forest (Table S2). The activity of respondent also influenced the main perennial crop, and it appeared that traders were more likely to grow cocoa, while farmers were more likely to grow oil palm. Hired labour depended on the crop type, the plantation size, and the previous land use. Family labour or mutual help was more common in small oil palm and coffee plantations, than in large cocoa plantations where hired labour was common. Ethnic group and road axis also influenced practices concerning perennial crop plantations. Natives tended to own small plantations and were most involved in oil palm cultivation, while non-natives owned large plantations and were more engaged in cocoa cultivation. The oil palm cultivation was common on the Yangambi and Lubutu axes, while cocoa was more frequent on the Alibuku and Ituri axes. Significant differences in the size of perennial crop plantations were observed along the Alibuku axis. The average size of plantations was 23 ha, compared to less than three ha along the other axes. These large plantations have been installed on mature forests, contributing directly to deforestation.

3.4. Stakeholder profiles

We identified three main profiles of stakeholders based on the multivariate analysis of variables related to access to land, economic

Table 2
Determinants of agricultural practices in perennial crop plantations (n = 850 respondents). The significance level of the relationships is indicated with * for $p < 0.05$, ** for $p < 0.01$ and *** for $p < 0.001$.

	Main perennial crop	Plantation size	Previous land use	Number of plantations
Socio-economic factors				
Gender				
Age				
Household size			*	*
Level of education				
Time in the village		***		
Year of plantation installation	***		***	
Land tenure				
Food crop field ownership	*			
Number of sources of income			**	
Source of income	**		**	
Production factors				
Land acquisition method	***	**	*	
Main activity	***	***	***	
Workforce	**	***	***	
Geographical factors				
Road axis	*	***	***	
Proximity to Kisangani city				
Distance village – field		**		
Cultural factor				
Ethnic group	***	*	***	

capital (main activity) and labour use (Fig. 5). The first and most common group (n = 683; 80.4 %) consisted of smallholder family farmers for whom agriculture is the main economic capital and who practice small-scale subsistence farming combined with oil palm cultivation on land acquired through inheritance (father to son) and relying solely on family labour. The second group consisted of smallholder tenant farmers (n = 159; 18.7 %) who are engaged in subsistence food crop production, but who rent land and rely on hired labour. They typically rent land for one or more cassava cycles and do not plant perennial crops due to a lack of land ownership. In some cases, the lease agreement could evolve into a definitive purchase of the plot, in exchange for a sum of money and some goods. These first two groups mainly manage fields smaller than two ha. The third group consisted of large-scale landholders (n = 8; 0.9 %) who purchase large plots of land for perennial crops, especially cocoa, and who employ permanent workers on site. Each of their plantations exceeded 10 ha. Although they were few in number, four respondents among them owned plantations larger than 50 ha, representing nearly 50 % of the total area recorded for perennial crop plantations (304.8 ha out of a total of 662 ha).

4. Discussion

In this study, we aimed to bridge the gap between the patterns of forest cover changes in the inner Congo basin detected from TMF products, and the determinants of deforestation, with the largest field assessment of households characteristics and agricultural practices of Congo basin smallholder farmers implemented to date. Our results showed significant changes in forest cover across the Tshopo province between 1990 and 2023, around villages and road axes, and an acceleration of deforestation and forest degradation around 2010. Our interviews identified common agricultural practices, with generalized food crops in family and subsistence small-scale agriculture, but also oil palm for local consumption and local market, and to a lesser extent cocoa and coffee plantations for export. Field interviews revealed that only a few food crop fields or perennial crop plantations were installed on mature forests, but multiplied by the number of people, it lead to massive changes in forest cover, a trend that has accelerated over the last

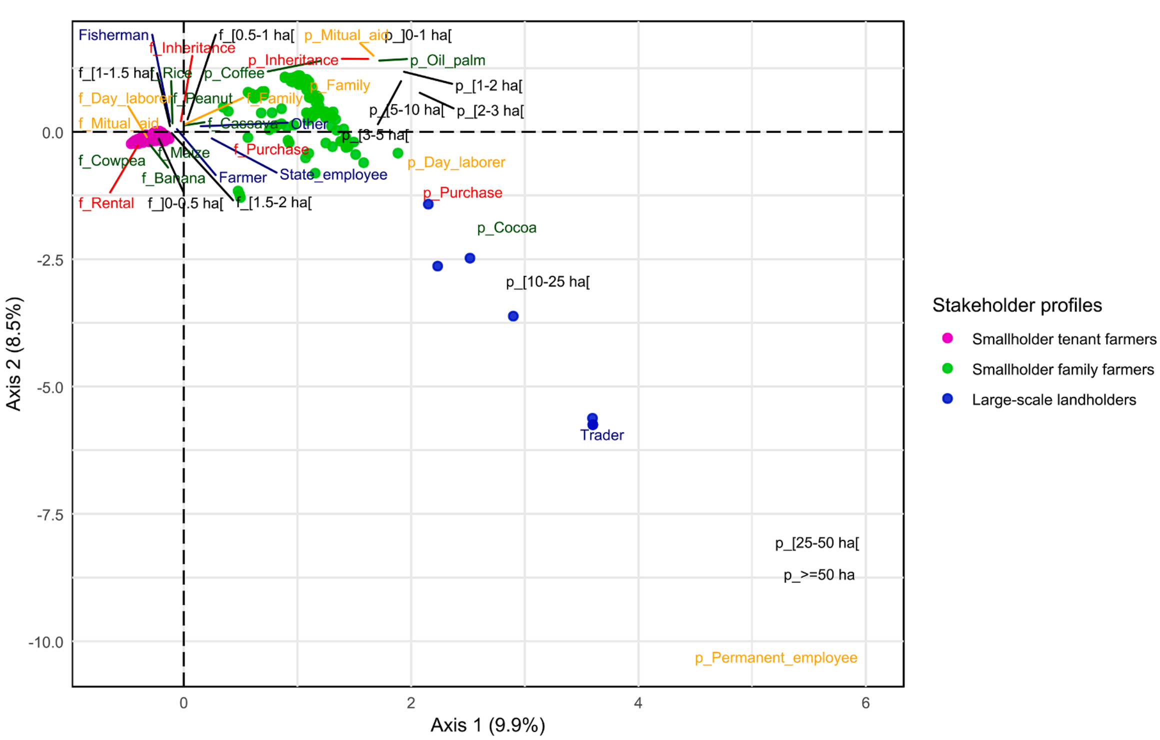

Fig. 5. Stakeholder profiles based on production factors, including access to land, economic capital (main activity) and labour use. The three stakeholder groups are presented with their relationship to agricultural practices, and variables are coloured according to their type: main crop (dark green), main activity (dark blue), access to land (red), labour (orange), field or plantation size (black), with the prefix “f” for food crop fields and “p” for perennial crop plantation.

decade.

