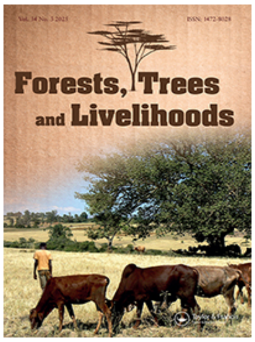

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Contribution of artisanal chainsaw milling to forest degradation in Central Africa

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ABSTRACT

Chainsaw milling is a neglected activity in forestry policies, because it is often carried out informally and by a large number of dispersed operators. Artisanal logging is also widely accused of contributing to forest degradation and deforestation. To test this hypothesis, we visited 120 chainsaw milling sites in Cameroon and the Democratic Republic of Congo (DRC) to assess its impact on the state of the forest and to analyse the rationales of artisanal loggers. Our findings paint a mixed picture of this activity: (1) 84% of the trees felled by chainsaw millers are located in the 'undisturbed' forest zone but at a short distance from degraded forest zones; (2) even when carried out without a licence, chainsaw milling complies with most of the legal technical requirements, except for the dabema species in Cameroon; (3) chainsaw millers adopt two profit maximisation strategies: in the DRC, the very high price of afrormosia and sapelli explains why these two species are still exploited intensively. In Cameroon, conversely, the low prices of sawn timber on the national market have encouraged operators to diversify the species felled to minimise the cost of removing sawn timber from the forest. Various interventions to regulate and professionalise chainsaw milling are needed to support the diversity of their production strategies, but two measures seem essential: formal chainsaw milling permits need to be made available at lower cost and the range of timber species on the national markets should be expanded, especially in DRC.

KEYWORDS

Illegal logging; deforestation; small-scale timber harvest; Cameroon; Democratic Republic of Congo; Congo basin

1. Introduction

For the past decade, the African continent has been experiencing accelerating rates of deforestation and forest degradation, in contrast to the American and Asian continents (FAO 2021). This is particularly true for tropical moist forests in Central Africa (Vancutsem et al. 2021). Although several factors explain this strong deforestation trend, in the countries bordering the Congo Basin slash-and-burn agriculture is the most significant cause (Tyukavina et al. 2018; Branthomme et al. 2023). This land use is mainly geared towards the production of food products for

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rural and urban consumers. However, small-scale farming is almost always combined with other uses of natural resources, such as the collection of non-timber forest products, hunting, fuelwood production or artisanal timber chainsaw milling. These activities take place within a 'rural complex' made up of a mosaic of natural spaces anthropized to varying degrees (crop fields, more or less ancient fallows, agroforestry plantations, wetlands, secondary forests, etc.). Access to and the use of these areas are governed by customary rules (Vermeulen et al. 2011; Ebai Ndip et al. 2023; Shapiro et al. 2023).

A very large proportion of the activities carried out by rural populations take place in this rural complex and feed domestic industries that are, often, informal but crucial to the country's economy. This is particularly true of artisanal small-scale logging (Robiglio et al. 2012; Shapiro et al. 2023), whose sawn timber supplies national and regional markets. In Central Africa, artisanal chainsaw milling has amounted to a greater volume of timber harvested than the industrial sector for at least the last decade (Lescuyer and Cerutti 2013; FAO 2017). In the countries of the Congo Basin, as in Ecuador (Sierra 2001) or Papua New Guinea (Scudder et al. 2019), the need for construction timber is significant and artisanal logging largely meets this demand, while remaining a blind spot in forestry policy due to the widespread informality of this activity (Carias et al. 2022).

While chainsaw milling is provided for in all Central African forestry codes, and is restricted to unclassified forest areas, this activity almost always remains informal, as it is carried out without the permits provided for in national regulations. These include Timber Exploitation Permits in Cameroon and Artisanal Cutting Permits in the Democratic Republic of Congo (DRC). These permits remain very difficult to obtain for artisanal loggers for technical, bureaucratic and financial reasons (Lescuyer et al. 2014, 2016; Jaza-Folefack and Darr 2022).

The informality of chainsaw milling is not the only feature shared by Central African countries. The modus operandi of artisanal logging is also similar in all of these countries: a chainsaw miller acquires one or more trees from local owners of the land and/or the tree according to customary rights (Lescuyer et al. 2013). The price of the standing tree is set according to the grade of the wood. Then, an operator equipped with a chainsaw – or sometimes a pit saw – and a small team of assistants cut down the trees and produce sawn timber to the dimensions determined by the markets. These sawn products are then taken to an evacuation point, where they are loaded onto vehicles and transported to urban markets. All these operations are carried out without official authorisation and perpetuate a chain of corruption stretching from the felling and processing of trees to their transport to urban markets and sale to urban buyers (Cerutti et al. 2013).

Although all chainsaw millers share the same operating methods, use the same means of transport and supply the same markets, there are two ways of conducting this activity, which are equally common. On the one hand, a first category of independent chainsaw millers fell a few trees, process them into sawn timber and then sell them at markets. This is an uncertain practice, as the volume and price of the products have not been negotiated in advance, but it limits transaction costs. Conversely, a second category of artisanal operators secures an order in advance and generally receives an advance payment before setting off to begin their activities in the forest. They also often have the 'protection' of their sponsor in case of difficulties, for example with the administration. This type of chainsaw milling is therefore more secure, but the operators receive a smaller share of the sale price of their sawn timber.

