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ANALYSIS

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Road expansion and persistence in forests of the Congo Basin

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Roads facilitate development in remote forest regions, often with detrimental consequences for ecosystems. In the Congo Basin, unpaved logging roads used by timber firms, as well as paved and unpaved public roads, have expanded greatly. Here, comparing old (before 2003) and new (2003–2018) road datasets derived from Landsat imagery, we show that the total length of road networks inside logging concessions in Central Africa has doubled since 2003, whereas the total length of roads outside concessions has increased by 40%. We estimate that 44% of roads in logging concessions were abandoned by 2018, whereas just 12% of roads outside concessions were abandoned. Yearly deforestation rates between 2000 and 2017 near (within 1 km) roads markedly increased during the course of this study and were highest for old roads, lowest for abandoned roads and generally higher outside logging concessions. The impact of logging on deforestation is partially ameliorated by the nearly fourfold higher rate of road abandonment inside concessions, but the marked overall expansion of logging roads in the Congo Basin is of broad concern for forest ecosystems, carbon storage and wildlife vulnerable to hunting. Road decommissioning after logging could play a crucial role in reducing the negative impacts of timber extraction on forest ecosystems.

Rapid global road development is currently underway[1]. The expanding global road network is threatening many intact natural habitats of high conservation value, especially in tropical regions[2–4]. Additional road development is planned for the Central African region, driven by national developmental priorities and foreign investments, especially from China and other nations promoting logging and extractive industries[5,6]. Continued logging is also leading to the incursion of logging roads into many intact-forest landscapes[7,8]. By providing access to remote regions, new roads cutting through intact forests are detrimental to the continued integrity of extensive forest areas, frequently opening a 'Pandora's box' of additional and often illicit activities such as mining, poaching, land colonization and deforestation[9–11].

The Congo Basin sustains the second-largest tropical forest in the world after Amazonia. In contrast to high rates of deforestation in other tropical forest regions, the extent of Central African forests has been moderately stable since 1900[12], at least with respect to forest-carbon stocks[13]. The single most important driver of forest loss across Africa is shifting agriculture[14]. Millions of people in rural communities depend on shifting agriculture and the direct use of forest products for their livelihoods[15]. Shifting agriculture is extending into many forest areas that have been opened up by logging activities, which also leaves behind large areas of disturbed forest to potentially regenerate[16,17]. Forest roads, especially those that link urban populations and forests[18], can also lead to sharp increases in bushmeat hunting and steep declines in wildlife populations[19,20].

Currently, large parts of the Congo Basin are used for selective logging, and require extensive road networks to access and transport timber[21]. Most of the Congo Basin forest is owned by nation states that grant concessions (long-term leases of up to 99 years) to logging companies[22]. Despite the extensive expansion of road networks into the Congo, many unpaved logging roads are subsequently abandoned after a few years of use, allowing forests to regenerate[23]. At local scales, temporary logging roads are associated with relatively low deforestation rates compared to more permanent roads, both paved and unpaved[24]. Logging provides a key economic impetus for initial road building in forests. However, the rate of road expansion inside and outside logging concessions is unknown, as is the fate of such roads after initial construction.

Rapid changes in Congo Basin forests. Logging roads and public roads are used and managed in different ways, and the associated impacts on surrounding forests vary substantially. Whereas some regions of the world have access to reliable road maps both digitally and on paper, a complete map of all roads in Central Africa is still not available. Within the Congo Basin, few roads are paved, and the vast majority consist of a linear opening in the forest canopy with compacted soil where forest-vehicles drive, often surfaced with a layer of weathered clay (laterite). Without regular maintenance, such roads rapidly deteriorate due to heavy rains and are overgrown by recovering vegetation. It is therefore common for roads to be abandoned, especially if they were built only for selective logging activities that progressively shift to different cutting areas every year[23]. Because of these dynamics, no road map of the Congo Basin is available that differentiates these various types of roads[3,25].

