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Conservation Biology

Contributed Paper

Effects of logging on roadless space in intact forest landscapes of the Congo Basin

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Abstract: *Forest degradation in the tropics is often associated with roads built for selective logging. The protection of intact forest landscapes (IFL) that are not accessible by roads is high on the biodiversity conservation agenda and a challenge for logging concessions certified by the Forest Stewardship Council (FSC). A frequently advocated conservation objective is to maximize the retention of roadless space, a concept that is based on distance to the nearest road from any point. We developed a novel use of the empty-space function – a general statistical tool based on stochastic geometry and random sets theory – to calculate roadless space in a part of the Congo Basin where road networks have been expanding rapidly. We compared the temporal development of roadless space in certified and uncertified logging concessions inside and outside areas declared IFL in 2000. Inside IFLs, road-network expansion led to a decrease in roadless space by more than half from 1999 to 2007. After 2007, loss leveled out in most areas to close to 0 due to an equilibrium between newly built roads and abandoned roads that became revegetated. However, concessions in IFL certified by FSC since around 2007 continuously lost roadless space and reached a level comparable to all other concessions. Only national parks remained mostly roadless. We recommend that forest-management policies make the preservation of large connected forest areas a top priority by effectively monitoring – and limiting – the occupation of space by roads that are permanently accessible.*

Keywords: biodiversity, Central Africa, forest certification, logging concessions, random sets, road density, road networks, roadless areas, sustainable forest management

Efectos de la Tala en Espacios sin Carreteras de los Paisajes de Bosque Intacto en la Cuenca del Congo

Resumen: *La degradación de bosques en los trópicos comúnmente se asocia con las carreteras construidas para la tala selectiva. La protección de los paisajes de bosques intactos (PBI) que no son accesibles por carretera es una prioridad en la agenda de conservación de la biodiversidad y un reto para las concesiones de tala certificadas por el Consejo de Administración Forestal (FSC). Un objetivo de conservación por el que se aboga frecuentemente es la maximización de la retención de los espacios sin carreteras, un concepto que está basado en la distancia a la carretera más cercana desde cualquier punto. Desarrollamos un uso novedoso de la función de espacio vacío – una herramienta estadística general basada en la geometría estocástica y la teoría de conjuntos aleatorios – para calcular el espacio sin carreteras en una parte de la Cuenca del Congo en donde las redes de caminos han estado expandiéndose rápidamente. Comparamos el desarrollo temporal del espacio sin carreteras en las concesiones de tala certificadas y no certificadas dentro y fuera de las áreas declaradas PBI en el 2000. Dentro de los PBI, la expansión de las redes de caminos resultó en una disminución del espacio sin carreteras de más de la mitad desde 1999 hasta 2007. Después de 2007,*

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la pérdida se niveló en la mayoría de las áreas cercanas al cero debido a un equilibrio entre las carreteras recién construidas y las carreteras abandonadas que se repoblaron con especies de plantas. Sin embargo, las concesiones certificadas por el FSC que se encontraban dentro de los PBI desde alrededor de 2007 perdieron continuamente espacio sin carreteras y alcanzaron un nivel comparable a todas las otras concesiones. Sólo los parques nacionales permanecieron sin carreteras en su mayoría. Recomendamos que las políticas de manejo de bosques hagan que la preservación de áreas grandes y conectadas de bosque sea una prioridad principal al monitorear efectivamente - y limitar - la ocupación del espacio por carreteras que son accesibles permanentemente.

Palabras Clave: África Central, áreas sin carreteras, biodiversidad, certificación de bosque, concesiones de tala, conjuntos aleatorios, densidad de carreteras, redes de caminos, manejo sustentable de bosques

Introduction

Road networks are expanding rapidly around the world, connecting people and resources, increasingly in remote regions (Laurance et al. 2014). This provides a huge challenge for species conservation because roads can act as a physical barrier to migration and therefore potentially limit gene flow and reduce effective population sizes (Benítez-López et al. 2010; Laurance 2015). Furthermore, roads can be corridors for species invasions into remote landscapes; people and their vehicles act as dispersal vectors (von der Lippe & Kowarik 2007; Veldman & Putz 2010). Consequently, roadlessness increases overall landscape connectivity for most forest species (Crist et al. 2005) and has been used successfully as a measure to predict, for example, species richness and composition of Amazonian bird communities (Ahmed et al. 2014). In tropical regions around the world, forest degradation, unregulated hunting, and deforestation due to agricultural expansion are associated with roads built for selective logging (e.g., Wilkie et al. 2000; Barber et al. 2014; Clements et al. 2014; Brandt et al. 2016).

Forest areas that are not accessible by roads are considered of highest conservation value because they provide habitats that are not immediately affected by major human activities. Inventoried roadless areas (IRA) became part of forest and conservation legislation in 1999 in the United States due to their effectiveness for conservation outside protected areas (DeVelice & Martin 2001). Laurance et al. (2014) extended this approach by proposing a global strategy to regulate road building. The protection of road-free intact forest landscapes (IFLs) is high on the biodiversity conservation agenda. Intact forest landscapes are defined as areas >500 km^2 with a minimum width of 10 km that lie outside a 1-km buffer around any road or settlement (Potapov et al. 2008). Although ecologically the intactness of a forest depends on many factors, in remote tropical regions the operational use of the term intact corresponds to the concept of roadlessness. The underlying assumption is that important impacts of roads inside IFLs are not only the dissection of formerly connected habitats but also the process of incision (Jaeger 2000) that opens the forest for anthropogenic disturbances (Laurance et al. 2009). Because of the easy detectability of newly constructed roads in otherwise closed canopy forests, the current identification of intact forests excludes any forest that has been recently penetrated by roads built for selective logging, independent of harvest intensity. However, in central Africa, for example, $<20\%$ of roads built for logging are permanently accessible; the remaining 80% are rapidly revegetating (Kleinschroth et al. 2016*a*, 2016*b*).