Specifically, although only 11 % of food crop fields were established on mature forest land, their cumulative impact is substantial when scaled to the provincial level, confirming the central role of smallholder agriculture in driving forest-cover change. Among the 850 households surveyed, 130 ha of mature forest were cleared per cropping season for food crops, equating to approximately 260 ha annually, given two cropping seasons per year in the region (Bolakonga et al., 2017; Kabila, 2025). Extrapolating this figure to the Tshopo's 238,000 agricultural households (83 % of the provincial population of 2.58 million, according to INS in 2021) reveals that food crop expansion alone accounts for the clearing of approximately 73,000 ha of mature forest across the province annually. Such conversion led to reduced mature forest land cover, forest fragmentation, erosion of biodiversity, depletion of carbon stocks and increased emissions (Gibbs et al., 2010; Gibson et al., 2011; Mangaza et al., 2022). Meanwhile, perennial crop plantations represent an even more permanent threat, with 8 % established on mature forest and 219 ha converted per cropping season among surveyed households, approximately 438 ha annually. Provincial-scale extrapolation suggests perennial crops drive an additional 122,000 ha of irreversible forest loss per year, as these systems (oil palm, cocoa, coffee) permanently occupy land and prevent natural regeneration (Mosnier et al., 2016; Mangaza et al., 2022). When combined, food crop fields and perennial crop plantations account for 349 ha of mature forest cleared per season, or 698 ha annually for the 850 households. Extrapolated to Tshopo's approximately 238,000 agricultural households (INS, 2021), the observed rate (0.82 ha per household per year) corresponds to nearly 195,000 ha of mature forest potentially cleared each year. This value should be interpreted as a rough estimation of the order of magnitude, since it is based on scaling local observations up to the provincial level. These results confirm the significant role of smallholder agriculture in driving cumulative forest cover loss across the province (Rudel, 2009; Van Vliet et al., 2013).

This cumulative effect was reflected in the forest cover dynamics captured by TMF products, which indicate a decline in the coverage of mature tropical moist forests in Tshopo province, falling from 98.1 % in 1990 to 88.4 % in 2023. Although a 9.7 % decline in forest cover over the 33 years may seem modest, it is significant in the context of the Tshopo province, which has a high level of forest cover (Vancutsem et al., 2021). This equates to the loss of 1905,800 ha (19,058 km^2) of forest cover. Furthermore, studies have demonstrated that even modest proportional reductions in the canopy cover of tropical forests can result in significant ecological repercussions (Betts et al., 2017; Taubert et al., 2018; Bourgoin et al., 2024). Notably, the TMF time series show that forest loss did not occur uniformly over time. Disturbance rates remained relatively low before 2010, but then accelerated significantly between 2010 and 2020, particularly around urban areas and along road networks as previously observed in the Congo Basin (Molinario et al., 2015; FAO, 2020a; Vancutsem et al., 2021; Balandi et al., 2024). Specifically, a strong spatial variation in forest cover loss was revealed depending on proximity to the city of Kisangani, with higher deforestation within the 0–100 km zone than within the 100–150 km zone. In the study area, this trend is primarily driven by the rapid population growth (INS, 2021), the expansion of Kisangani and other small cities (Harris et al., 2017; Tyukavina et al., 2018; Windey, 2020; Balandi et al., 2024), and the increased demand for agricultural commodities (Vancutsem et al., 2021). A similar pattern was observed in other parts of the country (Gond et al., 2016; Muteya et al., 2023) and in several other tropical regions (Nkwemoh and Tchindjang, 2018; Potapov et al., 2022). Furthermore, the increased rate of deforestation observed over the last decade may be indirectly linked to the movements of population fleeing conflict in eastern DRC and settling in the Tshopo province (OIM, 2019). Unlike conflict-affected eastern provinces, Tshopo Province has remained relatively stable (Baker et al., 2003; Windey, 2020), positioning it as a refuge destination for populations fleeing violence in North-Kivu and Ituri provinces (Lebailly et al., 2014; OIM, 2019). Many of these displaced households, who rely heavily on farming and agricultural expansion to rebuild their livelihoods (Bolakonga et al., 2017), have sought to re-establish stability in their new environment, which may have contributed to additional pressure on forest lands.

The results of our household interviews demonstrated that agricultural practices varied primarily with geographical factors, particularly in food crop fields, as previously observed by Bolakonga et al. (2017). Proximity to Kisangani city significantly influenced agricultural practices (Balandi et al., 2024). In areas located $\geq$100 km from Kisangani, the four main crops — cassava, rice, maize and banana (Moonen, 2017) — as well as peanuts and cowpeas were grown. Fields were small ($\leq$1 ha) and were often established on land that had been left fallow for a long time. This is likely due to the low population density (FONAREDD, 2016; INS, 2021), the absence of urban investment on land (Lebailly et al., 2014), limited market access due to poor feeder roads (Van Hoof, 2011; Mangaza et al., 2021), the lack of funds to hire labour (Mangaza et al., 2021) and low local food prices. Near Kisangani, the same main crops were grown (Moonen, 2017), but with a higher intensity in practices, with larger fields (>1 ha), more crop rotations per plot (>5) and more fields per household (>1), as well as shorter fallow periods (1–2 years). This trend can be attributed to the high demand for agricultural commodities in Kisangani, which is densely populated (Mayaux et al., 2013; Ernst et al., 2013; Akkermans et al., 2013; Harris et al., 2017; INS, 2021). The larger field size near the city can be explained by the availability of land (Lebailly et al., 2014), easier access in peri-urban areas (Galeana-Pizaña et al., 2024), and better access to labour. These results demonstrate how geographical and socio-economic factors influence farming strategies throughout the province. In the context of sustainable land use planning, these variations emphasise the importance of promoting agricultural practices that improve productivity while limiting further encroachment onto mature forest. This could include introducing agroforestry systems in degraded areas and improving soil fertility in plots with multiple crop rotations, for instance by encouraging natural regeneration or planting species that enrich the soil (Peltier et al., 2014; Mangaza et al., 2022).