In 2004, it was possible—for the first time—to travel along a road from Brazzaville, capital of the Republic of the Congo, to Bangui in the Central African Republic. Before this, extensive wetlands and dense humid tropical forests separated the two countries[26]. For many years, there has been an aspiration to construct a Trans-African Highway system, and this has slowly taken shape over the past two decades[27] (Fig. 1). Among the last missing elements of this network is the connection between the Republic of the Congo and Central African Republic. Logging companies in the Republic of the Congo, financed by the African Development Bank, have been contracted by the government to upgrade existing logging roads

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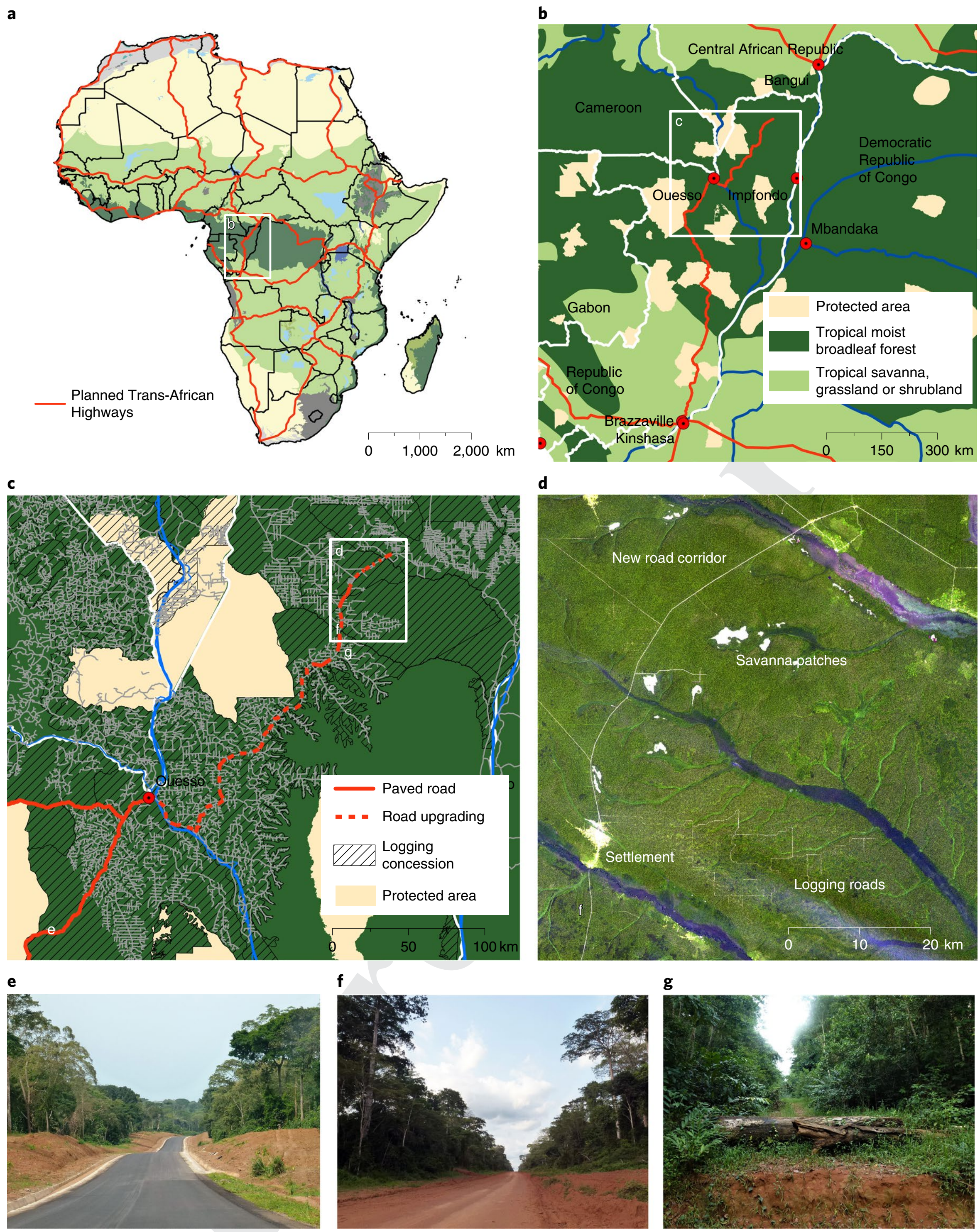

