

LETTER

Quantifying the road-effect zone for a critically endangered primate

1 | INTRODUCTION

The 21st century has experienced an unprecedented expansion in infrastructure development, with 97% of Earth's terrestrial surface no longer qualifying as intact (Plumptre et al., 2021). Since 2000, 12 million km of paved roads have been laid down globally, and an estimated \$33 trillion USD have been earmarked for the construction of an additional 25 million km by 2050 (Dulac, 2013). The majority of the global road network comprises roads in rural areas, with a few exceptions in highly urbanized countries such as Belgium (Coffin et al., 2021). The anticipated expansion of the global road network would place significant additional pressures on species diversity (Alamgir et al., 2019; Sloan et al., 2018). A better understanding of the extent to which roads impact species of conservation concern is therefore a priority if developers are to effectively mitigate the ecological effects of roads, which extend beyond their physical footprints (Benitez-Lopez et al., 2010).

One approach to measuring the ecological effects of roads is to quantify the distance up to which the density of a species is reduced, referred to as the road-effect zone, or REZ (Peaden et al., 2016; Semlitsch et al., 2007). REZs can be used by development planners and conservation practitioners to estimate the area where roads impact a particular species (Eigenbrod et al., 2009). This is important because some lenders such as the International Finance Corporation (IFC) have established a best practice standard (IFC PS6) for mitigation of impacts on biodiversity, to which the IFC's clients are required to adhere (IFC, 2012). At the heart of these recommendations is the "mitigation hierarchy", a tool for development planners and other stakeholders to limit the negative impacts of projects on biodiversity and ecosystem services (Ekstrom et al., 2015; IFC, 2012). It encompasses a hierarchy of strategies: (1) avoiding adverse impacts before they occur; (2) minimizing the severity of impacts that could not be avoided; (3) restoring habitats and/or species following impacts; and (4) offsetting residual impacts that remain. Not all

mitigation actions are sequential, for example, developers can start offsets at any time, and restoration may take place before minimization measures are effective. However, the first two strategies should be prioritized over the subsequent ones, as they often are more effective in maximizing the environmental sustainability of development projects (Ekstrom et al., 2015). Avoidance of impacts can be achieved in three major ways: through design (e.g., using existing infrastructure wherever possible to reduce additional road construction); through scheduling of activities (e.g., adapting the timing of construction/operational activities to avoid disturbing species); and through site selection (e.g., relocating projects away from critical habitats). REZs can inform avoidance through site selection by advising development planners on where roads should avoid critical habitats. However, if complete avoidance of development is not possible, REZs provide an estimate about the area where strategies lower down the mitigation hierarchy, such as "Minimization," need to be effective. Despite a growing abundance of literature on species' responses to linear infrastructure, studies that explicitly establish REZs are rare, especially in tropical areas which harbor high biodiversity and are undergoing rapid infrastructure development (Laurance et al., 2015). Moreover, variations in REZs for major and minor road categories are rarely quantified (Collinson et al., 2019) even though different road properties impact wildlife differently.

REZs are variable across taxonomic groups, ranging between 35 m for salamanders (Semlitsch et al., 2007), to 2.8 km for woodland birds (Reijnen et al., 1995) (Table S1), highlighting the importance of generating species-specific estimates. One taxonomic group for which there are no published REZs are nonhuman primates (hereafter primates). Approximately 60% of all primates are threatened with extinction and 75% have declining populations (Estrada et al., 2017), partly due to large-scale infrastructure development (Arcus Foundation, 2018). Roads are considered a major threat to primates through vehicle-induced mortality (Hetman et al., 2019); by providing

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easier access for hunters; and by degrading adjacent habitat through extractive industries (Strindberg et al., 2018). Furthermore, increased proximity between humans and primates might elevate disease transmission risk which can lead to further population declines. However, if primate densities are lower in proximity to roads this might attenuate disease transmission (Cameron et al., 2016; Strindberg et al., 2018).