Forest certification, such as that of the Forest Stewardship Council (FSC), provides market-based incentives for logging operators who are audited for their sustainable forest management and implies reduced-impact logging standards, traceability of timber, and social welfare for workers (Blackman & Rivera 2011). Adherence to these standards should require the prevention of long-term negative impacts of logging on forest ecosystems caused by, for example, poorly designed road networks (FSC 2010). Under increasing pressure from the international environmental organization Greenpeace, FSC has recently passed a motion to better protect IFLs as part of their "high conservation value forest" policy and to implement this as a new standard by the end of 2016 (Rodrigues et al. 2014). Central Africa, with some of the world's least exploited tropical forests, is at the center of attention for this policy change.

To quantify roadlessness in forest landscapes, new methods are required. This is essential to determine whether logging operations that are certified do limit road-network expansion. In the Sangha River catchment, a prime target area for selective logging activities in central Africa, we assessed the change in logging-road networks from 1999 to 2015 to determine how the amount of roadless area differed between forest areas with varying certification statuses and between forests inside and outside IFLs. To quantify and test the spatial distribution of road networks, we developed a novel use of the empty-space function F, an established mathematical tool that allows quantification and testing of the spatial distribution of roadless areas. We hypothesized that roadless space decreases less rapidly in FSC-certified than in uncertified concessions and even less rapidly inside intact forest

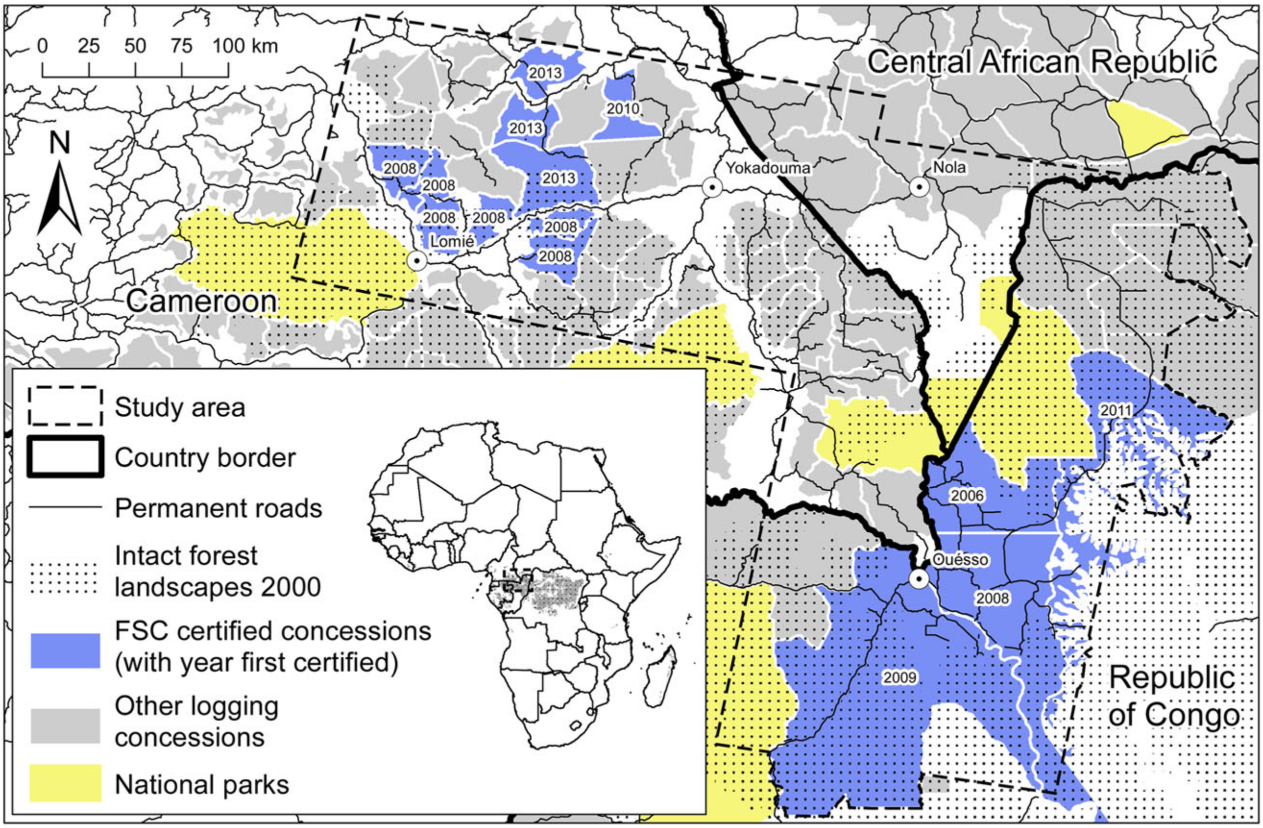

*Figure 1. Overview of the study area and its location in the central African region (inset). National parks (IUCN and UNEP-WCMC 2016), Forest Stewardship Council certified and uncertified concessions (WRI & MDDEFE 2012; WRI & MINFOF 2012), and their spatial overlap with intact forest landscapes as defined by Potapov et al. (2008) for the year 2000 are shown overlaid by permanent roads (Kleinschroth et al. 2016*a*).

landscapes, assuming a positive interaction between certification and IFL.