However, to design effective land use planning policies, it is crucial to consider the diversity of stakeholders and understand how their agricultural practices contribute differently to deforestation and forest degradation. Smallholder family farmers, who constituted most agricultural producers, typically manage less than two ha and practice shifting cultivation and slash-and-burn agriculture (Molinario et al., 2020). This system involves periodic clearing of forest for short-term use, followed by fallow (Van Vliet et al., 2013), resulting in progressive, scattered deforestation (Molinario et al., 2020). Although the individual impact seems limited, the cumulative effect is substantial (Van Vliet et al., 2012; Branthomme et al., 2023). According to Tyukavina et al. (2018), almost 92 % of forest loss in the DRC between 2000 and 2014 was due to small-scale clearing for rotational agriculture. This pressure is exacerbated by poverty, low productivity, insecure land tenure, lack of access to technical assistance, and population growth (Van Vliet et al., 2013; Ordway et al., 2017). In contrast, smallholder tenant farmers, although also cultivating small plots, are more market-oriented and grow diverse food and cash crops (Bolakonga et al., 2017). They have the greatest impact in peri-urban areas and along road networks, where they contribute to forest fragmentation due to increased competition for land (Molinario et al., 2015; Abernethy et al., 2016). While they contribute less than family farmers in absolute terms, their influence is growing with improved market access and infrastructure development (Hourticq et al., 2013). Large-scale landholders, although numerically marginal, have significant influence on forest cover (Windey, 2020). Supported by private capital, they establish monoculture plantations, specially cocoa, in previously undisturbed forests (Renier et al., 2025). These monoculture plantations lead to extensive deforestation, mechanized clearing, and infrastructure development, which also facilitates indirect deforestation (Kissinger et al., 2012; Windey, 2020). As cocoa farming in Tshopo is primarily driven by wealthy individuals, this indicates that capitalized agriculture and economic growth are significant drivers of deforestation in the region (Rudel, 2009; Windey, 2020; Ngouhouo-Poufoun et al., 2024). In addition, monoculture plantations practices increase biodiversity loss as demonstrated in Yangambi (Mangaza et al., 2022) and generate land conflicts (Molinario et al., 2015; Mudiayi, 2019). It has been reported that large plantations, especially cocoa plantations, are stifling small farms, by forcing their owners to move and settle far away from cocoa plantations. This situation increases the risk of land conflicts, as previously reported by Windey (2020) in the area and by Shamamba et al. (2023) elsewhere in the DRC, as well as by van Vliet et al. (2012) and Renier et al. (2025) in several other tropical countries. To a certain extent, it also causes small clearings to spread throughout the forest (Molinario et al., 2020). Furthermore, the hired labour drawn to these areas create communities that rely on shifting cultivation and non-timber forest products (NTFP) for food, energy, and building materials. The impact of the latter is often visible up to 5 km around the plantation (Molinario et al., 2020). Thus, despite differing scales, all three groups contribute to deforestation and forest degradation. Tailored support and policies addressing the specific socio-economic and environmental contexts of each group are essential to reduce deforestation in the region (Tegegne et al., 2016).

The loss of mature forest was most pronounced near the city of Kisangani, where agriculture is most intensive due to the proximity to markets and infrastructure (Molinario et al., 2015; Shapiro et al., 2021; Balandi et al., 2024; Zheng et al., 2025). This peri-urban area was characterized by cash crop cultivation, large field sizes, high crop rotation rates, short fallow periods and frequent food crop field/perennial crop plantation in mature forest land. In addition, smallholder family and tenant farmers around Kisangani, though operating on small plots, exerted significant pressure on forests due to high population density (Ickowitz et al., 2015; Shapiro et al., 2021). Poverty and limited access to resources force them to cultivate crops with a short growth cycle, resulting in frequent plot shifting and deforestation (Van Vliet et al., 2012; Barbier and Hochard, 2016). In contrast, although less common in the region, perennial crops were maintained over longer periods, stabilizing land use and helping to mitigate deforestation (Ickowitz et al., 2015; Batsi et al., 2021). Deforestation in Tshopo was also linked to the development of new small cities in the north-east, particularly along the Alibuku axis. This area has experienced intense human activity in recent years as people have settled along an old logging road to establish farms (Windey, 2020). Recent studies have identified Alibuku as one of the most active cocoa-producing zones in the province (Batsi et al., 2023), where large areas of mature forest have been converted into agricultural land, creating new deforestation hotspots (De Beule et al., 2014; Batsi et al., 2020). Our findings confirm that this area had the largest fields for both food crops and perennial crop plantations, specially cocoa, that some of which exceeded 50 ha (Batsi et al., 2023). The trade of Alibuku cocoa production is primarily transported to Kisangani for export, mainly to Uganda and Europe (Windey, 2020; Batsi et al., 2023). However, cocoa has been reported several times as one of major driver of direct and indirect deforestation in the DRC (De Beule et al., 2014; Batsi et al., 2021) and in many other countries (Lambin and Furumo, 2023; Ngouhouo-Poufoun et al., 2024; Renier et al., 2025). In contrast, older cocoa plantations established in previous decades, often in degraded forests, have been shown to support carbon storage and biodiversity (Batsi et al., 2021; Mangaza et al., 2022; Miharza et al., 2023). These agroforestry systems could represent a more sustainable alternative that is better aligned with environmental goals and sustainable land use planning.