The social, economic, and ecological values of great apes are recognized by the IFC, with any area where great apes occur likely considered as critical habitat (IFC, 2019). Thus the IFC's Guidance Note 6 (GN73) states that the IUCN Species Survival Commission (SSC) Primate Specialist Group (PSG) Section on Great Apes (SGA), (IUCN/SSC PSG SGA), must be consulted when developments are planned in areas where great apes potentially occur and in the development of mitigation strategies. The western chimpanzee (*Pan troglodytes verus*), a subspecies of chimpanzee which was once widespread across West Africa, has declined by 80% in the last 20 years and is currently classified as critically endangered (IUCN, 2020; Kühl et al., 2017). The human population in West Africa is growing rapidly (Table S2, Bradshaw & Brook, 2014) and chimpanzees face mounting pressure from the expansion of settlements and infrastructure (Humble et al., 2016). Four of Africa's 33 development corridors—designed to boost the export of natural resources and agricultural production—will cut through the habitat of western chimpanzees (Heinicke et al., 2019; Laurance et al., 2015). To avoid the negative impacts of such development, it is critical to provide conservation practitioners and development planners with clear information on the distance up to which chimpanzee abundance might be reduced. For instance, REZs could help the IUCN/SSC PSG SGA determine the presence of great apes within the “project's area of influence” (IFC, 2019) by pointing researchers to the area where great ape presence should be investigated. We address this critical knowledge gap to provide the first range-wide estimation of REZ for a primate taxon, the western chimpanzee (Figure 1). We use ecological threshold analysis to provide a robust estimation of the area that is impacted by roads and highlight how REZs differ between major and minor road categories.

2 | METHODS

2.1 | Road data

Road data for West Africa were obtained from OpenStreetMap (OSM) and accessed by Overpass Turbo (<https://overpass-turbo.eu/>). OSM is an open-access database

storing regularly updated information on the location, size, length, and function of the world's road network (OpenStreetMap, 2015). The data are sourced from individual or organization-level contributors, through surveying stretches of road with GPS or tracing over licensed satellite imagery. The global coverage of OSM transport network is more up-to-date and more accurate than other open datasets such as gRoads (CIESIN, 2010). Eleven road categories were obtained, which were grouped into major and minor roads (Figure 1) based on their size and properties, such as whether or not they were paved (Table S3). Railway lines were excluded due to their low number and high overlap with major roads.

2.2 | Chimpanzee density distribution and REZs

We used a modeled western chimpanzee density distribution (Figure 1) from Heinicke et al. (2019), accessed via the IUCN SSC A.P.E.S. database (<http://apesportal.eva.mpg.de>), which is available at a spatial resolution of half a minute (ca. 0.9 km); with estimated density values ranging from < 0.01 to 6.3 individuals/km².

To quantify the REZ, major roads for all eight countries intersecting the geographic range of western chimpanzees (Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mali, Senegal, and Sierra Leone; Figure 1) were overlaid with the range-wide chimpanzee density data. Bands of 1 km width were added to both sides of the physical footprint of the roads—defined as 10 m for major and 5 m for minor roads, respectively (OpenStreetMap, 2015)—using the “Buffer” tool in ArcGIS version 10.5.1 (ESRI, 2019). The values of the raster cells whose center fell into the bands were extracted and averaged to serve as an estimation of mean chimpanzee density per band. Each band was then moved consecutively 1 km further away until all raster cells had been sampled. The lower limit of band width was 1 km, which corresponds to the resolution of the chimpanzee density data (~1 km²).