All chainsaw millers focus primarily on species with high economic value, whose products can be easily sold. They also look for large-diameter trees to optimize log processing into sawn timber (Cerutti and Lescuyer 2011). However, chainsaw millers are limited by their technical and financial resources: on the one hand, they need only to fell two or three trees to fill the vehicle that will bring the sawnwood to market; on the other, they are incentivized to stay close to the evacuation routes, optimizing the opportunities offered by tracks and waterways, to limit the cost of getting the sawnwood out of the forest. As a result, the intensity of forest degradation due to felling gaps should decrease sharply with the distance sawn timber is evacuated. However, the spatial distribution of felling gaps can be explained by a multiplicity of factors whose importance varies according to the context, and which are difficult to anticipate.

Very few publications have attempted to assess the specific contribution of chainsaw milling to deforestation and forest degradation in Central Africa. An important recent study (Shapiro et al. 2023) partly assessed the extent of its impact by analyzing satellite images but did not seek to understand or describe the underlying practices and rationales of chainsaw millers. In the discourse of national administrations, donors and NGOs, 'wild sawing' is systematically classified as a deforestation activity, without any data being produced or mobilized to support these statements. Research organizations often struggle due to inappropriate satellite images – the gaps are too small, scattered and assimilated into other land uses to be easily spotted – and global macro-economic data – this informal sector is not subject to statistical monitoring – when estimating its impact on the country's forests or economy.

Based on three case studies, the dual aim of this article is to estimate the impact of artisanal chainsaw milling on deforestation and forest degradation and to analyze the main socio-economic and technical factors influencing artisanal operators' decisions. Four hypotheses are formulated to answer these two questions:

- Chainsaw logging and milling contribute more to forest degradation than to deforestation. Hence, felling gaps would be located within undisturbed or little-disturbed forests, contributing to their future degradation, rather than within degraded forests, contributing to their future deforestation.
- The gradient of landscape degradation influences the practices of small-scale operators: the more degraded the landscape, the greater the distance sawn timber has to be evacuated.
- Even when carried out without a permit, chainsaw milling complies with most of the technical legal requirements: tree felling diameters are above the minimum diameters set by the forestry authorities, the species harvested are not on the list of endangered species, and trees are cut in rural areas and not in gazetted areas.
- The increasing distance involved in transporting sawn timber to evacuation routes (trails or rivers) encourages operators to favour wood species with high commercial value (to maximize the sale price of sawn timber) and large-diameter trees (to optimize their log-to-sawn timber ratio).

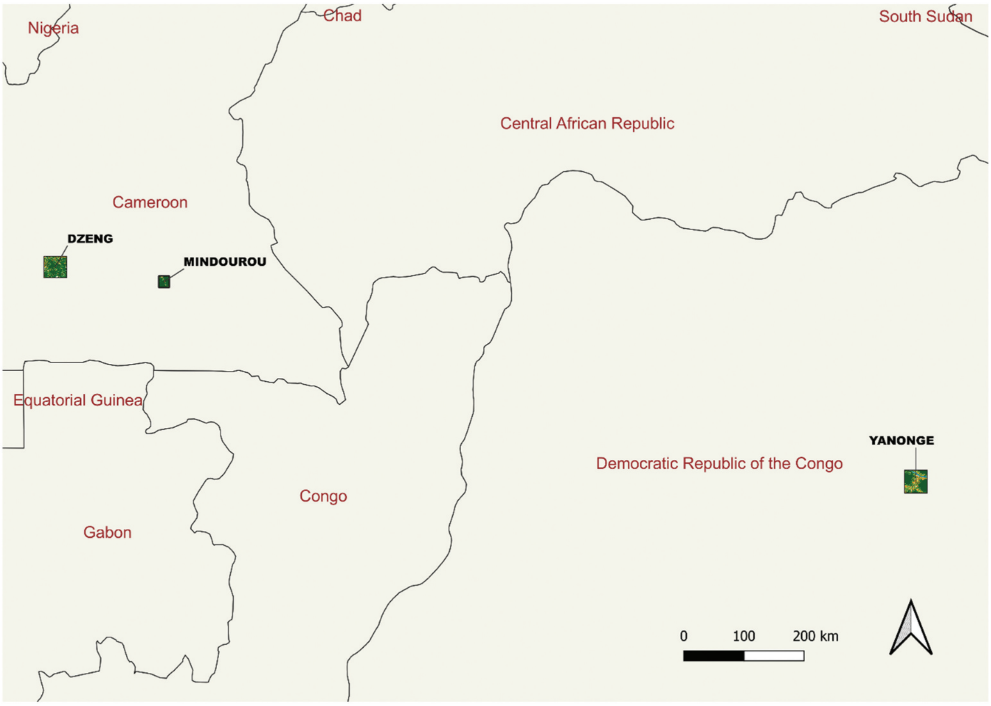

Figure 1. Location of study sites.

2. Study areas

Three chainsaw milling sites were selected in Central Africa: the communes of Mindourou and Dzeng in Cameroon, and the Yalikandja-Yanonge sector in the Democratic Republic of Congo (Figure 1, Table 1).