Fig. 1 | African road planning and construction from the continental to local levels. a, Overview of planned Trans-African Highways[27] with underlying country borders and ecoregions[69]. Outlined region is expanded in **b**. **b**, State of construction of the Ouesso–Bangui–Ndjamena road axis, with protected areas indicated[70]. Outlined region is expanded in **c**. **c**, Setting of the road corridor in the northern Republic of the Congo with logging concessions and logging-road networks showing the extent of forest exploitation. Outlined region is expanded in **d**. **d**, Forest clearing (90 m wide) as a corridor for road construction, linking existing logging-road networks, as seen on a Landsat 8 image (dated 18 January 2018; courtesy US Geological Survey). **e**, Newly paved road south of Ouésso at the location marked 'e' in **c**. **f**, A former logging road, upgraded to a major road corridor at the location marked 'f' in **c** and **d**. **g**, Abandoned logging road with excavation and a log barrier placed to help avoid unauthorized access at the location marked 'g' in **c**.

as a relatively inexpensive way to extend the public road network towards the Central African Republic[28,29], although maintenance costs for roads in high-rainfall environments can be surprisingly high, on the order of 20% of the initial road cost per year[25]. Landsat images from 2018 show clearing of forests for construction of the Congo–Central African Republic road (Fig. 1). To date, however, the major Brazzaville–Bangui road segment has not been included in any of the datasets recently used to analyse road impacts on either global or African scales[2,4,30,31], despite being one of the very few north–south connections that transect the Congo Basin forests.

A full account of road expansion in Central Africa is urgently needed to understand its impacts on forest cover. To address this need, we compared two road datasets for Congo Basin forests derived from Landsat images at different points in time: (1) before 2003[21] and (2) between 2003 and 2016[32], which we updated in 2018. Here we provide the first inventory of road expansion, road types and road persistence across Congo Basin forests. We also assess how different road types affected rates of nearby forest loss from 2000 to 2017[33].

Logging concessions boost road expansion but limit road persistence. Across the Congo Basin, we found that total road networks increased in length by 61% since 2003, from 143,700 to 230,800 km. Considering an average road width of 28 m, 14,000 km² or 0.8% of Congo Basin moist forests have been cleared for detectable road construction since the first Landsat images became available in the 1970s. Before 2003, 11% of forest was within 1 km of a road—this increased to 15% by 2017. Before 2003, 3% of wetlands were within 1 km of a road, increasing to 6% by 2017 (Fig. 2). Road expansion was most pronounced in logging concessions, in which total road length doubled from 50,300 km to 100,300 km. Outside logging concessions, road length increased by 40%, from 93,300 to 130,500 km (Supplementary Table 1).

Our analysis also identified roads built before 2003 (old), those built after 2003 (new) and roads that remained open until 2018 or were abandoned. Within logging concessions, 28% of all roads were classed as old and remained open in 2018. Outside logging concessions, more than twice as many roads (63%) remained open in 2018 (black lines in Fig. 2b). Conversely, 44% of all roads in logging concessions and 12% of roads outside concessions were abandoned by 2018. Overall, there was a net expansion of roads by 13% inside and by 23% outside logging concessions since 2003 (Supplementary Table 1). This suggests that logging companies tend to limit the lifespan of their road network relative to areas outside concessions.

Deforestation rates increase, except around abandoned roads. Deforestation within 1 km of roads was highest for old roads, followed by new roads, and was lowest for abandoned roads. From 2000 to 2017, yearly rates of forest loss around old, continuously open roads increased markedly over time, from 0.3% to 1.2% inside concessions, and from 0.5% to 1.9% outside concessions. For new, continuously open roads, forest-loss rates increased from 0.1% to 0.7% inside and from 0.3% to 1.3% outside concessions. Annual deforestation rates around abandoned roads were less than 0.1% inside concessions and less than 0.4% outside concessions (Fig. 3). This suggests that deforestation rates depend mostly on the type of road (abandoned or active) and secondarily on whether they are inside or outside logging concessions.

Logging concessions have been described as potential buffer zones for conservation purposes, for example, in the vicinity of protected areas[34]. Whereas selective logging does not maintain forest intactness, it provides economic value from forests while maintaining much higher carbon stocks and wildlife habitat than cleared areas outside of concessions[35]. It is now generally accepted that selectively logged forests retain important conservation values so long as they remain forested[36,37].

