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Legacy of logging roads in the Congo Basin: How persistent are the scars in forest cover?

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Abstract. Logging roads in the Congo Basin are often associated with forest degradation through fragmentation and access for other land uses. However, in concessions managed for timber production, secondary roads are usually closed after exploitation and are expected to disappear subsequently. Little is known about the effectiveness of this prescription and the factors affecting vegetation recovery rate on abandoned logging roads. In a novel approach we assessed logging roads as temporary elements in the forest landscape that vary in persistence depending on environmental conditions. We analyzed road persistence during the period 1986–2013 in adjacent parts of Cameroon, Central African Republic and Republic of Congo. Three successive phases of road recovery were identified on LANDSAT images: open roads with bare soil, roads in the process of revegetation after abandonment and disappeared roads no longer distinguishable from the surrounding forest. Field based inventories confirmed significant differences between all three categories in density and richness of woody species and cover of dominant herbs. We used dead-end road segments, built for timber exploitation, as sampling units. Only 6% of them were identified as being re-opened. Survival analyses showed median persistence of four years for open roads before changing to the revegetating state and 20 years for revegetating roads before disappearance. Persistence of revegetating roads was 25% longer on geologically poor substrates which might result from slower forest recovery in areas with lower levels of soil nutrient content. We highlight the contrast amongst forests growing on different types of substrate in their potential for ecosystem recovery over time after roads have been abandoned. Forest management plans need to take these constraints into account. Logging activities should be concentrated on the existing road network and sites of low soil resource levels should be spared from business-as-usual exploitation.

Key words: Central Africa; deforestation; geological substrate; GIS; land cover change; LANDSAT; land sharing–land sparing; regeneration; road ecology; selective logging; survival analysis; tropical rain forest.

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INTRODUCTION

Logging roads are often associated with forest degradation through fragmentation and by opening up the forest for subsequent encroachment by hunters, illegal loggers and farmers (Wilkie et al. 2000, Newman et al. 2014). Building a road into an unexploited rainforest has been compared to opening Pandora's box: a small intervention with escalating consequences for the forest ecosystem (Laurance et al. 2009, Fraser 2014). This, and the amount of forest clearing for the road itself, makes road building the most persistent form of forest damage associated with selective logging (Gullison and Hardner 1993). Accordingly, logging road networks have been used as a proxy to assess the extent of selective logging disturbance in tropical forests (Asner et al. 2002 for the Amazon, Laporte et al. 2007 for the Congo Basin).

Major logging operations in the Congo Basin take place in industrial concessions (Ruiz Perez et al. 2005, Nasi et al. 2012). An increasing proportion have produced forest management plans designed to ensure sustainability of their logging operations (Karsenty et al. 2008, Bayol et al. 2012). One important rule of sustainable forest management requires that logging roads are closed after harvesting (Putz et al. 2008). Therefore the forest contractor must, for example, erect physical barriers to stop road access by vehicles or remove temporary stream crossings at the end of a harvesting period (Applegate et al. 2004). By right, this rule should be applied in most parts of the study area, the Sangha river catchment, because it is included as a prescription in the forest management plans implemented in this area (Nicolas Bayol, co-author of several forest management plans in the region, *personal communication*). However, there has not yet been an evaluation of how long it takes until forest cover is reestablished after road abandonment and which site-specific drivers prolong persistence of logging roads.

Forest recovery after disturbance varies depending on local site conditions including soil fertility (Guariguata and Ostertag 2001, Chazdon 2014). For the northwestern Congo Basin it has been shown that the functional diversity of tree communities is heavily influenced by geological substrate (Fayolle et al. 2012). The range of substrates includes those that are sandy and of low fertility which are hypothesised to support slower recovery from deforestation and degradation (Chazdon 2003, Gourlet-Fleury et al. 2011). However, none of the forest management plans that are currently active in this region take account of these site conditions when assigning annual cut zones and potentially vulnerable areas (N. Bayol, *personal communication*).