These three sites were selected because they are located in forest massifs with varying levels of anthropic pressure and forest degradation. The level of anthropic pressure results from the combination of human density and distance from a major urban market (Yaoundé

Table 1. Main characteristics of study sites.

	Mindourou	Dzeng	Yanonge
Country	Cameroon	Cameroon	DRC
Region/Province	East	Centre	Tshopo
Department/Territory	Upper Nyong	Nyong and So'o	Isangi
Municipality/Sector	Mindourou	Dzeng	Yalikandja-Yanonge
Latitude	3°10′N – 3°57′N	3°45′N – 3°79′N	0°35′N – 0°49′N
Longitude	13°37′E – 13°44′E	11°55′E – 11°82′E	24°43′E – 24°79′E
Dominant ecosystem (Réjou-Méchain et al. 2021)	semi-deciduous evergreen transitional forest	degraded semi-deciduous forest	semi-deciduous evergreen transitional forest
Surveyed area (km^2)	346	1,347	1,439
Human density (inhab/km^2)	4.6	9.5	34
Distance to market by road and/or river (km)	280	40	60
Volume of sawn timber produced in 2021 (m^3)	267	5203	[200–300]

in Cameroon and Kisangani in the DRC), as shown in Table 1, as is generally seen in Central Africa (Marien and Bassaler 2011).

The commune of Dzeng is under considerable pressure due to high human density and the short distance to the Yaoundé market (Guizol et al. 2021a). There, artisanal logging is intense (Zengle Ntouh 2022). Conversely, the commune of Mindourou is sparsely populated and far from the capital (Guizol et al. 2021b). Therefore, artisanal timber harvesting is modest (Zengle Ntouh 2022).

The Yanonge sector's context falls between those of the two Cameroonian communes: it is densely populated but access to the city of Kisangani is difficult by river or road, especially for bulky goods, which explains the low presence of artisanal chainsaw milling in this area. A dozen operators with chainsaws are involved on an ad hoc basis in the sector, supplying the Kisangani market as best they can, mainly from areas close to the river. Away from the river, timber exploitation is chiefly carried out by loggers using hand saws, to meet local demand for furniture, frames and coffins (Lucas et al. 2021).

3. Materials and methods

Two sets of survey and analysis techniques were used to conduct this research. The first survey protocol is applied in the felling gaps opened by artisanal loggers. The second set of methods involves the analysis of satellite remote sensing maps to estimate the developments of deforestation and degradation of forest ecosystems at the study sites.

3.1. Survey protocol in felling gaps

Data were collected in November 2021 in Cameroon, and in May 2021 and March 2022 in the DRC. Felling sites were chosen based on the availability of operators to take the team to them, and their accessibility in terms of distance and terrain to be traversed. Artisanal logging sites close up quickly, so all the sites visited were less than three years old. Each gap corresponds to the felling of a single tree by the logger but other smaller trees all around may be broken by the fall of the main tree. In total, data were collected in 48, 33 and 39 felling gaps at the Yanonge, Mindourou and Dzeng sites, respectively. In each of these felling sites, a set of data was collected according to an identical protocol and with identical equipment (Table 2).

On a number of occasions, several items of information were missing, partly because certain parts of the tree to be measured were no longer present (e.g. log or tree absent from the site) and partly because the operator could no longer provide reliable information.

3.2. Analysis of cartographic data

Forest cover data were produced by the European Commission's Joint Research Centre (JRC). They are mapped by tropical rainforest type, using Landsat image time series at 30 m resolution. The approach used by the JRC is based on the analysis of each valid observation (cloud-free pixels) of Landsat data and enables short-lived disturbances to be identified for degradation analysis. The JRC 'Annual Change' collection between 1990 and 2022 was used as the main source of data. This collection of 33 map layers describes, for each year, the extent of undisturbed forest and the changes observed (deforestation, degradation and

Table 2. Information collected on felling gaps.

Data	Means used
GPS point at stump level	Average of six GPS points measured at the stump of the felled tree with a Garmin 60XCS GPS.
GPS point of the gap	Average of six GPS points measured within the gap (boundary between the canopy and the trunk of the felled tree) with a Garmin 60XCS GPS.
Height of felled tree (m)	Distance between stump and farthest branch measured by laser rangefinder (LaserAce(R) 300 model)
Log length (m)	Distance between stump and overstump measured with a laser rangefinder (LaserAce(R) 300 model)
Stump diameter, overstump diameter, diameter at 1m30 (cm)	Tape measure
Volume of sawn timber produced (m3)	Operator's declaration
Gap length (m)	Distance between the centre of the gap and the nearest intact trees, measured with a laser rangefinder in the direction of the tree's fall.
Gap width (m)	Distance between the centre of the gap and the nearest intact trees, measured with a laser rangefinder at the overhang, perpendicular to the tree's fall.
Surface of felling gap	Drone image acquired with DJI Mavic drones (DJI pro and DJI 2 models) equipped with an RGB camera. The Pix4D flight application was used to program flight plans at an altitude of 150 m and an overlap rate of 80%. Orthophotographs were created using OpenDroneMap (https://github.com/OpenDroneMap/ODM) software. Polygons delimiting the boundary between canopy and ground were manually discriminated using QGIS software.
Tree species vernacular name	Operator's declaration
Year of operation	Operator declarations, confirmed or invalidated by viewing monthly series of PLANET optical satellite images.

regeneration). This information is used to estimate the net deforestation and degradation of a forest massif over a period since 1990, by combining annual data. We have used the CCR classification to categorize each felling site as 'undisturbed forest', 'degraded forest' or 'deforested area', as well as recording any changes in class in the years following the felling and the distances of the gaps from these three land-use classes. Field experience leads us to mitigate the term 'undisturbed forest' used by the JRC given that some old or small-scale impacts may occur in such forests (Dupuis et al. 2023). At least in the study sites, the so-called 'undisturbed forests' could be more accurately described as minimally disturbed forests, still maintaining a largely closed canopy.