The limitations of this study are inherently linked to its research directions. Constraints such as the 30-m resolution of TMF products, the short-term socio-economic assessment and the partial consideration of indirect drivers limit the precision with which certain processes can be quantified. In addition, the intra-stratum variability and the uncertainty associated with extrapolating household-level data to the provincial scale could not be fully quantified, which is an inherent limitation of combining localised socio-economic data with large-scale satellite-derived forest monitoring. Furthermore, the TMF product does not identify the direct causes of forest-cover loss. The attribution of drivers (e.g., agricultural expansion) relies on the integration of TMF-derived transitions with household survey data and insights from the literature. Future studies should integrate TMF-derived forest-cover trajectories with long-term socio-economic assessment to gain a better understanding of the interaction between demographic pressures, economic growth, migration flows, market access and land tenure constraints in shaping forest cover dynamics. Furthermore, higher-resolution spatial analyses combining TMF products with updated settlement and road datasets would improve the detection of local forest conversion hotspots. Engaging the diverse farmer profiles identified in this study in participatory action research is essential to co-developing locally appropriate solutions for implementing sustainable land use planning and achieving effective land use transitions in the Congo Basin (Molinario et al., 2015; Shapiro et al., 2023); particularly in the context of projected population growth and accelerating deforestation. Finally, our results can guide land management strategies by highlighting areas where agricultural expansion is likely to encroach on mature forests, emphasizing the importance of promoting sustainable practices to increase productivity on cleared land.

5. Conclusion

Deforestation and forest degradation in the Tshopo province appear to be driven mainly by the expansion of Kisangani and other small cities, combined with forest conversion for agriculture, in the absence of other major activities such as mining or industrial logging in the region. Since 2010, the combination of small-scale food crop farming and the establishment of large perennial crop plantations has accelerated the rate of deforestation and forest degradation. The heavy loss of forest cover is concentrated around Kisangani city, where intensive small-scale farming is practised due to high urban demand and population growth. Stakeholders with more capital contribute significantly to deforestation and forest degradation because they can buy large area of land and pay more for labour each year to cultivate larger areas. In contrast, areas far from the city experienced low levels of human pressure and consequently low rates of forest cover loss. They are especially characterized by small-scale food crops farming for subsistence, due to the absence of urban investment on land and limited market access. In the context of sustainable land use planning, it is essential to develop agricultural practices that increase production yields and reduce the expansion onto mature forest land. Support from the governmental and non-governmental organisations should be tailored to the types of producers in the area, taking into account the challenging context of the region, including high levels of poverty and instability. Finally, future research should combine high-resolution remote sensing data with long-term socioeconomic monitoring to gain a better understanding of how demographic dynamics, economic growth, migration flows, market access and land tenure collectively influence changes in forest cover. This knowledge is essential for effective land-use planning and safeguarding the remaining mature forests in the Tshopo province.

Funding

This work was supported by the Belgian Development Agency (Enabel) under the PRECOB programme (grant number PRECOB/IM/CF/AAF/2021/24, 2021), the Académie de Recherche et d'Enseignement Supérieur (ARES) via the B-MOB programme (grant number : 2024-SV-046, 2024), and the International Foundation for Science (IFS) via the Basic Research Grant (Grant D-6593-1, 2021).

CRediT authorship contribution statement

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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.

Acknowledgments

The authors would like to express their sincere gratitude to the Belgian Development Agency (Enabel), through the Programme de Renforcement des Capacités par l'Octroi des Bourse (PRECOB), the Académie de Recherche et d'Enseignement Supérieur (ARES), through its doctoral mobility program (B-MOB), and the International Foundation for Science (IFS), through the Basic Research Grant; for their generous financial support that made this research possible. We also address our sincere thanks to all respodents for their collaboration during fieldwork.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2025.101126.

Data availability

Data will be made available on request.

References

Abernethy, K., Maisels, F., White, L.J.T., 2016. Environmental issues in Central Africa. Annu. Rev. Environ. Resour. 41, 1–33. https://doi.org/10.1146/annurev-environ-110615-085415.

Achard, F., Beuchle, R., Mayaux, P., Stibig, H.-J., Bodart, C., Brink, A., Carboni, S., Desclée, B., Donnay, F., Eva, H.D., Lupi, A., Raši, R., Seliger, R., Simonetti, D., 2014. Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. Glob. Chang. Biol. 20, 2540–2554. https://doi.org/10.1111/gcb.12605.

Akkermans, T., Van Rompaey, A., Van Lipzig, N., Moonen, P., Verbist, B., 2013. Quantifying successional land cover after clearing of tropical rainforest along forest frontiers in the Congo Basin. Phys. Geogr. 34, 417–440. https://doi.org/10.1080/02723646.2013.855698.

Baker, M., Clausen, R., Kanaan, R., N'Goma, M., Roule, T., Thomson, J., 2003. Conflict Timber: Dimensions of the Problem in Asia and Africa- Volume III - African Cases. ARD, Inc.

Balandi, J.B., Meniko, J.P., Hulu, T., Sambieni, K.R., Sikuzani, Y.U., Bastin, J., Musavandalo, C.M., Jesuka, R., Sodalo, C., Pika, M., Bogaert, J., 2024. Anthropogenic effects on green infrastructure spatial patterns in Kisangani City and its urban – Rural gradient.

Barbier, E.B., Hochard, J.P., 2016. Does land degradation increase poverty in developing countries? PLoS One 11, e0152973. https://doi.org/10.1371/journal.pone.0152973.

Batsi, G., Sonwa, D.J., Mangaza, L., Ebuy, J., Kahindo, J.-M., 2021. Preliminary estimation of above-ground carbon storage in cocoa agroforests of Bengamisa-Yangambi forest landscape (Democratic Republic of Congo). Agroforest. Syst. 95, 1505–1517. https://doi.org/10.1007/s10457-021-00657-z.