Forest regeneration on roads is not only of major interest for nature conservation but also from a commercial perspective. Vegetation cover protects the road surface from erosion damage, a frequent and severe problem on logging roads in forests with high amounts of rainfall (Sessions 2007, Negishi et al. 2008, Laurance et al. 2009). If roads are not re-opened for further harvesting operations, forest recovery on the road may even be of long-term commercial value for timber production if it eventually leads to regrowth of harvestable timber trees on the land area occupied by the road. Logging road networks can be classified into three hierarchical levels (Sessions 2007): (1) principal roads that form permanent transport links between forest roads, public roads and markets, (2) primary roads forming the basic structure of the forest road network and (3) secondary (feeder) roads that connect log landings to the primary forest roads. Secondary roads are the ones that are usually abandoned after logging operations (Malcolm and Ray 2000) and therefore no surfacing or subsurface drainage operations are carried out (Sessions 2007). Due to these predictable patterns of use frequency and duration, secondary roads are particularly suitable for the study of spontaneous forest recovery processes.

The strategic choice between land sparing and land sharing strategies applies equally to timber production as it does to agriculture (Healey et al. 2000, Edwards et al. 2014). To inform this forest management decision, a better understanding of how forest recovery on roads depends on site-specific factors will help identify more and less resilient forest areas. We therefore addressed two central study questions: (1) how long does it take until forest cover is re-established after secondary road abandonment and (2) what are the main biophysical and geographical factors that affect secondary road persistence?

Methods

Study area

The study region is in the catchment of the Sangha River, a major tributary in the north west of the Congo River basin. The specific study area was selected based on imagery collected over two scenes of the LANDSAT satellite missions 7