Spatial information on the road and river networks used to evacuate sawn timber from the three study sites was uploaded to the OpenStreetMap geographic database (OpenStreetMap contributors, 2021, http://download.geofabrik.de/). These data were used to calculate the distance of each logged tree (assimilated to the centroid of its borehole) from the road and hydrographic network.

4. Results

4.1. Deforestation and forest degradation facies of sampled landscapes

The gradient of anthropogenic pressure influences the level of deforestation and forest degradation in these three landscapes (Figure 2, Table 3). Forest cover data were produced by the JRC using Landsat time series with 30-meter resolution between 1990 and 2022.

All three sites have been experiencing deforestation and forest degradation over the past 30 years, albeit at different rates and to different extents. In Mindourou, rates of deforestation and forest degradation remain modest but have been increasing since 2012, especially along the road axis running through the area. In Dzeng, forest degradation has been

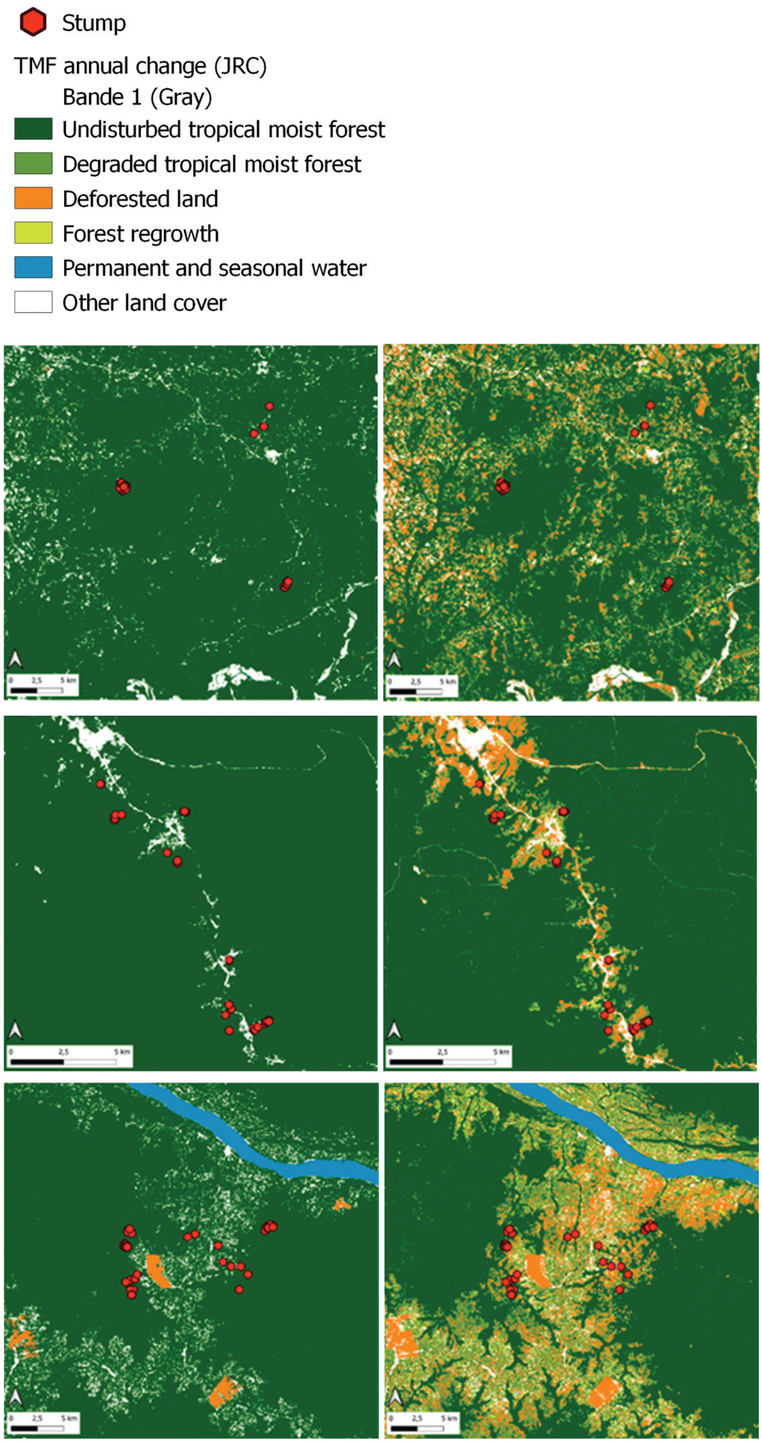

Figure 2. Forest cover maps and location of the studied felling sites for Dzeng in 1990 (a) and 2022 (b), Mindourou in 1990 (c) and 2022 (d), and Yanonge in 1990 (e) and 2022 (f). (data source: JRC).