Methods

Study Area and Data Collection

The study area was 107,000 km^2 in the Congo Basin. It covered parts of Republic of Congo, Cameroon, and Central African Republic (Fig. 1). Most of the area is characterized by Guineo-Congolian semideciduous forest (White 1983). This region has been recently subjected to a rapid expansion of logging road networks into previously intact forests (Laporte et al. 2007). These logging operations mostly take place in concessions, large state-owned forest areas that are allocated to companies for timber harvesting according to a forest management plan (Lescuyer et al. 2015). We analyzed 64 concessions ranging in size from 217 to 12,100 km^2 (mean 1197 km^2). The concessions were operated by 20 different companies, mostly in groups of several bordering concessions (range 351–20,640 km^2, mean 3209 km^2) to reduce infrastructure costs (Supporting Information). From 2006 to 2013, 14 concessions, which were expected to have already adopted FSC principles during preceding years, were awarded FSC certification (Bayol et al. 2012) and covered 40% of the total area of concessions. These certified concessions were operated by 5 different companies of which 3 had almost all their concession area certified and 2 had one-third certified. Fifty-five percent of the study area was classified as intact forest landscapes in 2000 (Potapov et al. 2008). We classified the overall area into 5 different management categories: FSC certified logging concession, uncertified or not certified by FSC, inside an IFL, outside an IFL, and national park (Fig. 1).

Given the economic dominance of logging in the study area, we associated the majority of roads constructed with timber extraction. Logging-road networks are highly dynamic; 50% of roads persist on LANDSAT imagery for <4 years due to vegetation regrowth (Kleinschroth et al. 2015). We manually delineated forest roads during 9 2-year intervals based on a time series of more than 130 LANDSAT 7 and 8 images captured from 1999 to 2015. Based on the contrasting spectral properties of bare soil and recovering vegetation, we differentiated between open (actively used) and abandoned (in process of revegetation) roads (Kleinschroth et al. 2015). We included

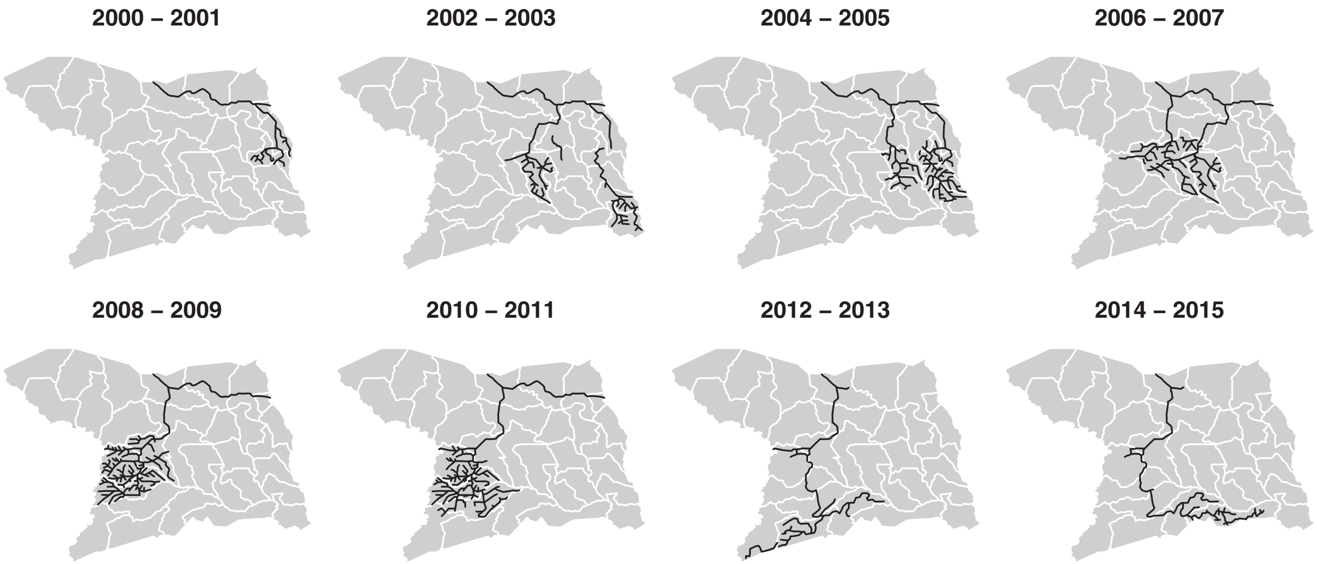

Figure 2. Temporal development of the road network in one logging concession in Cameroon (white lines, division of the concession into 30 annual felling areas; black lines, roads open during the respective 2-year intervals). The east–west extension of the concession is approximately 50 km.

only those roads that were open on any image over the 16-year period. The majority of logging concessions in the region were operated under a management plan, which effectively limits the amount of wood harvested annually by demarcating annual felling areas (assiettes annuelles de coupe [AAC]) based on timber inventories (Karsenty et al. 2008). The existence of these AACs is the most important factor determining where roads are built each year (Fig. 2).