Consistent with studies on birds (Reijnen et al., 1995), reptiles (Peaden et al., 2016), and amphibians (Semlitsch et al., 2007), the REZ was defined as the distance beyond which chimpanzee density did not increase. We used ecological threshold analysis as per Eigenbrod et al. (2009) and Muggeo (2008) to determine the exact position of the REZ. To do this, we fitted piecewise regression models requiring initial estimates of possible breakpoints, which are used by the model to compute “true” breakpoints and provide confidence intervals calculated as:

$$\hat{\psi} \pm z_{\alpha/2} SE(\hat{\psi})$$

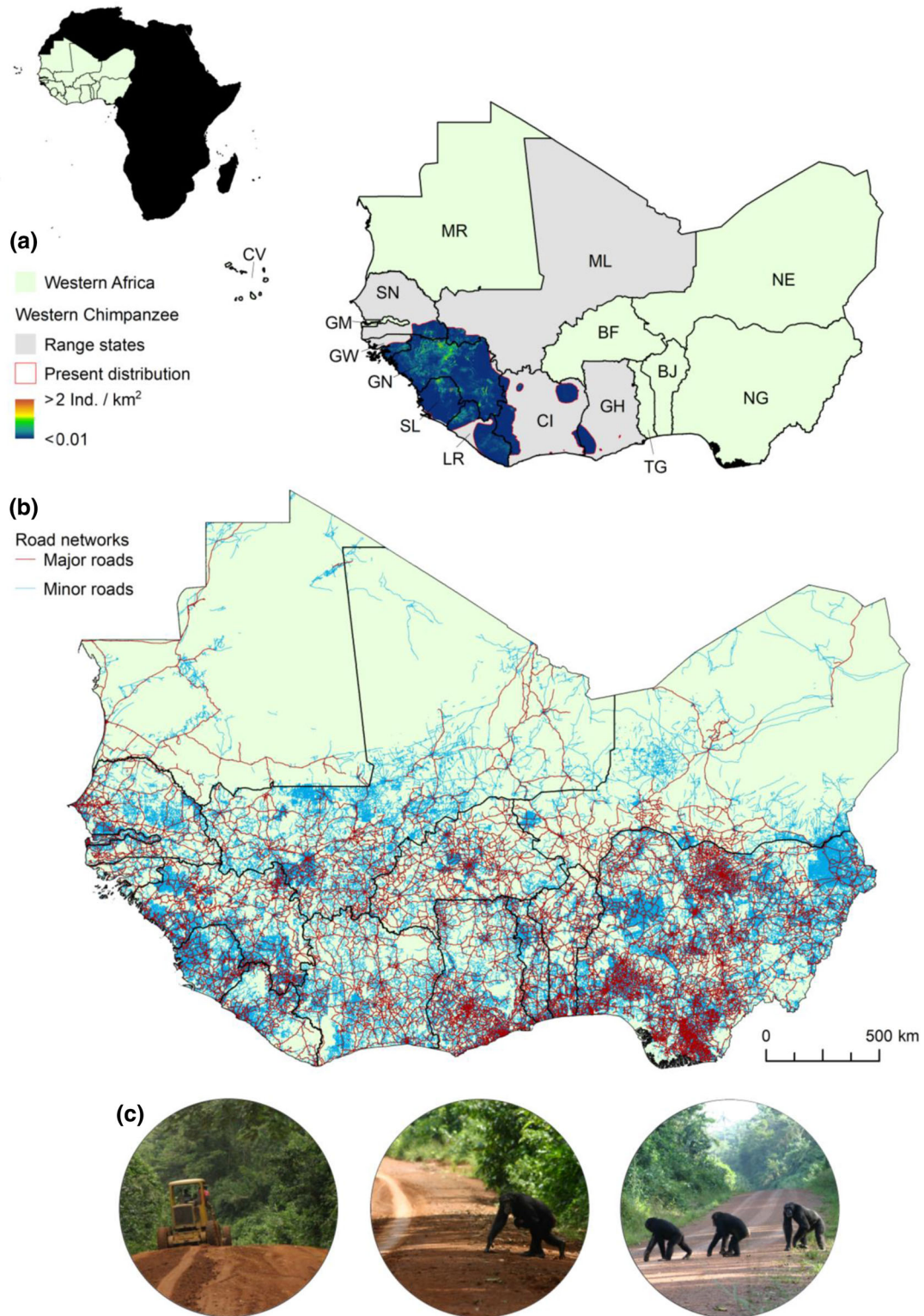


FIGURE 1 (a) western chimpanzee (*Pan troglodytes verus*) range states and modelled density (number of individuals per km²) across its present geographic range in West Africa; (b) distribution of major and minor roads across West Africa; and (c) examples of road widening projects and western chimpanzees crossing roads in Bossou, Guinea (Photograph credits: author KJH). West African countries (as defined by the United Nations) are labelled using ISO codes as follows: BF, Burkina Faso; BJ, Benin; CI, Ivory Coast; CV, Cape Verde; GH, Ghana; GM, Gambia; GW, Guinea Bissau; GN, Guinea; LR, Liberia; MR, Mauritania; ML, Mali; NE, Niger; NG, Nigeria; SL, Sierra Leone; SN, Senegal; TG, Togo

where $\hat{\psi}$ is the breakpoint estimated by the model, $z_{\alpha/2}$ is the quantile of the standard Normal, $SE(\hat{\psi})$ comes from the Delta method for the ratio $\frac{\hat{\gamma}}{\beta_2}$ where β_2 is the difference in slope between the estimated and “true” regression pieces, and $\hat{\gamma}$ is the gap between the initial and true breakpoints. All breakpoints which could be visually identified served as initial estimates (Figure S1).

For minor roads, we only included the stretches that extend beyond the REZ of major roads as identified above. This approach ensured that estimates of REZs for minor roads were not confounded by the influence of major roads.