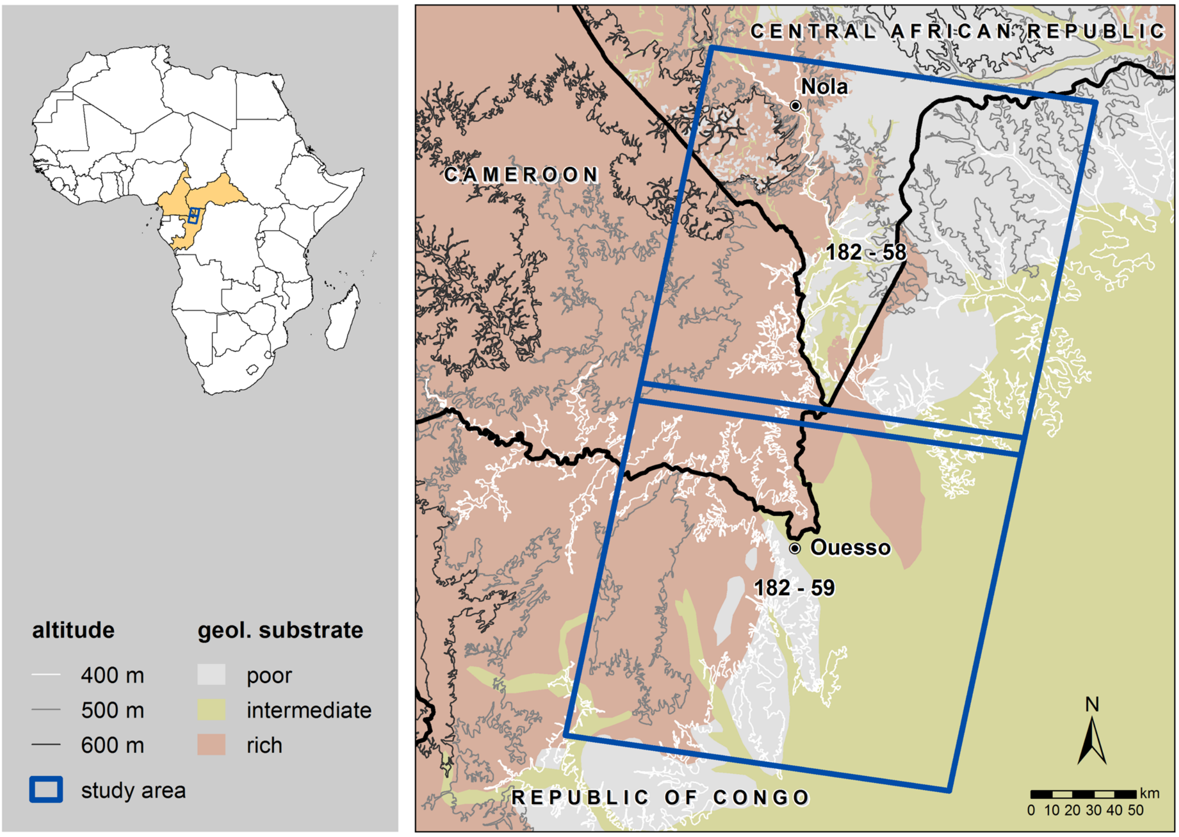

Fig. 1. Area of the study in the north-western Congo Basin, determined by the footprint of LANDSAT scenes path 182, rows 58 and 59 (blue boxes). Geological substrates according to their nutrient content type are shown using a color scale and 100-m contour lines are shown in a grey scale.

ETM+ and 4/5 TM (30-m pixel size). We chose the scenes located in path 182, rows 58 (centered at 2°54′ N, 16°21′ E) and 59 (1°27′ N, 16°3′ E) with the Sangha-Trinational conservation complex in the center to cover a range of different countries, geological substrates and logging histories. The main towns are Nola, Central African Republic (CAR) and Ouesso, Republic of Congo (Fig. 1).

The surface captured by the sensor has an extension of about 335 by 180 km (60,000 km^2). The vegetation is characterized by mixed moist semi-evergreen *Guineo-Congolian* forests (White 1983). The mean annual rainfall varies between 1400 and 1700 mm with three to four dry months (Hijmans et al. 2005) and the altitudinal range is between 330 and 745 m. Parts of three countries were included: Republic of Congo (40,877 km^2), CAR (10,766 km^2) and Cameroon (10,297 km^2). Around 16% of the area constitutes national parks (IUCN category II) and 5% special protection areas (IUCN category IV), established between 1963 and 2001. Sixty-seven percent of the study area is occupied by active logging concessions and, of their area, 92% has had a management plan implemented during the last 10 years (WRI and MEFCP 2010, WRI and MDDEFE 2012, WRI and MINFOF 2012).

Temporal dynamics in the road network

We analyzed the dynamics of road segments from first appearance to disappearance (due to re-establishment of forest cover) based on a time series of LANDSAT images. We classified road state into three categories. (1) Open roads were indicated by bare soil (lacking vegetation cover) due to current vehicular traffic (e.g., due to logging activity), or a lack of subsequent recovery. (2) In contrast, revegetating roads were in the

Table 1. Number of LANDSAT scenes of different dates in two locations (path/row) providing data in each of two spectral bands (red and near-infrared, NIR) during each four-year observation interval used for manual delineation of road networks.

Observation interval	Path/Row			
	182/58		182/59	
	Red	NIR	Red	NIR
1986–1989	3	6	5	4
1990–1993	1	1	1	1
1994–1997	2	4	3	4
1998–2001	5	7	4	3
2002–2005	6	6	6	3
2006–2009	11	6	5	4
2010–2013	5	7	5	7

process of re-establishment of vegetation cover after logging activities and vehicular traffic have stopped. (3) Disappeared roads could no longer be distinguished from the surrounding forest in the LANDSAT image. We included all images from 1986 to 2013 provided by the USGS National Center for Earth Resources Observation and Science (http://www.glovis.gov). Due to limits in image availability and quality, we clustered available images in seven four-year observation intervals (Table 1).

Manual delineation is a common procedure to detect roads on satellite images of closed forest landscapes (Brandão and Souza 2006, Laporte et al. 2007, Ahmed et al. 2014). This way of digitizing forest roads allowed us to clearly differentiate between roads and other linear features such as rivers by taking into account patterns such as linearity, connectivity and bifurcation angles. In a few doubtful cases comparison with a hydrological map proved to be helpful. The novelty in our approach is to differentiate categories of roads, depending on their vegetation cover in relation to the surrounding forest. Based on the contrasting reflective properties of bare soil ("open"), pioneer vegetation with high photosynthetic activity ("revegetating") and more mature forest ("forest"), forest roads differ depending on their surface cover in the spectral signatures captured by the LANDSAT sensor (de Wasseige and Defourny 2004, Bourbier et al. 2013). This difference is most pronounced between the reflective bands 3 (red) and 4 (near infrared, NIR) as band 4 is the only one that captures wavelengths where vegetation has a higher reflectance than soil (Richards 2012). The short wave infrared (SWIR) bands 5 and 7 proved to be less useful in differentiating bare soil and vegetation cover and were only used for corroboration (Fig. 2).