Quantifying Roadlessness With the Empty-Space Function

The method most commonly used to evaluate intactness of forests is based on one predefined buffer distance around any road or settlement (Potapov et al. 2008; Herold et al. 2011; Tyukavina et al. 2015). This approach is quick and easy but lacks accuracy in that it does not take into account the highly dynamic nature of forest degradation (Goetz et al. 2015). Different animal species have different radii of movement and different plant species have different dispersal distances, just as different human land uses affect forest functions over varying distances (Coffin 2007). The binary classification of an area based on a buffer (intact vs. degraded) is closely linked to road-length density and does not take road location in the overall landscape into account. More sophisticated measures such as the effective mesh size (Jaeger 2000) are useful to measure connectivity in fragmented landscapes but do not respond to the incision of roads built in intact areas. An alternative way to characterize landscapes is to quantify, for a certain area, the distance from each point to the nearest road (Riitters & Wickham 2003). This idea is implemented in the metric roadless volume (Watts et al. 2007), where a pixel of an area is assumed to have a higher value the farther away it is from a road, which then allows calculation of the volume under this pseudo-topographic surface as an index of roadlessness. We followed the approach of Riitters and Wickham (2003) by integrating their idea in an established mathematical function.

The empty space function F (or spherical contact distribution function) is based on stochastic geometry and random sets theory (Lieshout & Baddeley 1996; Foxall & Baddeley 2002; Gelfand et al. 2010). Our main hypothesis is that the road network is the realization of a random set. For a stationary random set X, the distance from an arbitrary point $u \in \mathbb{R}$ to the nearest element of X is $\text{dist}(u, X)$. For a given radius r, F can be described as $F\ (r) = \mathcal{P}(\text{dist}(u, X) \leq r)$. Given the assumption of stationarity, this does not depend on u. Similar to random variables, the F function can be interpreted as a moment characterizing the considered random pattern. Knowing one such moment provides a characteristic of the studied object but will not completely describe it. Nevertheless, it provides an important general feature of the entire analyzed pattern and is therefore valuable for data analysis and interpretation (Baddeley et al. 2006).

The observation window W serves as a sampling frame in a larger overall study area. This includes an inherent bias for the estimation of F due to the edge effect wherever the borders obscure the actual distance to an element that lies outside W. Based on the analogy with estimation of a survival function, the distance of a reference point u to X is assumed to be right-censored by its distance to the boundary of W. Several estimators built on these ideas are available in the literature (Baddeley 1999). We implemented the estimator of F given by Foxall and Baddeley (2002).

We applied this type of analysis to our road-networks data. The F estimation requires the evaluation of the probability that circles of increasing radii centered on any point in W intersect the line pattern. We used a toy model (Fig. 3) to demonstrate the use of F for linear features that can occupy a limited available space in different ways. The considered model simulates line patterns of the same length, but with a different topology. The situations depicted in Fig. 3 are a simple and naive replica of the characteristics of three types of network: main roads, secondary roads, and rivers.

We performed multiple simulations for each model. The F function was evaluated for each model simulation on a finite set of values of r. This allowed a statistical analysis as in Illian et al. (2008) and enabled the construction of range envelopes for F. The envelopes then characterized the linear pattern corresponding to each model. To synthesize all the information gathered using this statistical approach, we considered the median curve obtained from these envelopes. The results obtained from 100 simulations are given in Fig. 3. Clearly, the length of the line patterns is not the only element characterizing such an object. The F function appeared to successfully integrate more information related to the entire line-network topology.

Sampling and Statistical Analyses

Following its mathematical definition, the F function for analyzing roadless space was estimated using disk-shaped observation windows. The points in the continuous observation domain were approximated with a finite grid (the steps of the grid were 250 m). To reduce edge effects and save computational time, we computed the distances from any point in the grid (the discretized observation domain) to the entire road network. After this, the values needed were simply collected for a local analysis. The radius of each window was set at 10 km because this was the average maximum distance to a road of any point in the study area. For each year, we ran 10,000 replications and kept only those windows that had at least 90% of their area in the same management category. This gave for each year and category a number of samples n from 485 to 808. For each replicated window, we derived F. The r domain for the application of the empty-space function was the interval given by [0, 20] km, which we divided into discrete steps of 0.2 km. Thus, for year and category, for the fixed values of r, we had n corresponding values for F. Empirical quantiles were computed for each r value and, finally, the median was considered. Therefore, by considering all the medians for all the radius values, we obtained a median curve $\tilde{F}$ for each management category.

We next compared these median curves between 2 management categories $\tilde{F}_A$ and $\tilde{F}_B$. The obtained functions $\tilde{F}$ are not guaranteed to be empirical distribution functions; hence, we had to use an alternative to the Kolmogorov–Smirnoff test. We therefore developed an alternative representation of these values. Consider the set of differences $d_i = \tilde{F}_A(i) - \tilde{F}_B(i)$. Assuming the sample $d_i, i = 1 \ldots, n$ is the realization of some independent and identically distributed random variables, under the hypothesis that $\tilde{F}_A = \tilde{F}_B$, $E\,[d] = 0$. We tested this statement using a 1-sided t test. We interpreted the t-test statistics as the change intensity in $\tilde{F}_B$ compared with $\tilde{F}_A$. The drawback of this test is that if the null hypothesis H_0 is not rejected, this does not mean that $\tilde{F}_A$ and $\tilde{F}_B$ are equal. Therefore, our focus was on those cases where H_0 was rejected. For all $E\,[d] \neq 0$, we compared d_i between multiple categories with pairwise t tests with pooled standard deviations and Holm-adjusted p values for all possible comparisons (Holm 1979).