3 | RESULTS

3.1 | REZ estimations for western chimpanzees

Across the present geographic range of the western chimpanzee, covering ~528,010 km² (IUCN, 2018), there are 41,925 km of major roads, with 14.5% of their range located within 1 km of a major road (Figure 2A). Average density of the western chimpanzee first peaked at 17 km from the closest major road (0.1 individuals per km²). The ecological threshold analysis identified the corresponding breakpoint at 17.2 km (95% CI [15.8–18.6 km]). Accordingly, the REZ of major roads for the western chimpanzee is estimated to be between 15.8 and 18.6 km (Figure 2A). The area within the REZ across the present geographic range of the western chimpanzee is 472,797 km² (\pm 95% CI [462,430–483,164 km²]), which leaves 55,213 km², or 10.4% outside the impact of major roads (Figure 3; Table S4).

There are a total of 206,110 km of minor roads within the chimpanzee range, with 41.7% of their distribution located within 1 km of a minor road. Average chimpanzee density values first peaked at 5 km from the closest minor road (0.1 individuals per km²). The ecological threshold analysis identified the corresponding breakpoint at 5.4 km (95% CI [4.9–5.8 km]). Therefore, the REZ of minor roads for the western chimpanzee is estimated to be between 4.9 and 5.8 km (Figure 2B). The area within the REZ across the present geographic range of the western chimpanzee is 437,809 km² (\pm 95% CI [427,113–448,505 km²]) which leaves 90,201 km², or 17.1% of the geographic range of western chimpanzees outside of the impact of minor roads (Figure 3; Table S4).

The combined area of the REZs is 505,306 km² (\pm 95% CI [500,549–510,063 km²]), which leaves 22,711 km² (\pm 95% CI [17,954–27,468 km²]), or 4.3% of the present geographic range of western chimpanzees unimpacted by any road (Figure 3; Table S4).