Batsi, G., Sonwa, D.J., Mangaza, L., Ebuy, J., Kahindo, J.-M., 2020. Biodiversity of the Cocoa agroforests of the Bengamisa-Yangambi forest landscape in the democratic Republic of the Congo (DRC). https://doi.org/10.3390/f11101096.

Batsi, G., Sonwa, D.J., Mangaza, L., Ebuy, J., Kibambe, J.-P., Janssens, M., Ewango, C., 2023. Trajectories of cocoa production in Tshopo Province. ASC-TUFS Work. Pap. 3, 93–105. https://doi.org/10.51062/ascwp.3.0_93.

Benneker, C., Assumani, D., Maindo, A., Bola, F., Kimbuani, G., Lescuyer, G., Esuka, J., Kasongo, E., Begaa, S., 2012. Le Bois à L'ordre Du jour. Exploitation artisanale De Bois D'œuvre En RD Congo : Secteur porteur D'espoir Pour Le Développement Des Petites Et Moyennes Entreprises, Tropenbos International RD Congo. ed. Wageningen, Pays-Bas.

Betts, M.G., Wolf, C., Ripple, W.J., Phalan, B., Millers, K.A., Duarte, A., Butchart, S.H.M., Levi, T., 2017. Global forest loss disproportionately erodes biodiversity in intact landscapes. Nature 547, 441–444. https://doi.org/10.1038/nature23285.

Bolakonga, B., 2013. Influence De L'enclavement Sur Le Développement Rural (cas du Territoire d'Opala, District De La Tshopo, R.D. Congo). Université de Liège, Liège.

Bolakonga, B., Nkulu, J., Mushakulwa, W., 2017. Filières agricoles en République Démocratique du Congo: maïs, riz, bananes plantains et pêche.

Bourgoin, C., Betbeder, J., Le Roux, R., Gond, V., Oszwald, J., Arvor, D., Baudry, J., Boussard, H., Le Clech, S., Mazzei, L., Dessard, H., Läderach, P., Reymondin, L., Blanc, L., 2021. Looking beyond forest cover: an analysis of landscape-scale predictors of forest degradation in the Brazilian Amazon. Environ. Res. Lett. 16. https://doi.org/10.1088/1748-9326/ac31eb.

Bourgoin, C., Ceccherini, G., Girardello, M., Vancutsem, C., Avitabile, V., Beck, P.S.A., Beuchle, R., Blanc, L., Duveiller, G., Migliavacca, M., Vieilledent, G., Cescatti, A., Achard, F., 2024. Human degradation of tropical moist forests is greater than previously estimated. Nature 631, 570–576. https://doi.org/10.1038/s41586-024-07629-0.

Branthomme, A., Merle, C., Kindgard, A., Lourenço, A., Ng, W.-T., D'Annunzio, R., Shapiro, 2023. How Much Do Large-Scale and Small-Scale Farming Contribute to Global deforestation? Results from a Remote Sensing Pilot Approach. FAO, Rome. https://doi.org/10.4060/cc5723en.

De Beule, H., Jassogne, L., Van Asten, P., 2014. Cocoa: driver of deforestation in the Democratic Republic of the Congo? CCAFS Work. Pap. 31.

Dray, S., Dufour, A.-B., 2007. The **ade4** Package: implementing the duality diagram for ecologists. J. Stat. Soft 22. https://doi.org/10.18637/jss.v022.i04.

Dupuis, C., Lejeune, P., Michez, A., Fayolle, A., 2020. How can remote sensing help monitor tropical moist forest degradation ?— A systematic review. Remote Sens. (Basel) 12, 1–24. https://doi.org/10.3390/rs12071087.

Ernst, C., Mayaux, P., Verhegghen, A., Bodart, C., Christophe, M., Defourny, P., 2013. National forest cover change in Congo Basin: deforestation, reforestation, degradation and regeneration for the years 1990, 2000 and 2005. Glob. Chang. Biol. 19, 1173–1187. https://doi.org/10.1111/gcb.12092.

FAO, 2020a. Global Forest Resources Assessment 2020: Main report. Rome.

FAO, 2020b. Global Forest Resources Assessment 2020 – Key findings. FAO. https://doi.org/10.4060/ca8753en. Rome.

Feng, Y., Zeng, Z., Searchinger, T.D., Ziegler, A.D., Wu, J., Wang, D., He, X., Elsen, P.R., Ciais, P., Xu, R., Guo, Z., Peng, L., Tao, Y., Spracklen, D.V., Holden, J., Liu, X., Zheng, Y., Xu, P., Chen, J., Jiang, X., Song, X.P., Lakshmi, V., Wood, E.F., Zheng, C., 2022. Doubling of annual forest carbon loss over the tropics during the early twenty-first century. Nat. Sustain. 5, 444–451. https://doi.org/10.1038/s41893-022-00854-3.

FONAREDD, 2016. Programme Intégré Oriental. Central African Forest Initiative (CAFI), Kinshasa, RDC.

Galeana-Pizaña, J.M., Morales-Martínez, G., Perevochtchikova, M., 2024. Forest fates: Unraveling the peri-urban social–ecological trajectories in Mexico City's conservation land. Ambio. https://doi.org/10.1007/s13280-024-02082-9.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc. Natl. Acad. Sci. 107, 16732–16737. https://doi.org/10.1073/pnas.0910275107.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381. https://doi.org/10.1038/nature10425.

Gillet, P., Vermeulen, C., Feintrenie, L., Dessard, H., Garcia, C., 2016. Quelles sont les causes de la déforestation dans le bassin du Congo ? Synthèse bibliographique et études de cas. Biotechnol. Agron. Soc. Environ. https://doi.org/10.25518/1780-4507.13022.

Gond, V., Dubiez, E., Boulogne, M., Gigaud, M., Péroches, A., Pennec, A., Fauvet, N., Peltier, R., 2016. Dynamics of forest cover and carbon stock change in the democratic republic of Congo: case of wood-fuel supply basin for Kinshasa. Bois For. Trop.

Guidance, O., Agricultural, R., Chains, S., 2021. OECD-FAO practical business tool on deforestation. For. Degrad. Due Dilig. Agric. Supply Chains 361, 1–3. https://doi.org/10.1126/science.aau3445.