To validate the accuracy of our method, we tested it on river networks. We used the HydroSHEDS data set, which has a 90-m resolution (Lehner et al. 2008). It has mainly been derived from a digital elevation model and thus directly reflects the topography. Despite the fundamental difference in ecological characteristics between rivers and roads, both are general random sets and can be analyzed with the same tool. A priori the distribution of the rivers in the region should be independent of the management and intactness of forests. Therefore, $\tilde{F}$ is expected to show no difference for rivers between zones of different forest management categories (because rivers are not managed in that region) but to vary for roads due to the effects of management. We duly found that empty-space curves for river networks were very similar throughout all management categories (Supporting Information). Pairwise t tests showed no significant differences: P values were >0.9 for all combinations. This does not mean the river networks were identical, but it is consistent with the assumption that the distribution of rivers is independent of forest management across the study area. This indicates the method was accurate in that it did not show variation between equally distributed patterns such as the existing river network.

All analyses were carried out in R (R Core Team 2016) with the spatstat package (Baddeley & Turner 2005).

Results

In 2015 roadless space was very similar (no significant differences in $\tilde{F}$) inside and outside IFLs, in certified and uncertified concession areas, and outside national parks (Fig. 4a). For all areas outside national parks, the maximum distance from any point to a road was 13 km. This means the maximum possible distance between

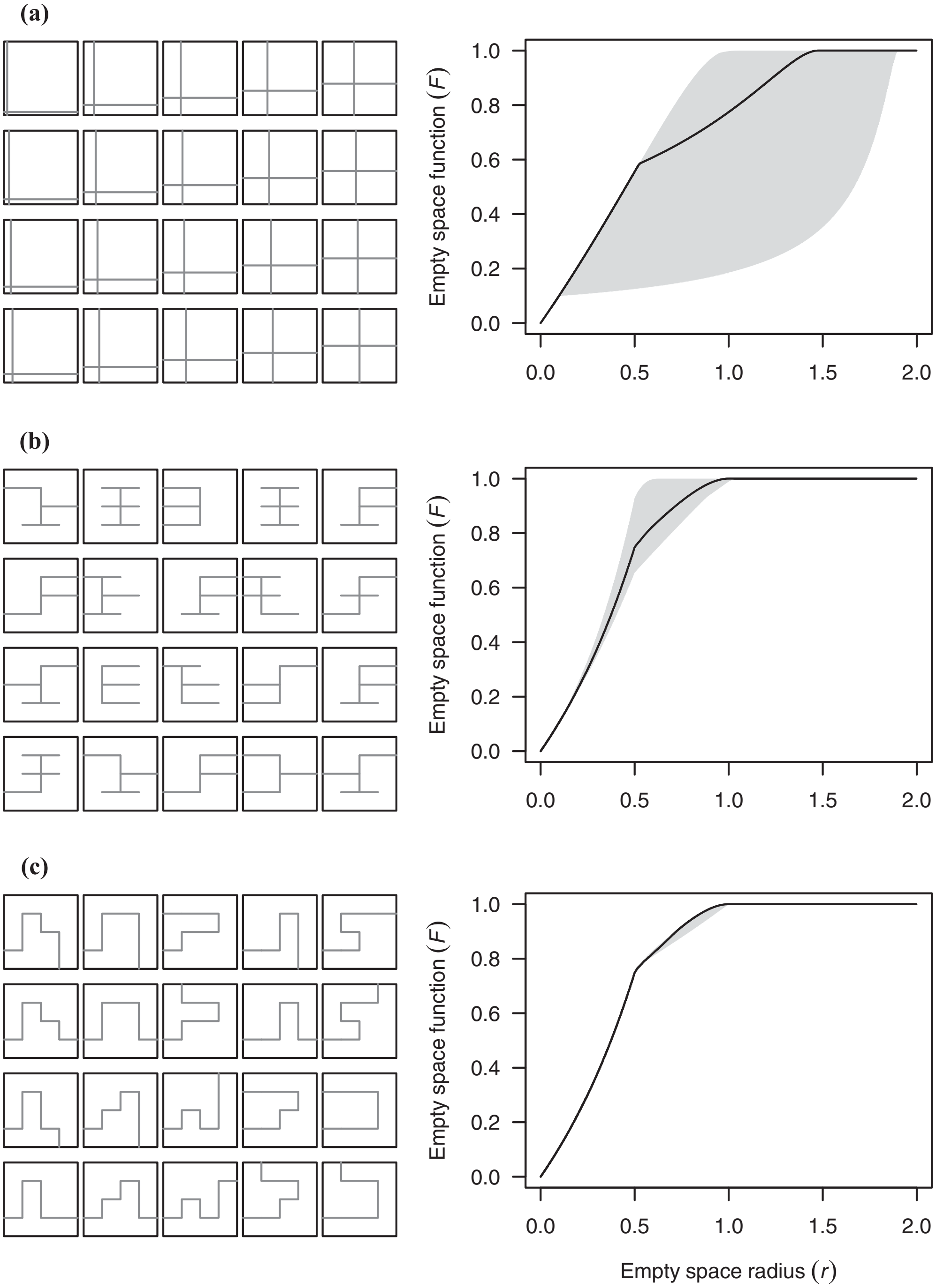

Figure 3. Computation of the empty space function F for 3 toy models of line patterns: (a) main roads, (b) secondary roads, and (c) rivers. All patterns have the same line length of 8 and observation windows of 4 × 4. Twenty examples for each pattern are shown on the left. The 5–95% range envelope (gray) and the median (black) are shown on the right. The y-axes are the values of the estimation of F, and the x-axes are the radii. These computations were done with 100 simulations for each model.

two roads was 26 km. Very few roads were detected inside national parks. The small rise of the curve for radii >15 km was due to the effect of roads in adjacent areas outside national parks. Intact forest landscapes were defined based on road networks in 2000 (Potapov et al. 2008), and accordingly the *F* function we calculated also consistently showed low values for all concessions inside IFLs in 1999 (Fig. 4b,c). Subsequently, there was a clear decrease in roadless space inside IFLs over time (Fig. 4b,c). Specifically, roadless space in uncertified concessions (Fig. 4b) decreased rapidly from 1999 to 2003; remained on a similar level to the concessions