4 | DISCUSSION

REZ estimations support the development of evidence-based measures to avoid and/or minimize impacts on wildlife, without which future road expansion will lead to catastrophic biodiversity declines (Alamgir et al., 2019; Sloan et al., 2018). Our analysis shows that the western chimpanzee is negatively impacted by roads across 95.7% of its present geographic range, with the REZ of major roads estimated as between 15.8 and 18.6 km, which is three times wider than that of minor roads. These impacts are compounded by planned development corridors which will be constructed in the savannah and rainforest regions in Africa, home to many threatened megafauna (Laurance et al., 2015).

Although chimpanzees are documented to be ecologically flexible (Hockings et al., 2015), their slow life histories make them sensitive to many human activities. This might explain why the REZ for this subspecies is more than three times greater than the 5 km average reported for other mammal species (Benitez-Lopez et al., 2010; Table S1). There are several explanations for why roads reduce the density of western chimpanzees. First, roads open up unexploited areas to large-scale extractive industry such as mining and agriculture which replace the forests that chimpanzees need to meet their basic ecological requirements. Second, roads can restrict the movements of chimpanzees, with busy major roads leading to higher fragmentation of populations and genetic isolation (Knight et al., 2016). Third, hunting is a persistent threat for most large-bodied mammals including the western chimpanzee (Brodie et al., 2021; IUCN, 2020), with roads used as access points from which hunters target adults for meat and/or infants to sell (Arcus Foundation, 2018).

The considerable extent to which western chimpanzees are impacted by roads should facilitate discussion between stakeholders about avoidance and other mitigation strategies to ensure new road projects adhere to best practices as defined by the IFC. However, the complete avoidance of important western chimpanzee habitat is likely to be a challenge, given the subspecies' restricted distribution. When avoidance is not possible, resources will need to be prioritized for the implementation of strategies lower down the mitigation hierarchy such as minimizing the severity of residual impacts (Ekstrom et al., 2015). Specifically, the implementation of long-term, large-scale monitoring of legal and illegal resource extraction, including logging, mining, and hunting along the length of the road is critical. This would include long-term funding for patrols, which benefit protected species including western lowland gorillas (*Gorilla gorilla gorilla*) and central chimpanzees (*Pan troglodytes troglodytes*) in Western Equatorial Africa