Hansen, A.J., Burns, P., Ervin, J., Goetz, S.J., Hansen, M., Venter, O., Watson, J.E.M., Jantz, P.A., Virnig, A.L.S., Barnett, K., Pillay, R., Atkinson, S., Supples, C., Rodríguez-Buritica, S., Armenteras, D., 2020. A policy-driven framework for conserving the best of Earth's remaining moist tropical forests. Nat. Ecol. Evol. 4, 1377–1384. https://doi.org/10.1038/s41559-020-1274-7.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693.

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Lippmann, M., Bennett, L., Raad, M., Hansen, M., Potapov, P., 2017. Using spatial statistics to identify emerging hot spots of forest loss. Environ. Res. Lett. 12, 024012. https://doi.org/10.1088/1748-9326/aa5a2f.

Hijmans, R.J., 2024. terra: spatial data analysis. Version 1.8-60.

Hourticq, J., Megevand, C., Tollens, E., Wehkamp, J., Dulal, H., 2013. Deforestation Trends in the Congo Basin : Reconciling Economic Growth and Forest Protection. The World Bank. https://doi.org/10.1596/978-0-8213-9742-8.

Ickowitz, A., Slayback, D., Asanzi, P., Nasi, R., 2015. Agriculture and Deforestation in the Democratic Republic of the Congo: A synthesis of the Current State of Knowledge. CIFOR-ICRAF. https://doi.org/10.17528/cifor/005458.

Imani, G., Moore-Delate, E., 2021. Rapport D'étude De La Consommation De Bois-Énergie Et Des équipements de Cuisson De La Ville De Kisangani. Centre de recherche forestière internationale (CIFOR), Bogor, Indonesia.

INS, 2021. Annuaire Statistique RDC 2020 (No. 9). Institut National de la Statistique (INS), KInshasa, RDC.

ITTO, 2002. ITTO Guidelines For the restoration, Management and Rehabilitation of Degraded and Secondary Tropical forests, International Tropical Timber Organization. ed, ITTO Policy Development Series. International Tropical Timber Organization, Yokohama.

Kabila, S., 2025. RDC : À Tshopo, La Technique De Contre-Saison Renforce La Résilience Des Agriculteurs Face Aux Aléas Climatiques. Mongabay. URL. https://fr.mongabay.com/2025/10/rdc-a-tshopo-la-technique-de-contre-saison-renforce-la-resilience-des-agriculteurs-face-aux-aleas-climatiques/. accessed 11.6.25.

Kissinger, G., Herold, M., De Sy, V., 2012. Drivers of Deforestation and Forest Degradation : A Synthesis Report for REDD+ Policymakers. Lexeme Consulting, Vancouver Canada.

Ladewig, M., Angelsen, A., Masolele, R.N., Chervier, C., 2024. Deforestation triggered by artisanal mining in eastern Democratic Republic of the Congo. Nat. Sustain. https://doi.org/10.1038/s41893-024-01421-8.

Lambin, E.F., Furumo, P.R., 2023. Deforestation-free commodity supply chains : myth or reality ? 237–261.

Lebailly, P., Michel, B., Ntoto, R., 2014. Quel développement pour la RDC? Conjonct. Congo. 45–63.

Mangaza, L., Makana, J.-R., Hubau, W., Sonwa, D., Batsi, G., Fayolle, A., 2022. Impacts du changement d'utilisation des terres sur la biomasse et la diversité dans le paysage forestier de la réserve de biosphère de Yangambi en République démocratique du Congo. BOIS. FORETS. DES. TROP. 353, 61–73. https://doi.org/10.19182/bft2022.353.a36836.

Mangaza, L., Sonwa, D.J., Batsi, G., Ebuy, J., Kahindo, J.-M., 2021. Building a framework towards climate-smart agriculture in the Yangambi landscape, Democratic Republic of Congo (DRC). Int. J. Clim. Change Strateg. Manag. 13, 320–338. https://doi.org/10.1108/IJCCSM-08-2020-0084.

Marquant, B., Mosnier, A., Bodin, B., Dessard, H., Feintrenie, L., Molto, Q., Gond, V., Bayol, N., 2015. Importance des forêts d'afrIque centrale. Les Forêts Du Bassin du Congo - Forêts Et Changements Climatiques. Weyrich, Belgium, pp. 17–35.

Masha, M., Bojago, E., Belayneh, M., Tadila, G., Abera, A., 2024. Quantifying forest degradation rates and their drivers in Alle district, southwestern Ethiopia: implications for sustainable forest management practices. Geomatica 76, 100009. https://doi.org/10.1016/j.geomat.2024.100009. –100009.

Mayaux, P., Descle, B., Clerici, M., Bodart, C., Lupi, A., Brink, A., Nasi, R., Belward, A., Mayaux, P., 2013. State and evolution of the African rainforests between 1990 and 2010.

Miharza, T., Wijayanto, N., Roshetko, J.M., Siregar, I.Z., 2023. Carbon stocks and footprints of smallholder cacao systems in Polewali Mandar, West Sulawesi. Front. Environ. Sci. 11. https://doi.org/10.3389/fenvs.2023.680984.

Molinario, G., Hansen, M., Potapov, P., Tyukavina, A., Stehman, S., 2020. Contextualizing landscape-scale forest cover loss in the Democratic Republic of Congo (DRC) between 2000 and 2015. Land. (Basel) 9, 1–22. https://doi.org/10.3390/land9010023.

Molinario, G., Hansen, M.C., Potapov, P.V., 2015. Forest cover dynamics of shifting cultivation in the Democratic Republic of Congo: a remote sensing-based assessment for 2000–2010. Environ. Res. Lett. 10, 094009. https://doi.org/10.1088/1748-9326/10/9/094009.

Moloba, Y.L., Mobula, V.M., Ntoto, R.M., Mahunguu, M.N., 2019. Dynamique Socio-Économique de l'adoption des Variétés Améliorées du Manioc en République Démocratique du Congo (RDC) : cas des Provinces de Kongo Central et la Tshopo. Eur. Sci. J. ESJ 15, 346. https://doi.org/10.19044/esj.2019.v15n15p346. –346.