Table 3. Trends in deforestation and forest degradation between 1990 and 2022 for the three sites studied.

	Mindourou	Dzeng	Yanonge
Undisturbed forests in 1990	98%	94%	90%
Undisturbed forests in 2022	88%	63%	55%
Deforested areas in 1990	0%	0%	1%
Deforested areas in 2022	4%	9%	12%
Degraded forest areas in 1990	0%	1%	1%
Degraded forest areas in 2022	5%	23%	23%

Table 4. Distribution of felling sites among the three land-use classes.

	Land-use class		
Sites sampled	Undisturbed forest	Degraded forest	Deforested area
Mindourou	28	4	1
Dzeng	38	1	0
Yanonge	35	8	3

increasing since the 2000s and has likely contributed to a sharp rise in deforestation since 2018. In Yanonge, forest degradation has been continuous since 1998, while deforestation has been increasing since 2014.

4.2. Geographical, ecosystem and administrative locations of felled trees

Each tree stump felled by chainsaw millers was geolocated, as shown in Figure 3. Three pieces of information were generated from this data: (1) the land-use class where the logging took place i.e. undisturbed forest, degraded forest or deforested area according to the JRC nomenclature; (2) the distances between the felling site and the fronts of forest degradation and deforestation; (3) the distance between the felling site and the road or river evacuation route.

The vast majority of trees are felled in the forests mapped as undisturbed at all three study sites. Compared with the other two sites, a larger proportion (24%) of trees felled came from degraded or deforested areas at Yanonge, where the degraded landscape facies is the most extensive (Table 4).

The distances between each felled tree and the nearest limits of degraded forest and deforested area are plotted in Figure 4 for the three study sites.

The average evacuation distances of the sawn products for each of the study sites are estimated in Table 5. For the Dzeng and Mindourou sites, all sawn timber is transported by road. At Yanonge, sawings produced in the eastern part of the site are transported by river, while all other sawn products are transported by track.

The average distances between felled trees and the closest forest degradation and deforestation fronts are short for the Mindourou and Yanonge sites. At these two sites, the deforestation trend closely follows that of forest degradation, with only 50–70 metres separating the two fronts. But while these two trends appear to be strongly correlated, their magnitude differs greatly between the two sites since the degradation-deforestation combination operates more than two kilometres from the evacuation routes at Yanonge, whereas it takes place less than 700 meters from the main track at Mindourou.

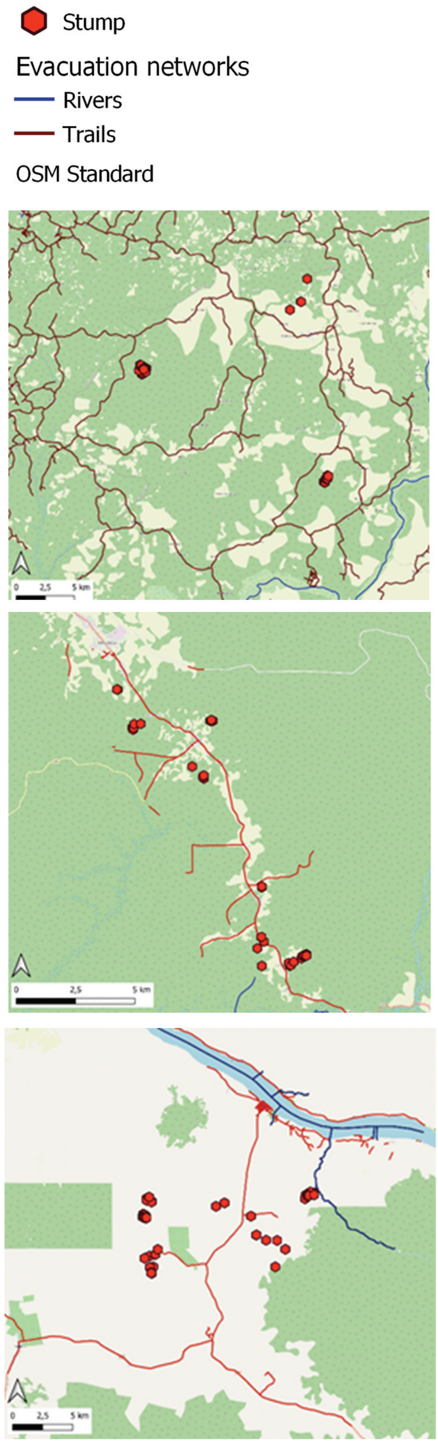

Figure 3. Locations of sampled felling sites at Dzeng (a), Mindourou (b), Yanonge (c).