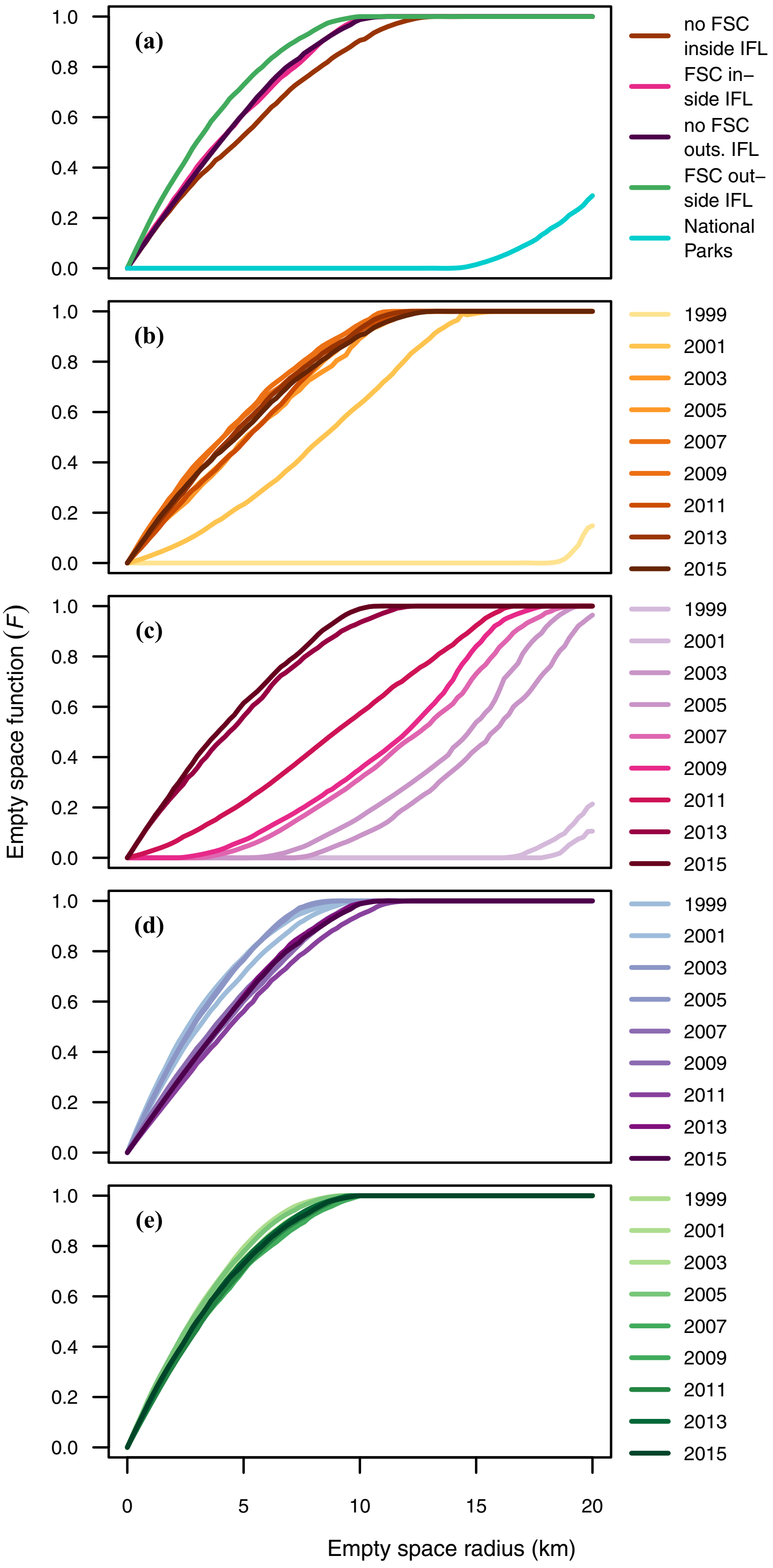

Figure 4. Median curves of the empty space function $\tilde{F}$ (probability that from any point in the observed domain there is a road at distance r) relative to r for (a) the 5 management categories in 2015, (b) uncertified concessions inside intact forest landscapes (IFL), (c) Forest Stewardship Council (FSC)-certified concessions inside IFL, (d) uncertified concessions outside IFL, and (e) FSC-certified concessions outside IFL. Panels (b–e) show 2-year steps from 1999 to 2015 (shading from light to dark with change over time).

outside IFLs in subsequent years (Fig. 4d); and increased slightly after 2009. Concessions inside IFLs certified since 2006 showed a slower but continuous decrease in roadless space, as indicated by regularly increasing curves (Fig. 4c). By 2013 these areas had reached the same level as all other concessions. Roadless space in certified and uncertified concessions outside IFLs changed little from 1999 to 2015 (Fig. 4d,e). Only for uncertified concessions outside IFLs (Fig. 4d) did roadless space increase slightly.

Extracting the probability of encountering the nearest road within 5 km of a point for each year illustrated continuous trends over time. In 2001 the probability of encountering a road within 5 km of a point was almost 80% outside IFLs and 20% or less inside IFLs (Supporting Information). By 2015 it was 50–60% for all management categories except certified concessions outside IFLs, which showed a higher probability of approximately 70%. In general, roadless space inside IFLs decreased dramatically; certified concessions showed a continuous trend up to 2013. Outside IFLs roadless space remained at a similar level; in uncertified concessions there was a slight but continuous increase (Supporting Information).