The detection of linear features that are thinner than the pixel size of the images depends mostly on the contrast with the surrounding landscape. If this contrast is apparent, even roads of only 5 or 6 m width can become visible (Albertz and Tauch 1994). In the case of logging roads in the study area, the actual width of the forest clearing for a road is around 15 m (distance between the nearest old growth trees on the two sides of the road, *personal observation*). This results from the common practice of clearing trees to allow the road surface to dry after rain, which is carried out on each side for a distance at least equal to the width of the roadway (Sessions 2007). Visibility of the images was enhanced for the human eye through histogram stretching and equalization (Albertz and Tauch 1994). We manually delineated road segments (henceforth referred to as 'roads'), each defined by the coordinates of two vertices (a vertex occurs at any change of direction). Through the overlay of several images in each four-year interval, continuous absence of data caused by the scan line corrector problem (SLC-off, Chen et al. 2011) since 2003 could be eliminated. Digitization scale was between 1:50,000 and 1:80,000.

The shapefiles of the seven intervals were overlayed in ArcGIS, using the "Spatial Join" tool, until each road carried the temporal information about its evolution from interval to interval. This information showed in which interval a road was first observed as open. For roads showing a change in classification in subsequent images this would normally be followed by the revegetating state until the road finally "disappeared", i.e., it was no longer distinguishable from adjacent forest. In very open forest types and highly degraded forests the contrast between revegetating roads and the forest could not be relied on as a criterion for detection. We therefore excluded all roads from the analysis that were only detectable in the open state (i.e., with bare soil) but subsequently (i.e., once covered with vegetation) disappeared from the images without being detectable as revege-