Our study reveals that, outside the vast Democratic Republic of Congo (DRC), road building within logging concessions has not yet markedly advanced the deforestation frontier, and many roads seem to be effectively closed—which is a positive outcome for forests. However, given fragile or even failed statehood and poor governance in many countries in the region, mechanisms to maintain long-term sustainable use of forests remain far from certain, particularly given rapid population growth, heavy foreign investment, new development schemes[31] and an associated expansion of shifting agriculture[14,38]. Logging concessions are major drivers of road construction and neither the national origin of the logging companies[39] nor the use of forest-management plans guarantees avoidance of deforestation[40,41].

Regional differences in the Congo Basin. We identified distinct regions with contrasting types of road networks in the Congo Basin (Fig. 2). The first region comprises dense terra firme forests under concessionary logging regimes where the development of the road network has been most extensive in the past 15 years. The second region is the carbon-rich wetlands of the Cuvette Centrale, which remain mostly free of roads and deforestation, but are surrounded by increasingly dense road networks extending to the wetland edge. Finally, there are forests that are already degraded or have naturally lower biomass, mostly located in the DRC and western Cameroon, which are often outside designated forest concessions and are accessible to the public via old road networks. This last region has experienced the highest deforestation rates (Supplementary Fig. 1), which are partially associated with improvements in the road network[42].

We documented the highest forest loss around roads in the DRC, with annual deforestation rates of 2.6% near old roads and 1.6% near new roads inside concessions, and 2.5% near old roads and 2.2% near new roads outside concessions. Abandoned roads had substantially lower mean annual deforestation rates of 0.3% inside concessions and 0.6% outside concessions. For all other countries in the Congo Basin, mean annual deforestation rates inside concessions were less than 1% for old and new roads and less than 0.3% for abandoned roads (Supplementary Fig. 1). Hence, deforestation and forest degradation rates inside concessions were two to three times higher in the DRC than in other Congo Basin countries[16].

The DRC is the only country in the region that has had a moratorium on new logging concessions; the moratorium has been in place since 2002[43]. However, this policy was substantially changed in early 2018 with the award of 6,500 km² of new concessions awarded to Chinese logging corporations[44]. Concessions in the DRC still cover a smaller proportion of the overall forest area than in other Congo Basin countries, but the situation has the potential to change rapidly. At present, informal (and often illegal) logging activities and chainsaw milling account for up to 90% of all logging operations in the DRC[45]. The remaining concessions have been criticized for illegal and unsustainable forestry practices[46]. Compared to other Congo Basin countries, a smaller proportion of roads inside concessions have been abandoned in the DRC (see Supplementary Fig. 2). If the aim of the DRC's moratorium was to reduce deforestation and forest degradation, it has been marginally successful at best. Prevailing corruption, lack of law enforcement and tenure conflicts[47] exacerbate the damaging effects of roads by facilitating forest conversion.

Pathways to limit road impacts. Road management needs to become an integral part of the cycle of sustainable forest management. We show here that inside well-managed concessions, the impact of logging roads on forest loss is ameliorated by the nearly fourfold higher rate of road abandonment than in areas outside concessions. This process could be aided and scaled up by a wider application of road decommissioning. Depending on the local context, a combination of physical barriers, removal of stream crossings, road surface decompaction and active forest restoration may be effective measures for avoiding unauthorized vehicle access to forest resources; however, it is considerably more challenging to prevent access for people on foot or on motorcycles[23]. In the larger picture, reducing the overall spatial footprint of roads in the Congo's many areas of high conservation value can only be achieved by strategic planning and long-term spatial prioritization. This includes optimal