Comparing changes in roadless space in 2 longer (8-year) time steps highlighted the contrasts among the 4 management categories. Inside IFLs roadless space decreased by more than half during 1999–2007. Then during 2007–2015 this decrease continued in the concessions that were certified after 2005, whereas it stagnated in uncertified concessions (Fig. 5). The change in roadless space from 2007 to 2015 was significantly different between certified concessions inside IFLs and all other categories, which remained at a similar level (Supporting Information).

The level of change in roadless space was much less outside IFLs. There was a slight increase during 1999–2007, then, during 2007–2015, the level of change was close to zero. Although there was a slight increase in roadless space in uncertified concessions and a decrease in concessions that were certified after 2005 (Fig. 5).

Discussion

The areas with the highest probability of being subjected to a recent expansion of logging activities were those that had been classified as IFLs in 2000. With the ongoing process of government leasing of concessions for areas of unlogged forest, our result that roadless space greatly decreased inside IFLs during 1999–2007 was expected. However, that this process continued during 2007–2015 in concessions certified by FSC since 2006, whereas it stopped in non-FSC concessions, was surprising. Selective logging in the region focuses on only a few commercial timber species of high market value, and expanding logging into previously unlogged areas is more lucrative than repeated logging in the same area (Laurance 2000). Recent discussions about certified logging in IFLs highlight the importance of maximizing conserved roadless space as a new component in sustainable forest management.

Roadless Space in Certified Forests

The only net losses of roadless space we recorded since 2007 occurred in FSC-certified concessions. The same FSC forest stewardship standards that, for example, restrict logging intensity and impose strict requirements to reduce road-related impacts, such as poaching, erosion, and disturbance of watercourses, are applied in the different countries of the Congo Basin (FSC 2012). However, recommendations about road networks only suggest avoiding “poorly designed patterns of roading” (FSC 2010). This commonly means reducing road lengths to a minimum while allowing sufficient access to the timber resource (Gullison & Hardner 1993; Picard et al. 2006). Annual felling areas (Fig. 2) are a determining factor for where new roads are built in managed logging concessions (Cerutti et al. 2008). So far, no limitation has been imposed on the maximum size and position of these areas. Instead, FSC and other forest-management guidelines focus on the annual allowable cut, the maximum volume of wood per area that can be harvested per year, and the minimum size of trees that can be harvested (Cerutti et al. 2011). The environmental advantage of reducing logging intensity is equivocal if, instead, a greater area needs to be exploited (and made accessible by roads) in order to produce the same volume of timber as before (Healey et al. 2000).

Because of the high costs of road construction and maintenance, we assumed that the length of roads built in each concession was limited by the capital resources of the operating companies. The intensity of forest exploitation in the region is fluctuating and was strongly affected by the global economic crisis in 2009 (Karsenty et al. 2010), when a reduction in the volume of timber exports resulted in temporary shutdowns of logging activities. However, official data on wood-production volume (de Wasseige 2015) show that in subsequent years exploitation increased progressively. This was especially true for the 2 companies, Industrie Forestière d’Ouesso (IFO) and Congolaise Industrielle des Bois (CIB), which operate 4 of the largest concessions in the study area, all of which obtained FSC certification between 2006 and 2009. The annual wood-production volume increased by 45% from 2009 to 2013 in the IFO concession and by 24% in the CIB concessions (de Wasseige 2015). There are several potentially confounding factors that may have influenced these trends. Well-capitalized companies may have adopted both FSC certification and efficient means of exploitation, leading to a higher density of roads, whereas less-capitalized companies did not. Logging

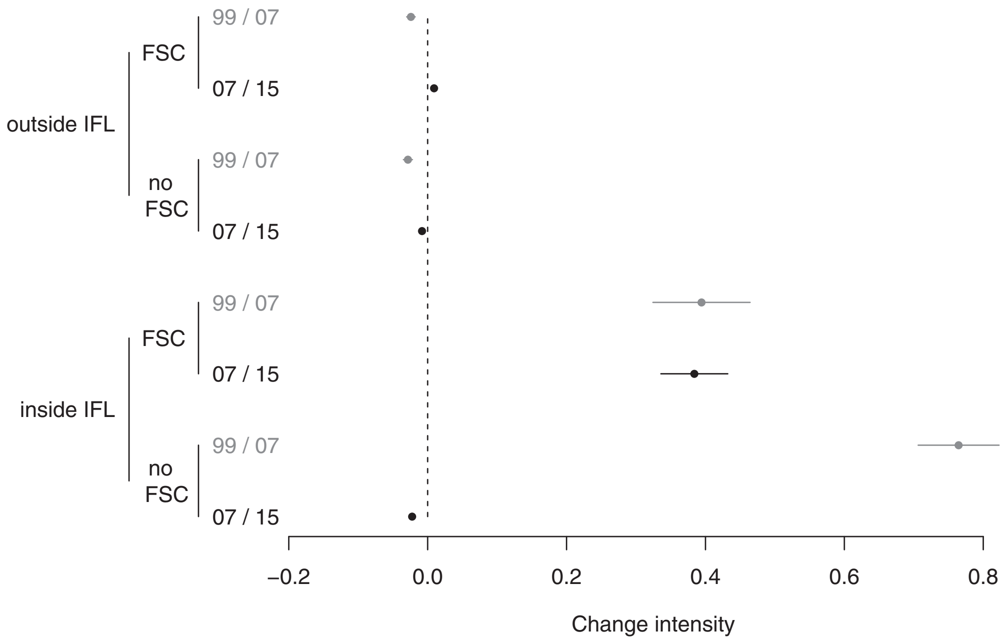

Figure 5. Results of t tests (95% CI) as measures of change intensity in roadless space ($\tilde{F}$) during each of 2, 8-year periods (gray, 1999–2007; black, 2007–2015) for 4 management categories: logging concessions with and without Forest Stewardship Council certification (FSC and no FSC, respectively) located inside and outside intact forest landscapes (IFL). No overlap of the confidence intervals with zero indicates significant changes between the 2 years. Where the confidence interval bars are not visible, they are shorter than the radius of the circle showing the t statistic.