Moonen, P.C.J., 2017. Integrated Assessment of Options to Reduce Emissions from Deforestation in Tshopo, DR Congo. KU Leuven, Leuven.

Moonen, P.C.J., Verbist, B., Boyemba Bosela, F., Norgrove, L., Dondeyne, S., Van Meerbeek, K., Kearsley, E., Verbeeck, H., Vermeir, P., Boeckx, P., Muys, B., 2019. Disentangling how management affects biomass stock and productivity of tropical secondary forests fallows. Sci. Total Environ. 659, 101–114. https://doi.org/10.1016/j.scitotenv.2018.12.138.

Moonen, P.C.J., Verbist, B., Schaepherders, J., Bwama Meyi, M., Van Rompaey, A., Muys, B., 2016. Actor-based identification of deforestation drivers paves the road to effective REDD+ in DR Congo. Land Use Policy. 58, 123–132. https://doi.org/10.1016/j.landusepol.2016.07.019.

Mosnier, A., Mant, R., Pirker, J., Bodin, B., Ndinga, R., Tonga, P., Havlík, P., Bocqueho, G., Maukonen, P., Obersteiner, M., Kapos, V., Tadoum, M., 2016. Modélisation des changements d'utilisation des terres pour la République du Congo 2000–2030. IIASA, COMIFAC, UNEP-WCMC.

Mudiayi, A., 2019. RDC : Greenpeace Afrique Alerte Sur Les Violations De Droits Humains Suite à Un Conflit Forestier Dans La Province De Tshopo [WWW Document]. Farmlandgrab-RDC. URL. https://farmlandgrab.org/post/view/29232. accessed 7.11.25.

Muteya, K., Nghonda, D.N.T., Kalenda, F.M., Strammer, H., Kankumbi, F.M., Malaisse, F., Bastin, J., Sikuzani, Y.U., Bogaert, J., 2023. Mapping and quantification of Miombo deforestation in the extent and changes between 1990 and 2022.

Nelson, A., Weiss, D.J., Etten, J.V., Cattaneo, A., Mcmenomy, T.S., Koo, J., 2019. A suite of global accessibility indicators. Sci. Data 1–9. https://doi.org/10.1038/s41597-019-0265-5.

Ngouhouo-Poufoun, J., Chaupain-Guillot, S., Ndiaye, Y., Sonwa, D.J., Njabo, K.Y., Delacote, P., 2024. Cocoa, livelihoods, and deforestation within the Tridom landscape in the Congo Basin: a spatial analysis. PLoS One 19, e0302598. https://doi.org/10.1371/journal.pone.0302598.

Nkwemoh, C.A., Tchindjang, M., 2018. Urban sprawl and agriculture : a case study of the Yaounde metropolis (Cameroon) 10, 45–58.

OIM, 2019. Cartographie De La Mobilité Des populations : Préparation et Réponse à La Maladie à Virus Ebola en RDC : Kisangani - Province De La Tshopo (7-8/12/2019). OIM, REPUBLIQUE DEMOCRATIQUE DU CONGO.

Omasombo, J.T., Otemikongo, J.M., Stroobant, É., Obotela, N.R., Bolakonga, B., Olela Nonga, D.S., Krawczyk, J., Laghmouch, M., 2020. Tshopo Africa: laborieuse construction politico-administrative coloniale muée en bastion du nationalisme congolais. Mus. R. Afr. Cent.

Ordway, E.M., Asner, G.P., Lambin, E.F., 2017. Deforestation risk due to commodity crop expansion in sub-Saharan Africa. Environ. Res. Lett. 12, 044015. https://doi.org/10.1088/1748-9326/aa6509.

Peltier, R., Dubiez, É., Diowo, S., Gigaud, M., Marien, J.N., Marquant, B., Peroches, A., Proces, P., Vermeulen, C., 2014. Assisted natural regeneration in slash-and-burn agriculture: results in the democratic republic of the congo. Bois For. Trop. 68, 67–79. https://doi.org/10.19182/bft2014.321.a31220.

Potapov, P., Hansen, M.C., Pickens, A., Hernandez-serna, A., Tyukavina, A., Turubanova, S., Zalles, V., Li, X., Khan, A., 2022. The global 2000-2020 land cover and land use change dataset derived from the landsat archive. First Results 3, 1–22. https://doi.org/10.3389/frsen.2022.856903.

Potapov, P.V., Turubanova, S.A., Hansen, M.C., Adusei, B., Broich, M., Altstatt, A., Mane, L., Justice, C.O., 2012. Quantifying forest cover loss in Democratic Republic of the Congo, 2000-2010, with Landsat ETM+ data. Remote Sens. Environ. https://doi.org/10.1016/j.rse.2011.08.027.

Renier, C., Addoah, T., Guye, V., Garrett, R., Van den Broeck, G., Zu Ermgassen, E.K.H.J., Meyfroidt, P., 2025. Direct and indirect deforestation for cocoa in the tropical moist forests of Ghana. Environ. Res.: Food Syst. 2, 025006. https://doi.org/10.1088/2976-601X/add01b.

Ross, C.W., Hanan, N.P., Prihodko, L., Anchang, J., Ji, W., Yu, Q., 2021. Woody-biomass projections and drivers of change in sub-Saharan Africa. Nat. Clim. Chang. 11, 449–455. https://doi.org/10.1038/s41558-021-01034-5.

Rudel, T.K., 2009. Tropical deforestation how do people transform landscapes ? Sociol. Perspect. Suburb. Sprawl Trop. Deforestation 1 115, 129–154.

Sasaki, N., Asner, G.P., Pan, Y., Knorr, W., Durst, P.B., Ma, H.O., Abe, I., Lowe, A.J., Koh, L.P., Putz, F.E., 2016. Sustainable management of tropical forests can reduce carbon emissions and stabilize timber production. Front. Environ. Sci. 4, 1–13. https://doi.org/10.3389/fenvs.2016.00050.