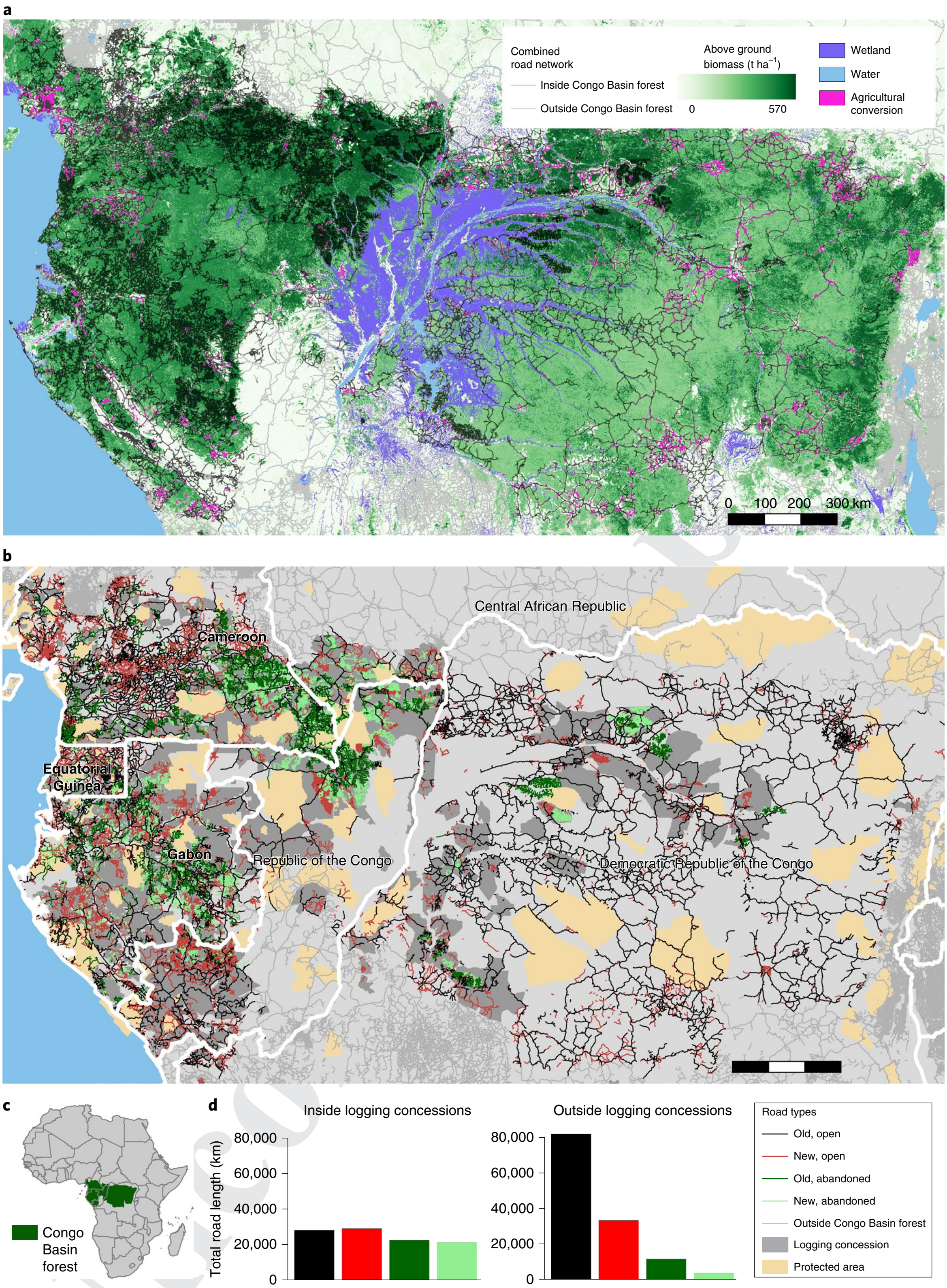

Fig. 2 | Congo Basin road networks. a, Full road network overlaid on the above-ground biomass[71], water, wetland and forest conversion to agriculture between 1992 and 2015 (ESA Climate Change Initiative—Land Cover led by UCLouvain, 2017)[66]. **b**, Road classification, showing expansion and persistence of the full road network within the Congo Basin forest as detected on Landsat in context with logging concessions[53–58] and protected areas[70]. Old, roads from Laporte et al. (2007)[21], detected before 2003; new, roads from Open Street Map (http://www.openstreetmap.org) detected since 2003; open, bare soil visible on Landsat images in 2017–2018; abandoned, bare soil visible on older Landsat images but not in 2017–2018. **c**, Location of the Congo Basin forest on the African continent. **d**, Length summary of the different road types shown in **b**.