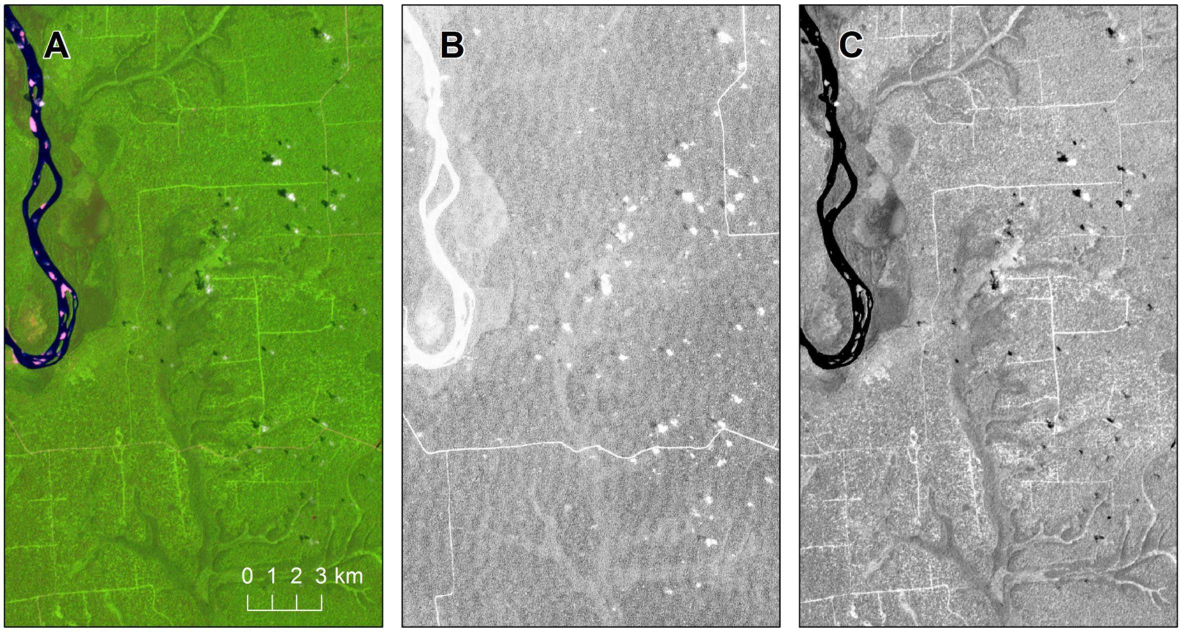

Fig. 2. (A) Combination of LANDSAT bands 5, 4, 3 (short wave infrared, near infrared and red channels), (B) band 3 (red channel) and (C) band 4 (near infrared channel) of an identical detailed view from LANDSAT 7 ETM+, dated 15 February 2003. Band 3 is sensitive to bare soil, all roads visible here are classified as "open" roads. Band 4 is sensitive to photosynthetic activity, all roads that are not visible on band 3 but are visible on band 4 are classified as "revegetating" roads. Image contrast enhancement is based on histogram transformation of local standard deviation.

tating. This was the case in 6% of all road segments. We also differentiated where roads have been re-opened, i.e., the reverse order (transition of revegetating or disappeared roads back to open) was observed. In cases where the re-opened state was again followed by the revegetating state, this was marked accordingly (Fig. 3).

Accuracy assessment

Given the fact that no systematic assessment of logging activities in the study region exists, we used a combined approach to validate our maps, based on other existing GIS data, high resolution satellite images and field data.

We determined how much information each image of the same scene in the same observation interval added. This was done by calculating the proportion of the final data that was based on each of the available images that we had added in the iterative process of road digitization. We then compared the length of our road network with maps of roads (both public roads and those built for logging operations) published by WRI (WRI and MEFCP 2010, WRI and MDDEFE 2012, WRI and MINFOF 2012). These maps were based on a combination of information from logging companies with satellite images for the year 2008 but it is not clear what time period the information spans over. As a conservative estimate we used all roads that we detected before 2005 to compare with the reference data. We additionally compared the length of our roads with those visible on four SPOT5 images (10-m resolution) from the year 2008, covering 27% of the center of our study area.

We carried out forest inventories in the South-East of Cameroon in February and March 2014, where we set up 76 plots of 5 × 5 m on roads classified on recent LANDSAT 8 images into the different categories (open, revegetating, undetectable). With the help of four experienced local forest surveyors we counted all trees (>1 cm DBH) and identified them wherever possible to the species level. In addition, we estimated the ground cover of the dominant herbaceous genus