Shapiro, A., D'Annunzio, R., Desclée, B., Jungers, Q., Kondjo, H.K., Iyanga, J.M., Gangyo, F.I., Nana, T., Obame, C.V., Milandou, C., Rambaud, P., Sonwa, D.J., Mertens, B., Tchana, E., Khasa, D., Bourgoin, C., Ouissika, C.B., Kipute, D.D., 2023. Small scale agriculture continues to drive deforestation and degradation in fragmented forests in the Congo Basin (2015–2020). Land Use Policy. 134. https://doi.org/10.1016/j.landusepol.2023.106922.

Shamamba, D.B., Bashangwa Mpozi, B., Egesa, A.O., Basengere, E.B., 2023. Adaptation to land scarcity among small-scale farming households in South Kivu in the Democratic Republic of the Congo. Front. Sustain. Food Syst. 7. https://doi.org/10.3389/fsufs.2023.1277031.

Shapiro, A.C., Bernhard, K.P., Zenobi, S., Müller, D., Aguilar-Amuchastegui, N., d'Annunzio, R., 2021. Proximate causes of forest degradation in the Democratic Republic of the Congo vary in space and time. Front. Conserv. Sci. 2. https://doi.org/10.3389/fcosc.2021.690562.

Sonwa, D.J., Mangaza, L., Batsi, G., Ebuy, J., 2020. Preliminary reflections of the potential of climate smart agriculture (CSA) in the Tshopo Province (DRC).

Taubert, F., Fischer, R., Groeneveld, J., Lehmann, S., Müller, M.S., Rödig, E., Wiegand, T., Huth, A., 2018. Global patterns of tropical forest fragmentation. Nature 554, 519–522. https://doi.org/10.1038/nature25508.

Tegegne, Y.T., Lindner, M., Fobissie, K., Kanninen, M., 2016. Evolution of drivers of deforestation and forest degradation in the Congo Basin forests: exploring possible policy options to address forest loss. Land Use Policy. 51, 312–324. https://doi.org/10.1016/j.landusepol.2015.11.024.

The World Bank Group, 2023. World Bank Open Data [WWW Document]. World Bank Open Data. URL https://data.worldbank.org (accessed 4.29.25).

Tyukavina, A., Hansen, M.C., Potapov, P., Parker, D., Okpa, C., Stehman, S.V., Kommareddy, I., Turubanova, S., 2018. Congo Basin forest loss dominated by increasing smallholder clearing. Sci. Adv. 4, eaat2993. https://doi.org/10.1126/sciadv.aat2993.

United Nations, Department of Economic and Social Affairs, Population Division, 2024. World population prospects: the 2024 revision [WWW Document]. Population

Division Data Portal. URL https://population.un.org/dataportal/data/indicators/49/locations/180/start/2020/end/2100/table/pivotbylocation?df=aed06eaa-318f-4d48-b6c0-2f63be555cb8 (accessed 4.29.25).

Van Hoof, F., 2011. Changer l'agriculture congolaise en faveur des familles paysannes_ des dynamiques paysannes dans les différentes provinces de la RD.

Van Vliet, N., Adams, C., Vieira, I.C.G., Mertz, O., 2013. "Slash and burn" and "shifting" cultivation systems in forest agriculture frontiers from the brazilian Amazon. Soc. Nat. Resour. 1920, 1454–1467. https://doi.org/10.1080/08941920.2013.820813.

Van Vliet, N., Mertz, O., Heinimann, A., Langanke, T., Pascual, U., Schmook, B., Adams, C., Schmidt-vogt, D., Messerli, P., Leisz, S., Castella, J., Jørgensen, L., Birch-thomsen, T., Hett, C., Bech-bruun, T., Ickowitz, A., Chi, K., Yasuyuki, K., Fox, J., Padoch, C., Dressler, W., Ziegler, A.D., 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers : a global assessment. Glob. Environ. Change 22, 418–429. https://doi.org/10.1016/j.gloenvcha.2011.10.009.

Van Vliet, N., Vanegas, L., F, S., D, C., S, L.B., E, D., OO, G., N, G., C, F., E, E., J-C, S., M, G., G, L., A, B., R, N., C, J., I, A., L, B., J, M., F, H., R, F., SA, M.B.Z., E, G., A, K., F, Y., D, N., 2015. Diagnostic Approfondi Pour La Mise En Oeuvre De La Gestion Communautaire De La Chasse villageoise: Guide pratique Et Exemples D'application En Afrique centrale (Guide 1). Center for International Forestry Research (CIFOR). https://doi.org/10.17528/cifor/005706.

Vancutsem, C., Achard, F., Pekel, J.F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., Nasi, R., 2021. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. Sci. Adv. 7, 1–21. https://doi.org/10.1126/sciadv.abe1603.

Verbeeck, H., Boeckx, P., Steppe, K., 2011. Tropical forests: include Congo basin. Nature 479, 179. https://doi.org/10.1038/479179b. –179.

Wickham, H., 2016. ggplot2: Elegant Graphics For Data Analysis, 2nd Edition. Use R! Springer International Publishing, Houston, Texas, USA. https://doi.org/10.1007/978-3-319-24277-4.

Windey, C., 2020. Abstracting Congolese forests: mappings, Representational narratives, and the Production of the Plantation Space Under REDD+. Institute of Development Policy and Management (IOB), University of Antwerp 1.

WRI, 2025. Fires Drove Record-Breaking Tropical Forest Loss in 2024 [WWW Document]. World Resources Institute. URL. https://gfr.wri.org/latest-analysis-deforestation-trends. accessed 6.15.25.

Zheng, X., Chen, J., Zou, Z., Zhen, S., Liu, S., Li, Jiazheng, Zuo, X., Lin, S., Wu, Z., Zhang, L., Lin, Q., Yan, G., Hong, T., Qiu, R., Li, Jian, Wu, C., Hu, X., 2025. Sprawling roads enhanced tropical forest loss during the period 2001–2020. Commun. Earth Environ. 6, 1–11. https://doi.org/10.1038/s43247-025-02158-8.