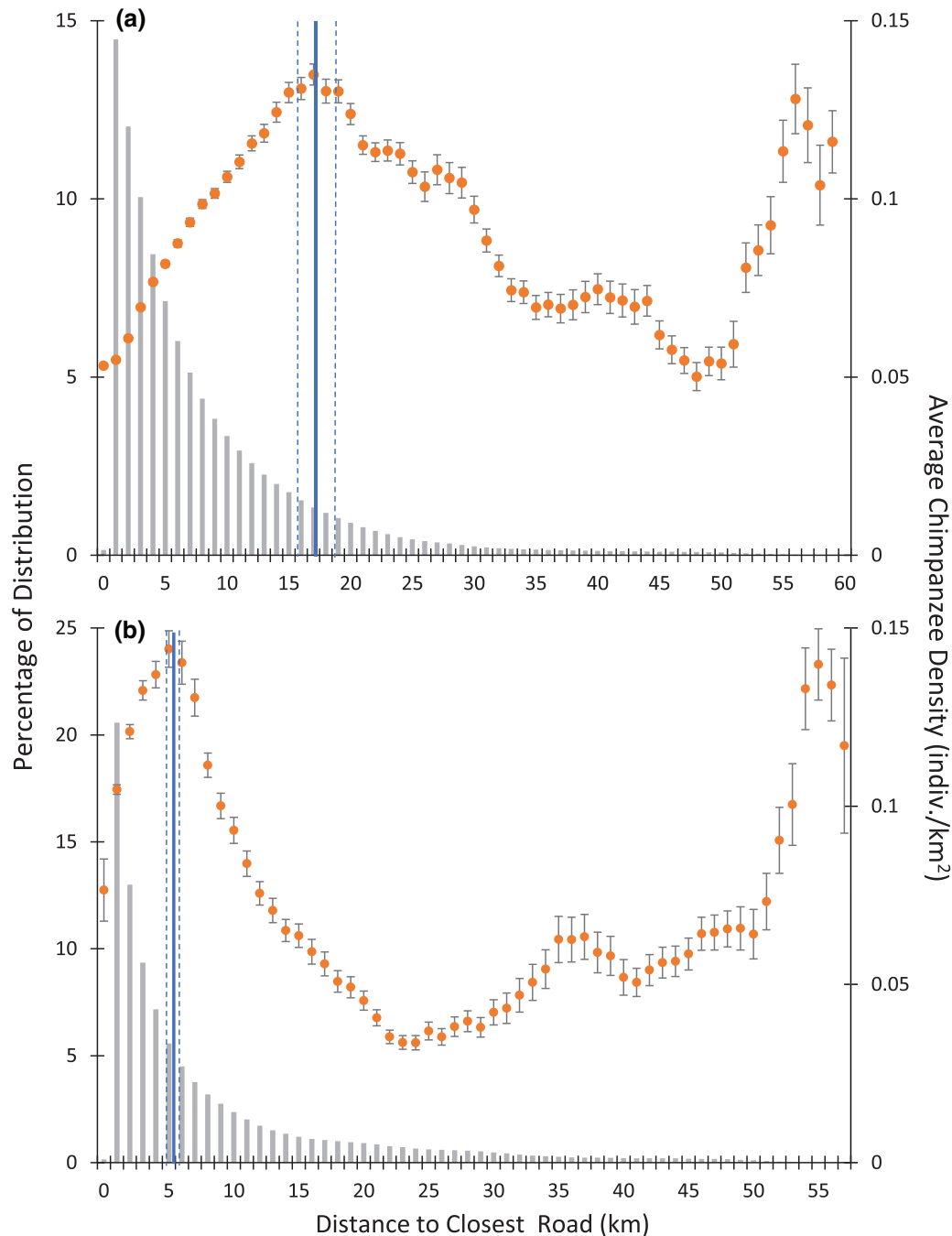


FIGURE 2 Estimated road-effect zone (REZ) of (a) major and (b) minor roads for the western chimpanzee (*Pan troglodytes verus*). REZ quantified by the ecological threshold analysis are highlighted by the solid blue line. The dashed lines show the 95% confidence interval of the breakpoint estimate. Orange points indicate the mean chimpanzee density at each 1 km wide band, where 0 km is the physical footprint of the road (10 m for major and 5 m for minor roads, respectively). The percentage of the geographic area of the chimpanzee distribution within each band is indicated by gray bars. Error bars represent the standard error of average chimpanzee density. Please note that minor roads were considered only when they were beyond the REZ identified for major roads, as detailed in the methods

(Strindberg et al., 2018). Additional interventions proposed to minimize the impacts of roads on primates include the installation of roadblocks to inspect vehicles for illegally acquired forest resources; the removal of snares to reduce the trapping of great apes; and to reduce vehicle speed, the installation of road bumps, implementation of speed limits

with clear signage, and the reduction of road width (Junker et al., 2017). The establishment of secondary roads within the REZ should also be restricted to avoid an increase in human activities. However, the effectiveness of many of these interventions has not yet been evaluated. Developers should consult the Conservation Evidence database