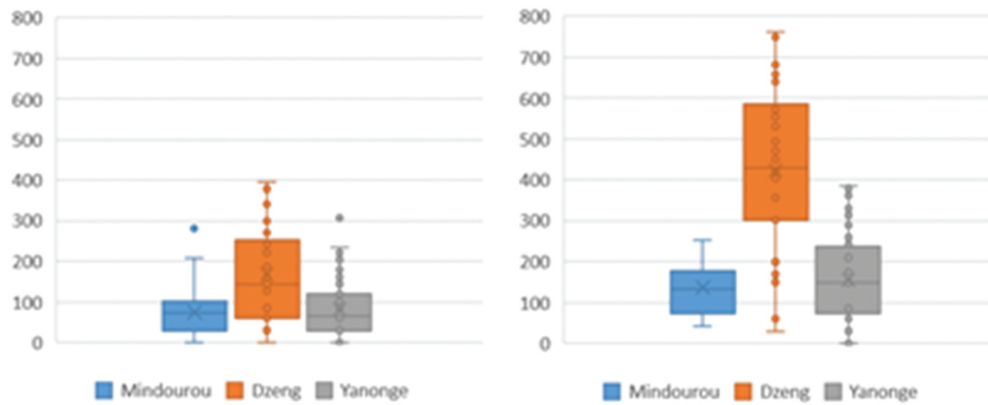

Figure 4. Distance (in metres) between felling sites and the 'degradation' class (a) and the 'deforestation' class (b) of the JRC 'annual change' collection.

Table 5. Average distances (in metres) between felled trees and deforestation front, forest degradation front and evacuation route.

	Distance to degradation front	Distance to deforestation front	Evacuation distance
Mindourou	82	132	692
Dzeng	185	440	1568
Yanonge	82	155	2236

Dzeng presents an intermediate configuration with a 250-meter-wide strip of forest degradation, situated 1.5 kilometres from the nearest deforested area.

Dzeng is also unusual in that 46% of the trees felled by artisanal loggers are located in the communal forest i.e. the permanent forest estate where such a practice is prohibited. Conversely, in Mindourou and Yanonge, all artisanal logging gaps are located in rural areas.

4.3. Spectrum of species harvested

At each of the three sites sampled, chainsaw millers harvest between 10 and 13 tree species (Table 6). This diversity of species is counterbalanced at each site by the predominance of two flagship species, which make up a significant share of the total trees felled.

Dabema (*Piptadeniastrum africanum)* is the species most commonly felled by artisanal loggers in Cameroon's two communes. This species was very rarely found on urban timber markets in Cameroon in 2009 (Cerutti and Lescuyer 2011) and barely present in 2016 (Lescuyer et al. 2016), which is evidently no longer the case in 2023. Conversely, ayous (*Triplochiton scleroxylon*) and kosipo (*Entandrophragma candollei*) have been common species on Cameroon's domestic markets for at least 15 years. Similarly, sapelli (*Entandrophragma cylindricum*) and afrormosia (*Pericopsis elata*) are traditionally the most widely sold species in the markets of Kisangani in the DRC (Lescuyer et al. 2014).

Of the species exploited by artisanal loggers, only afrormosia was listed in Appendix II of the Washington Convention in 2023.

Table 6. Tree species harvested by the sample of chain sawmillers in the three sites.

			Location		
Usual name of tree species	Genus	Species	Dzeng, Cameroon	Mindourou, Cameroon	Yanonge, DRC
Afrormosia	*Pericopsis*	*elata*			*15*
Aiélé	*Canarium*	*schweinfurthii*			*1*
Ayous	*Triplochiton*	*scleroxylon*	*7*		
Boliti	*unidentified*	*unidentified*			*1*
Bossé clair	*Leplaea*	*cedrata*		*1*	*1*
Dabema	*Piptadeniastrum*	*africanum*	*13*	*17*	
Dibétou	*Lovoa*	*trichilioides*	*2*		
Douka (Makoré)	*Tieghemella*	*africana*		*1*	
Emien	*Alstonia*	*boonei*	*2*	*1*	*2*
Essia	*Petersianthus*	*macrocarpus*		*2*	
Eveuss	*Klainedoxa*	*gabonensis*	*1*		
Iroko	*Milicia*	*excelsa*			*1*
Kosipo	*Entandrophragma*	*candollei*	*2*	*5*	*2*
Limbali	*Gilbertiodendron*	*dewevrei*			*1*
Lotofa (Nkanang)	*Sterculia*	*rhinopetala*	*3*		
Lusambya (Atag)	*Markhamia*	*lutea*	*1*		
Movingui	*Distemonanthus*	*benthamianus*	*2*		
Mubala (Mbalaka)	*Pentaclethra*	*macrophylla*		*1*	
Obero (quinine)	*Picralima*	*nitida*	*2*		
Okan	*Cylicodiscus*	*gabonensis*		*1*	
Onzabili	*Antrocaryon*	*klaineanum*		*1*	
Safoutier	*Dacryodes*	*edulis*		*1*	
Sapelli	*Entandrophragma*	*cylindricum*	*1*	*2*	*22*
Tali	*Erythrophleum*	*suaveolens*	*2*		
Tola	*Gossweilerodendron*	*balsamiferum*	*1*		*2*

4.4. Chainsaw millers' operational strategies

The number of trees felled and the choice of species depend on the chainsaw millers' production strategies. These operators seek to maximize their profits and rely on three influential variables to do so: the diameter of the tree, which enables them to maximize the coefficient of processing of the log into sawn products, the evacuation distance, which is their main cost, and the selling price of the sawnwood on the domestic market. This information has been summarized in Table 7 by combining data from the three study sites and the urban market prices observed in 2024 in Kisangani and Yaoundé.