history also differs between concession areas. In concessions that have been logged previously, there is less likelihood of yielding high timber volumes in the present cycle and therefore companies may be less likely to accept the costs of FSC certification or to build many new roads.

The protection of IFLs has to be approached at a larger scale than individual logging concessions. Given that the extent of most IFLs exceeds the size of individual concessions by far, there is still the potential to retain much greater roadless areas than can be achieved by a single operating company within one concession. The most important factor driving the reduction of roadless space was the position of roads in the overall forest landscape within which the space is located. Roads built closer to the edge of an area of continuous forest cover had a less fragmenting effect than those in the center. Larger concessions and those located in the center of the overall forest landscape therefore have a more important role in retaining a large, contiguous area that is road-free.

Roadless Space Outside IFLs

Outside IFLs there was a low rate of change in roadless space. In uncertified concessions, there was a small increase in roadless space during 1999–2015. Here, roads that disappeared outweighed those that were newly built, which is linked with the relatively short time that secondary logging roads remain open after abandonment (Kleinschroth et al. 2016*b*). Sometime after the commencement of timber exploitation, forest areas appeared to be saturated with permanent roads. It is expensive for companies to maintain and control roads that are permanently accessible, and they have a strong interest in reducing the extent of open roads to the minimum necessary for their operational efficiency. Overall, over 80% of all logging roads are closed and abandoned after a short harvest period (Kleinschroth et al. 2016*a*), a practice in accordance with recommendations for good forest management (Dykstra & Heinrich 1996). Our results indicate that recently inside uncertified concessions in areas with a longer logging history (i.e., outside IFL), the ratio between abandoned and newly created roads led to a slight increase in roadless space.

Dissection of Tropical Forests by Permanent Roads

We suggest that forest road-building recommendations account for the spatial layout of the road network and thus the conserved roadless space at a landscape scale. The key consideration in choosing among road layouts should be to retain undissected blocks of forest; this requires control of the position of permanent roads in the overall forest landscape. Based on our findings of limited persistence of abandoned roads (Kleinschroth et al. 2016*b*), we suggest logging roads be managed as transient elements in the landscape that affect only a small part of the overall area of forest at a given time. Road networks should be planned so that the majority of the forest area remains inaccessible to damaging human activity (i.e., as roadless space) at all times but the exact configuration of the roadless space should be allowed to shift over time (Supporting Information). Other than the theoretical model of conservation concessions, where after a first cut the concession area becomes protected (Gullison et al. 2001), logging companies should be held responsible for conserving the integrity of the forest except for the small portion where logging takes place every year. Key to this integrity will be the planning and management of the road network. A particular danger is posed by permanent access roads that often transect forest areas, thus keeping the core of the forest open to permanent threats. Wherever necessary, these roads should be closed effectively and replaced by less fragmenting ones in the periphery of the forest. We suggest this as a principle for all logging-road management in tropical forests.

A New Approach to Evaluate Roadless Space

To the best of our knowledge, this is the first time the empty-space function has been used to characterize road networks. Spatially explicit measurements of road proximity are needed to predict where ecological effects are likely to occur (Riitters & Wickham 2003). We used an example of road networks that are highly dynamic in space and time to demonstrate the usefulness of the empty space function for conservation purposes. The most common indicator used to measure landscape-level road influence is road density, defined as the average total road length per unit area (Robinson et al. 2010). However, this indicator does not account for the spatial arrangement (packing) within the analysis window (i.e., the degree to which the network is dispersed or clustered). Buffers, used to evaluate roadlessness and intactness of landscapes, such as in Potapov et al. (2008), lead to a binary classification based on a fixed distance. This classification does not capture effects that occur with increasing or decreasing intensity depending on distance to a road. In contrast, the empty-space function allows the limitations of both these common approaches to be overcome, and it is computationally efficient enough to be repeated at high rates. However, further research is needed on how spatial and temporal dynamics of road networks can be captured simultaneously.

Policy Implications

The protection of IFLs is currently being incorporated into FSC certification policy. Given that the extent of most IFLs exceeds the size of individual concessions and frequently crosses country borders, this process affects multiple stakeholders. Based on our findings, we suggest that control of the spatial arrangement of permanent roads is an essential requirement to protect IFL. We recommend that measures to reduce the impacts of selective logging should not only be based on amounts of timber extracted per time and area but also include the size of forest areas that remain undissected by roads. The preservation of large, connected areas of roadless space needs to become a high priority in forest management, and this can only be achieved by effectively monitoring the spatial arrangement of roads that are permanently accessible, for which we advocate the use of the empty-space function.

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Supporting Information

Counts and characteristics of studied concessions (Appendix S1), changes in the median empty space function (Appendix S2), comparison of changes in roadless space over time (Appendix S3), river network analysis (Appendix S4), probabilities of intersecting a road within a distance of 5 km (Appendix S5), and the effect of logging on roadless space in 2 contrasting logging concessions (Appendix S6) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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