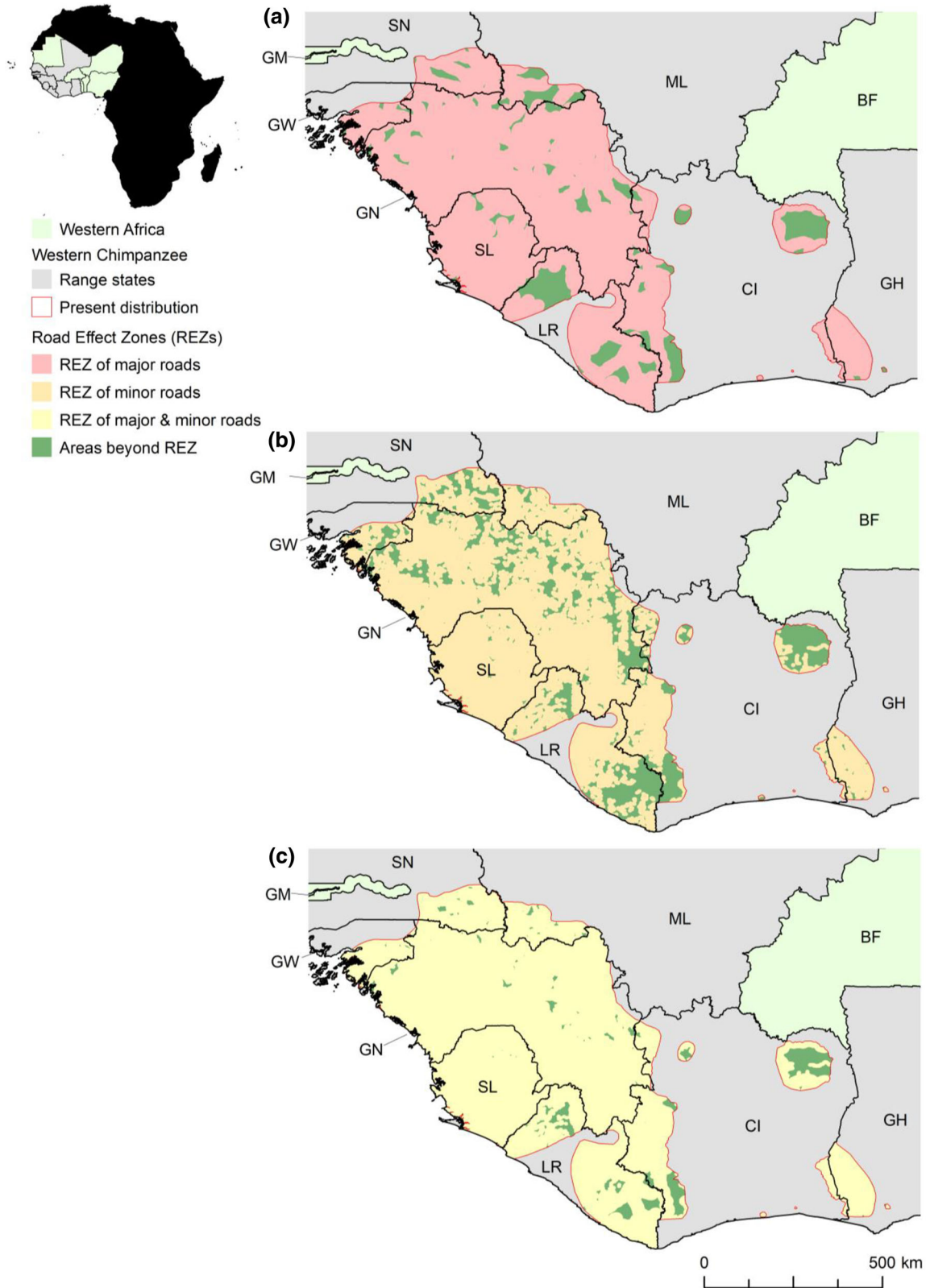


FIGURE 3 The road-effect zones (REZ) of (a) major roads (17.2 km); (b) minor roads (5.4 km); and (c) major and minor roads combined across the geographic range of the western chimpanzee. Countries are labelled using ISO codes as follows: BF, Burkina Faso; CI, Ivory Coast; GH, Ghana; GM, Gambia; GW, Guinea Bissau; GN, Guinea; LR, Liberia; ML, Mali; SL, Sierra Leone; SN, Senegal

(which is continually updated) to ensure the development of effective mitigation strategy is evidence-based, and that the effectiveness of interventions on chimpanzees and other wildlife are properly evaluated (Junker et al., 2017). It is worth noting that commitments to strategies lower down the mitigation hierarchy often become increasingly challenging to fulfil (Ekstrom et al., 2015). The financial burden of long-term minimization efforts can be too high for the governments of economically developing countries, such as countries in the western chimpanzee range. Furthermore, the success of offsetting residual impacts on great ape conservation has proved controversial and should be an absolute last resort (Kormos et al., 2014).