Chainsaw millers adopt two profit maximization strategies. In the DRC, the very high price of afrormosia and sapelli explains why these two species are exploited intensively by

Table 7. Main variables in chainsaw millers' choice of production strategy.

	Cameroon				DRC		
	Dabema	Ayous	Kosipo	Other species	Sapelli	Afrormosia	Other species
Number of trees felled	30	7	5	26	23	16	7
Average Diameter at Breast Height (cm)	90	112	129	91	121	92	99
Minimum harvestable diameter (MHD) (cm)	80	80	80	–	80	70	
% of trees under MHD	27%	0%	0%	–	9%	0%	
Average evacuation distance (m)	1 069	1 501	877	1 228	1 473	3 198	2 499
Average selling price on urban markets (F.CFA/ m^3, 2024)	114 066	74 294	111 612	118 630	313 036	331 698	144 888

The average conversion rate in 2024 was 1US$ = 606,30 XAF (CFA Francs).

chainsaw millers, as was already the case a decade ago (Lescuyer et al. 2014). In Cameroon, the modest prices at which sawn timber is sold have encouraged operators to diversify the species felled in order to minimize the cost of evacuating sawn timber out of the forest. Dabema has thus become the flagship species for artisanal loggers, whereas it was scarcely traded in Yaoundé markets over the past 15 years (Cerutti and Lescuyer 2011; Lescuyer et al. 2016).

Very few trees are felled to diameters below the minimum harvestable diameter (MHD), except for the dabema species. Therefore, for the purposes of this study, and except for dabema, chainsaw milling complies with this national regulation.

5. Discussion

5.1. Study limits

The choice to work in three study sites along a gradient of forest degradation increased the cost of implementing this research and contributed to a reduction in the sample size of felling gaps. The limited number of gaps studied does not allow statistical or geographical simulation of the overall impact of this work. However, a complementary ongoing remote sensing approach will provide some insight into the overall impact. The fieldwork carried out in each logging plot also made it possible to gather information on the species and trees harvested, as well as on the destination of the sawn timber: this is an essential step in understanding the logic of these stakeholders and thinking about realistic ways of improving the sustainability of their work.

This research may also suffer from a selection bias since the choice of artisanal logging sites was not random. Possibly, the Cameroonian operators preferred to show logging sites located in the forest, which was situated relatively close to the villages, whereas the Congolese operators more often chose trees located in fallow land or on the edge of the forest. It is not possible to assess the significance of such a bias in the absence of exhaustive data on the number and extent of artisanal logging sites in the two countries.

5.2. Chainsaw milling and forest degradation

The vast majority (84%) of trees felled by chainsaw millers are located in the 'undisturbed' forest zone but at short distances from degraded forest areas (80-180 m). Chainsaw milling is therefore not directly involved in the front line of degradation (let alone deforestation) but anticipates it. However, the expansion trends of the rural mosaic are well documented in Central Africa (Nounamo and Yemefack 2002; Robiglio 2008) and the information collected at the three study sites shows that artisanal logging anticipates and prepares the process of forest degradation and subsequent deforestation. It enables customary owners to assert a customary right of appropriation over certain areas not yet claimed by other rights-holders, by felling the trees of commercial value (or selling them to operators) (Lescuyer 2013). This is the famous practice of 'axe right' (Diaw 1997). The second major advantage of felling trees is that it prepares land that will be converted to plantations or crop fields in subsequent years, as the short distance of 50-250 m between degradation and deforestation fronts shows.

The degree of degradation of the landscape has an impact on the modus operandi of chainsaw milling since the distance sawn timber is evacuated is positively correlated with the state of degradation of the site and scarcity of trees of interest. But the level of degradation has little effect on the scale of chainsaw milling: the permanent demand for sawn timber and agricultural products, and the need to expand fields and plantations, produce a spatial trend for chainsaw milling that is similar in all three landscapes studied, as Shapiro et al. (2023) also showed.

5.3. Chainsaw milling, more informal than illegal

Only one species (afrormosia) of all those sought by operators is on the endangered species list but its exploitation is not prohibited within the annual quota established by the Washington Convention.

With the exception of dabema in Cameroon and, to a lesser extent, sapelli in Yanonge, the vast majority of felled trees have a diameter greater than the MHD set for each species by the forestry authorities. In 27% of cases in our sample, demand for dabema and its availability close to evacuation routes seem to have led some operators to select trees with diameters incompatible with regulatory requirements.

In Yanonge as in Mindourou, all trees are cut in rural areas and not in gazetted areas, as required by national regulations. Therefore, customary rights regulate the harvesting of these trees. In Dzeng, on the other hand, around half of the trees felled by chainsaw millers are located in the communal forest, which is legally reserved for industrial timber exploitation according to a sustainable management plan. There are two reasons for this illegal harvesting in Dzeng. Firstly, the Yaoundé market is close and exerts strong pressure on forest resources. Secondly, the boundaries of the communal forest were drawn up with little regard for the customary rights of the local population. As a result, they find themselves taking a significant proportion of their agricultural and forestry resources from the communal forest (Guizol et al. 2021a).