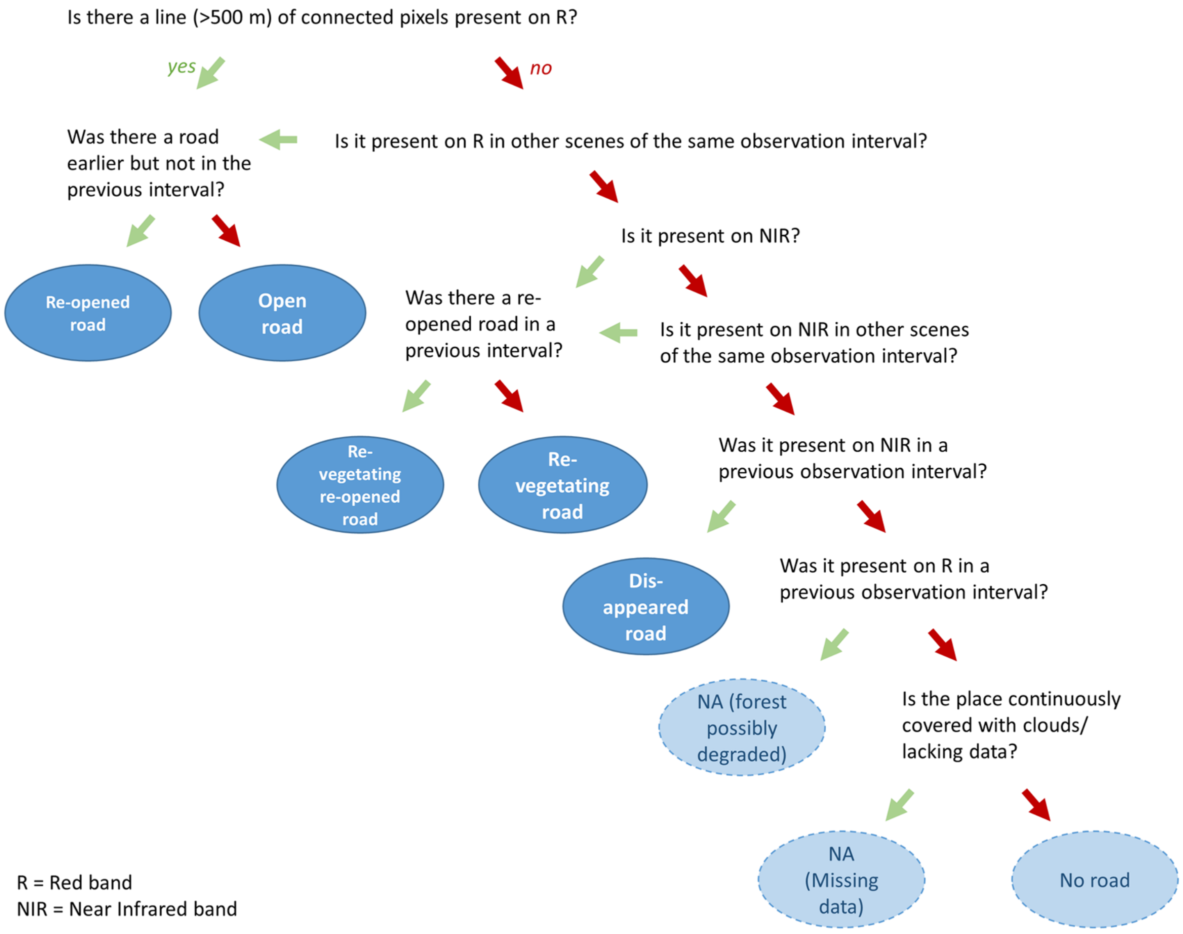

Fig. 3. Decision tree for the classification of road segments based on the red and near infrared reflective bands, including potential sources of error.

Aframomum (Zingiberaceae). Based on hemispherical photographs taken in each plot, we calculated the gap fraction in the canopy on a 180° half globe over the road using the CanEye software (http://www6.paca.inra.fr/can-eye). We also measured the width of the actual or former road (delimited by the banks of soil accumulated on both sides during road construction) and of the adjacent forest clearing (delimited by the presence of old-growth trees).

Environmental and human infrastructure factors

A homogenized geological map (Fayolle et al. 2012) based on three national maps (Gazel 1956, Orstom 1967, Boulvert 1996) was used to identify areas of contrasting "substrate fertility". Geological types were characterized analogous to Gourlet-Fleury et al. (2011). Sandstone and ironstone-capped plateaux and terraces provide a base for nutrient-poor substrates, and alluviums for intermediate substrates. All the other geological formations, sedimentary rocks (tillite, carbonate), acid metamorphic rocks (schist and gneiss), acid igneous rock (granite), basic rocks (dolerite and amphibolite-facies), and mixtures of metamorphic and sedimentary quartzite-sandstone rocks (quartzite), were considered to provide a base for nutrient-rich substrates. This simplified approach allowed us to assign each position in the study area to one of the three substrate fertility classes "poor" (27% of the study area), "intermediate" (30%) or "rich" (43%). We were unable to systematically assess these geological maps, given the lack of other available data. As an approximation (though aware of the substantial differences in the information reported), we used the recent soil map of Africa (Dewitte et al. 2013) as a general reference to identify the main soil types in the region. We roughly grouped the soil types by their nutrient richness for comparison with our classification based on geological substrates. We used Arenosols as the reference for poor soils, Ferralsols and Gleysols for intermediate soils and Plinthosols, Alisols, Fluvisols and Nitisols for rich soils (Jones et al. 2013). In a GIS overlay analysis we calculated the area where these three soil classes matched those based on the regional geological map.