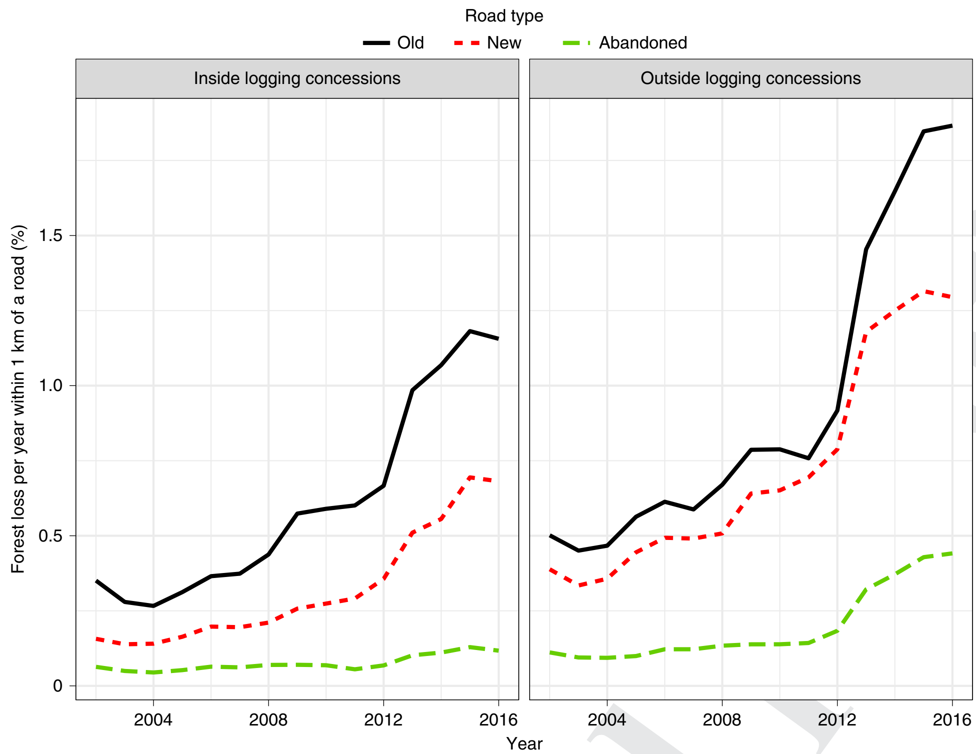

Fig. 3 | Forest loss around roads. Three-year moving average of annual forest loss between 2000 and 2017[33] for different road classifications relative to percentage forest cover in 2000 (within a buffer of 1 km from roads).

geographical distribution and territorial confinement of new concessions as well as mitigating the effects of large-scale road-building schemes currently underway across Africa[31]. Within the tropical forest domain, this process often begins as logging roads that are subsequently converted to public roads. Despite substantial road abandonment, we found that 28% of logging roads in the Congo remained open over the long term (for more than 15 years after concessions commenced). Even if these roads have measures in place to restrict access, the effectiveness of such measures is limited. Such 'permanent' roads are more likely to lead to fragmentation and conversion of forests via advancing shifting agriculture, mining and other forms of encroachment[10]. The most powerful impact-mitigation efforts should therefore focus on carefully planning and, where possible, limiting the expansion of permanent roads. Among other factors, the high expense of maintaining roads in wet tropical environments provides a powerful incentive for tropical countries to be conservative and minimalist in expanding their road networks[3,25].

We conclude that the most vulnerable areas where the greatest negative impacts might occur are the dense, slow-growing forests[48] of the border region between the Republic of the Congo and Central African Republic and the carbon-rich wetlands of the Cuvette Centrale[49]. Rapid expansion of logging-road networks and their subsequent transformation to a new Trans-African Highway, will create substantial threats to the integrity of these unique and biologically rich forests. Of particular concern for conservation are the gorillas and chimpanzees that are still relatively abundant in this region[50]. Logging-concession holders together with governments, local communities and international funders need to engage in proactive environmental planning, especially focusing on road projects[3] and identifying economically marginal projects that should be discouraged from a conservation standpoint[51].