The chainsaw miller's predilection for large-diameter trees, the presence of only one endangered species among all those exploited, and the location of the majority of felling gaps in rural areas show that most artisanal chainsaw milling practices comply with the main regulatory prescriptions in the three study sites. The challenge of formalizing artisanal logging seems to be more one of procedures and the cost of access to permits than of compliance with the technical standards governing this activity.

5.4. Production strategies adapted to environmental and economic constraints

Throughout Central Africa, the cost of transporting sawn timber to evacuation routes is a major component of the total cost incurred by artisanal operators. Therefore, it seems reasonable to assume that increasing evacuation distance would lead operators to seek out more expensive species with larger diameters to offset this extra cost. This assumption is not substantiated in either Cameroon or the DRC, for different reasons.

In Yanonge, the attractive prices fetched for afrormosia and sapelli on the Kisangani market allow chainsaw millers to extend evacuation distances without jeopardizing their profits. This persistent specialization in these two precious woods prevents a broadening of the range of species sold on the Kisangani market.

In Cameroon, the selling price is relatively similar for all species exploited – except for ayous, which is frequently used for formwork in construction – and profit maximization is based more on reducing production costs, chiefly the cost of evacuating sawn timber out of the forest. Rather than extending evacuation distances to exploit the same species over and over again, operators have redirected their exploitation towards the dabema species, which was little exploited before and is still present close to evacuation routes. The enthusiasm for this species and the need to minimize evacuation distances have prompted around a quarter of the sawyers sampled to fell trees with diameters smaller than the MHD.

The case of kosipo in Mindourou appears to contradict this reasoning, the evacuation distance of its sawn timber is the shortest and its trees have the largest average diameter in our sample. Therefore, this species should be heavily harvested by loggers. However, the *Entandrophragma* group (including kosipo and sapelli) has been and continues to be felled intensively in Cameroon in recent decades, by both industrial and artisanal (Cerutti and Lescuyer 2011) loggers. It is likely that harvestable trees from this group are now infrequent at the study sites, unlike dabema, whose popularity is more recent.

Thus, chainsaw millers adopt a variety of production strategies, depending on the socio-economic and ecological context, to maximize their profits. As a result, different methods of intervention to regulate and professionalize this sector need to be considered, in order to take better account of the diversity of their production and marketing strategies. However, there are two approaches that seem likely to help maintain, or even increase, profits, reduce the contribution to forest degradation and formalize the trade. On the one hand, formal chainsaw milling permits need to be made available at lower cost, in order to make a moderate contribution to the cost price of sawn timber and prevent operators from offsetting the additional cost by extending the outward distances of sawn timber from large-diameter trees and valuable species. On the other hand, the range of species harvested by chainsaw millers needs to be further expanded by convincing buyers of the technical merits of species considered 'secondary'. The process of species diversification has been proven for some 15 years in Cameroonian markets (Cerutti and Lescuyer 2011), unlike the markets of Kisangani (DRC), where the same two species have remained in strong demand for at least 10 years (Lescuyer et al. 2014).

6. Conclusion

All the indicators point to the expansion of chainsaw milling in Central Africa over the next few years: domestic demand (both urban and rural) for sawn timber is substantial and growing, the practice provides significant income to rural economies, the harvesting of trees enhances customary rights, and the means of enforcing the relevant national regulations remain limited. Under these conditions, it is likely that artisanal chainsaw milling will continue to facilitate the advance of the forest degradation front and, subsequently, the deforestation front that accompanies the development of traditional agriculture. Consequently, these deforestation and degradation fronts will encourage the opening up of carriage roads to maintain acceptable extraction distances for artisanal sawn timber.

Yet, despite the publication of several studies on this subject over the last 10 years, this sector remains neglected by public authorities. Part of this lack of interest is probably due to the informal income that this activity generates for many government officials who exercise control over the various sections of this commodity chain (Cerutti et al. 2013; Lescuyer et al. 2014). However, beyond the profits derived from widespread corruption in the domestic timber markets of Central Africa, the attention of sectoral ministries and international donors remains focused primarily on industrial timber exploitation for export (Bayol et al. 2022). The financial spin-offs of chainsaw milling in rural areas and its contribution to national economic development are concealed, even though artisanal operators are present in most Central African villages and have met rural and urban demands for timber without fail. The sector is often criminalized for its perceived negative impact on forest cover. This negative perception of chainsaw milling does not facilitate the emergence of solutions to improve the performance and legality of this sub-sector. Most national administrations and international donors would like to see it replaced by industrial or semi-industrial sawmills supplying domestic timber markets, without fully considering the economic and other costs of such a reversal.

The current informality of chainsaw milling cannot be used as a pretext for failing to assess and document the real impacts of this activity, for example by deciphering the factors transforming the landscape mosaic, or by carrying out an analysis of the political economy of this value chain. The absence of such objective, up-to-date data prevents informed decision-making to steer this value chain towards a trajectory that fully meets the three pillars of sustainable development.

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Data availability statement

The data used to write this article are archived in the CIRAD Dataverse repository: https://dataverse.cirad.fr/privateurl.xhtml?token=5de24a71-8911-4669-ba04-87fd360676d0.

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