Similarly, the integrity of protected areas in the vicinity of transport infrastructure must be safeguarded, to prevent legal changes that ease restrictions, shrink their boundaries or eliminate their protection entirely. Between 1892 and 2018, an area of 519,857 km² globally was removed from protection whilst another 1,659,972 km² of protected area was deregulated and exposed to various human activities (Kroner et al., 2019). We argue that in cases where the REZs overlap protected areas, it is imperative that their legal status is maintained through better funding from developers to support the enforcement of existing laws, which can help reduce human pressures inside park boundaries. For instance, Liberia's oldest protected area, the Sapo National Park, experienced high levels of human encroachment partly mediated by the surrounding major roads. However, in 2018, after Community Watch Teams and the Forest Development Authority ramped up efforts to enforce the protection of the park, illegal mining activities within its borders ceased (Boesch et al., 2020). Finally, adherence to the mitigation hierarchy, based on REZ values, could yield positive conservation outcomes for a rich assemblage of trees and mammals, such as the endangered pygmy hippopotamus (*Choeropsis liberiensis*) and Temminck's red colobus (*Piliocolobus badius temminckii*), whose taxonomic diversity positively correlates with chimpanzee abundance (Junker et al., 2015).

It is worth noting that the road data compiled by OSM are ~83% complete. This is particularly evident for countries with weaker governance and/or poorer internet access (Barrington & Millard, 2019), and so could underestimate the true extent of roads in West Africa. Similarly, while the modeled western chimpanzee density distribution allows for large scale estimations of REZs, less than 50% of their geographic range has been surveyed, and considerable data gaps remain, particularly in Mali, Senegal, and Guinea Bissau (Heinicke et al., 2019; Kühl et al., 2017). It is important to note that the area of REZs is not always constant along the length of a road, and spatial and temporal variations exist (Parsons et al., 2020). For example,

disease outbreaks could result in rapid declines of apes near roads (Strindberg et al., 2018) possibly widening REZs beyond the distances estimated in this study. Additional data on chimpanzee densities and road networks (and associated human activities) coupled with habitat suitability analysis, will further strengthen estimates of the REZ for western chimpanzees. Moreover, country-specific differences in REZs might exist and these should be carefully examined, especially in relation to robust and up-to-date information on anthropogenic threats. Additional research should also be carried out to quantify the REZ for different species with diverse life history traits to ensure mitigation strategies are effective for a range of taxonomic groups, with intervention strategies evaluated across taxa (Sutherland et al., 2012). The REZs identified in this study serve as an important baseline for large-bodied wildlife inhabiting the tropics. Without mitigating the substantial impact that infrastructure development is having on the critically endangered western chimpanzee, this charismatic and iconic subspecies will be pushed closer to the brink of extinction.

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CONFLICT OF INTEREST




The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and writing of the manuscript. S.H. provided western chimpanzee density data; B.A. extracted road data and conducted spatial analyses; J.A.G.J. and K.M. provided analytical support for calculation of REZ; and all co-authors developed this draft and gave final approval for publication.

DATA AVAILABILITY STATEMENT

OpenStreetMap data is freely available via Overpass Turbo (<https://overpass-turbo.eu/>). Western chimpanzee density data is available via the IUCN SSC A.P.E.S. database (<http://apesportal.eva.mpg.de>).

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great ape conservation, major and minor roads, mitigation hierarchy, road development, road-effect zone, West Africa, western chimpanzee

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