Effective road planning spans the interests of different stakeholders and decision-makers and clearly has the potential to determine the fate of forested ecosystems for the benefit of people, biodiversity and carbon storage. On the landscape scale, forest-certification systems offer an important platform for guiding standards and practices; for instance, regarding effective road decommissioning after logging. A key challenge is scaling up regional planning that encompasses several nation states and a variety of conservation and development interests. An organization such as the Commission of Central African Forests can play a key role in this regard. In the Congo region, forests and natural resources are being rapidly exploited, but there is much scope to improve the social equitability and environmental sustainability of projects through greater transparency and rule of law, which are in the immediate interests of these sovereign nations.

Methods

Study area. We defined the Congo Basin forests as the tropical moist forests with >75% tree cover within the Central African countries Cameroon, Gabon, Equatorial Guinea, Central African Republic, Republic of the Congo and the DRC.

Road data. We compared two large road datasets for Central Africa that are mostly based on Landsat satellite imagery. The old logging roads and public roads dataset is from Laporte et al. (2007)[21], who manually digitized roads in more than 300 Landsat images taken between the 1970s and 2003.

The new logging-roads dataset is based on crowd-sourced data from Open Street Map (OSM). The quality of OSM data has increased greatly over recent years and has been successfully used to estimate global road coverage[2]. OSM data in the Central African Region results from a collective effort of research institutions and a citizen science initiative, in which logging roads were digitized manually from Landsat images (www.loggingroads.org). For one of the hotspot regions for logging in Cameroon, Republic of the Congo and Central African Republic, data from Kleinschroth et al. (2017)[7] were used. Overall, the OSM data covers roads built between the 1980s and 2016.

We downloaded the full country datasets from six Central African countries provided by Geofabrik (http://download.geofabrik.de/africa.html). To filter all roads from the full dataset, we used the Osmosis command line application for processing OSM data[52] using the tag filters 'accept-ways highway=*' and 'accept-ways abandoned:highway =*' to capture both open and abandoned roads. We excluded urban roads from the OSM dataset using the tags 'residential', 'cycleway', 'living_street' and 'pedestrian'.

The Laporte et al. (2007) dataset is limited to the road network in the forested region of Central Africa with >75 % tree cover (updated in ref. [33]). We therefore clipped the OSM map to the same extent. We kept roads from the OSM outside this area only for illustration purposes in Fig. 2. We manually updated OSM data to 2018 on the basis of the most recent Landsat images.

Road age classification. Due to the temporal overlap in the two datasets, we used 2003 as the cut-off and defined any road that existed before 2003 as old and any road built after 2003 as new. To make the two manually digitized datasets coincident, we used the 'integrate' tool in ArcGIS with a tolerance level of 300 m. We then removed all parts of the OSM dataset that coincided with the Laporte dataset. As an attribute, we added to each road segment the information on which of the two original datasets it appeared. Roads that appeared in both datasets were labelled 'old, open', those that only appeared on the old dataset were labelled 'old, abandoned' and those that were only in the new dataset were labelled 'new, open'. Particularly in the densely populated regions of Cameroon, the OSM dataset appeared to be more detailed than the Laporte (2007) data. The length of 'new, open' roads outside logging concessions might therefore be overestimated and the length of 'old, open' might be underestimated.

The locations of roads inside and outside formally designated logging concessions were identified on the basis of data from the World Resources Institute (http://www.wri.org/our-work/project/congo-basin-forest-atlases)[53–58]. We intersected the merged road dataset with concessions and split lines at the point of intersection. We could then select all roads depending on their locations inside and outside concessions.

Road abandonment. To improve the identification of road abandonment, we used the red bands of 135 Landsat 8 images from 2017 and 2018 covering the Congo Basin. Following the approach of Kleinschroth et al. (2015)[59], this allowed us to distinguish between open and abandoned roads. While the road surface itself is on average 7 m wide, actively used roads in the Congo Basin are typically maintained with 10 m-wide cleared strips on both sides of the actual track[10]. The main purpose of this is to open the canopy to allow the sun to dry the road surface after the frequent rains[60]. The contrast between the bare soil of the road surface and the surrounding forest allows relatively straightforward visual detection of open road networks mainly due to their strong signal in the red band of the Landsat images. Abandoned roads typically become overgrown within a year, both due to vegetation establishment on the road track and from lateral ingrowth[23]. This vegetation recovery leads to a gradual disappearance of the road signal from the red band of Landsat images. Abandoned roads can still be used by people on foot or on motorbikes and remain detectable for 20 years in the infrared bands of Landsat images, indicating higher photosynthetic activity[59].

Due to abundant cloud cover in Gabon and southern Republic of the Congo, an estimated 10% of the forest area was not clearly visible on any image in 2017 and 2018 and road abandonment could not be identified. Overall abandonment is therefore a conservative estimate.

We calculated the sum of the length of different types of roads (old, new, abandoned, open, inside and outside of concessions) using QGIS[61]. We used field-based maps and photographs collected during three phases of fieldwork in 2014, 2015 and 2017 to correct the remotely sensed maps.

Forest-loss data. We calculated forest loss within a buffer of 1 km around roads. While road-related impacts may well spread beyond this distance, we followed the approach of Ibisch et al. (2016)[2], who considered 1 km as a minimum value for road-effect zones that is applicable globally. This corresponds with the typical maximum distance that loggers in the Congo Basin use for skidding; that is, where they enter the forest with bulldozers to drag tree logs to a road[21]. In logging-road layouts that systematically cover a forest area, using a buffer wider than 1 km would capture several parallel roads at once and confound the forest-loss effect of each individual road.

We used QGIS to create a 1 km buffer around the different types and locations of roads (old, new and abandoned roads in six countries, inside and outside of concessions). This resulted in 36 polygons that we uploaded to Google Earth Engine[62]. Within each polygon we quantified forest cover loss based on Hansen Global Forest Change v.1.5 annual forest-loss data from 2000 to 2017[33]. To correct for the different size of the road networks (for example, in countries of different size) we calculated the percentage of the annually lost forest area compared to the forest area in 2000 (according to the Hansen Global Forest Change dataset) within the road buffer. The annual forest-loss estimates in the Hansen Global Forest Change dataset contain map errors of unknown directions (bias towards omission or commission) and magnitude. Therefore, we calculated three-year moving averages of annual tree-cover loss to show a general trend from map pixel counts over time, following the approach of Tyukavina (2018)[63]. The resulting temporal trend needs to be interpreted with caution as the Hansen Global Forest Change[33] map tends to underestimate forest-loss area at the beginning of the 2000s and overestimate loss after 2010[64].

Additionally, Hansen et al. (2013)[33] only covers gross forest loss and does not take into account forest regrowth. Both selective logging and shifting agriculture are highly dynamic processes and forest loss is often followed by long periods of vegetation recovery[65]. Between 2000 and 2005, net deforestation in the overall Congo Basin was 35% lower than gross deforestation. This reforestation ratio varied widely between different countries: in Gabon, 100% of lost forests were regained, compared with 82% in Cameroon, 50% in Republic of the Congo, 40% in Central African Republic and 31% in the DRC[16]. We assume that net deforestation is lower than the gross forest-loss we report here. To illustrate the location of permanent conversion of forest to agriculture in Fig. 2a, we used land-cover-change data from 1992 to 2015 from the ESA Climate Change Initiative—Land Cover led by UCLouvain (2017)[66]. To a certain extent, forest loss can be seen as an indicator for other, less visible impacts on the forest, such as forest degradation and defaunation. Forest edges next to new canopy openings are typically most prone to degradation due to climatic effects and the presence of people who use the forest, for example, for hunting[67].

All further analyses were done in R[68], using the packages raster, rgdal, rgeos, zoo and ggplot2.

Data availability

The spatial datasets generated and analysed during the current study will be made available on the Oak Ridge National Laboratory Distributed Active Archive Center (https://daac.ornl.gov) on acceptance of the manuscript.

Code availability

Google Earth Engine codes used during the current study are publicly available at https://code.earthengine.google.com/9758a45a0a19a1d48f7453b406b8cb66. R codes used during the current study are available from the corresponding author on reasonable request.

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Author contributions

F.K. and W.F.L. conceived the ideas, F.K. and N.L. collected and analysed the data. All authors contributed to the writing.

Competing interests

The authors declare no competing interests.

Additional information

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