Altitude was obtained from the Shuttle Radar Topography Mission (van Zyl 2001) with a resolution of 90 m. This dataset also enabled calculation of slope as the ratio between the length of each road and the altitudinal difference between its start and end points. Mean annual rainfall was obtained from the "worldclim" dataset (Hijmans et al. 2005). The distance to nearest settlement was generated as a variable in ArcGIS by calculating Euclidian distance using the "NEAR"-tool. Due to the lack of recent official maps, positions of towns were obtained from the OpenStreetMap project (http://www.openstreetmap.org), completed and corrected through comparison with older population data but also through visual interpretation of LANDSAT imagery from different years. We identified those settlements that have timber landing sites next to a river or a major road as an indicator that they are a timber transport hub.

Statistical modeling

We compared the field data (tree density, species richness, herbaceous vegetation, canopy cover, road width) amongst the three different satellite-image derived road categories with a Kruskal-Wallis rank sum test and a post-hoc test using pairwise Mann-Whitney tests with Bonferroni correction.

A survival analysis was used to analyze time-to-event data (Kleinbaum 2012). While this event is conventionally the death of an individual in a medical study, the applicability of this analysis for land-use-change data has been demonstrated (An and Brown 2008). A key analytical problem in survival analysis is the fact that the time until an event occurs is not known for all samples, mostly because the study has ended early. The last observation time before the event has occurred, which is called censoring time, provides some information (Kleinbaum 2012). In the present study the response variable is the "survival" (i.e., persistence) of each road state (open or revegetating) until a "death"-event occurred, i.e., a change in classification from one interval to the next. We did two separate analyses, one for open roads that changed to the revegetating state and another for revegetating roads that disappeared. Data were marked in the analysis as "right censored" if a road did not change in its state until the final observation interval (2010–2013). To avoid confounding related to differences in timing of the logging history, all roads that already existed in the first observation interval (1986–1989) were excluded from the analysis. This allowed us to identify clearly the time interval in which each road originated in its respective state (initial creation as an open road, or conversion to a revegetating road after abandonment from use) from 1990 onwards.

Persistence for roads was calculated based on Kaplan-Meier survival distributions. These are non-parametric discrete stepped survivorship curves, adding information as each event occurs (Crawley 2005). They are frequently used for descriptive statistics of survival data. Means of these curves are restricted due to the fact that the time when an event happens is not known for all observations and the expected end date is projected. We therefore state medians with 95% confidence intervals whenever applicable. We used the persistence of revegetating roads as the response variable in a Cox proportional hazard model, which provides a robust multivariate regression analysis for survival data. Being semi-parametric it does not require any assumption about the distribution of survival times. It takes into account survival time and censoring, considering different starting times for a sample to enter the study (Kleinbaum 2012), and is particularly applicable for coarse geospatial time-series data (An and Brown 2008). For factorial variables the reference level was set to the most abundant factor. Information about the relative importance of a variable for the model fit was based on the hazard ratio, generated through exponentiation of the specific regression coefficient (Liu 2012). The closer the hazard ratio gets to 1 the lower is the indicated effect of a variable on the model. As a formal model selection method to identify which of the tested explanatory variables made an important distinct contribution to variation in the response variables we stepwise selected explanatory variables, based on the best model fit, indicated by the Akaike Information Criterion (AIC) (Burnham and Anderson 2002).

All statistical analyses were exclusively based on dead-end (i.e., terminal branch) road segments, to make sure that exclusively secondary roads of the same hierarchical level were included, each treated as one sample (Fig. 4). Only the accuracy assessment with other sources of data (high resolution images, existing road maps) was based on the total length of roads.

All statistical analyses were carried out using R statistical software (R Core Team 2014), applying the packages "maptools" (Bivand and Lewin-Koh 2014) and "survival" (Therneau 2014).

RESULTS

Accuracy assessment

For most of the observation intervals we had more than three images with low cloud cover available. On average, the first three images contributed 90% of all detected road segments, while additional images only added minor information to the overall map (Fig. 5). We expect uncertainties due to absence of data, mainly in the two observation intervals between 1990 and 1997, when less than three useful images were available.

The total length of all detected roads was 12% greater on the SPOT images from 2008 than on our LANDSAT based observations in the interval 2006–2009. However, only 5% of the length of all detectable roads on SPOT had not been detected on LANDSAT images in previous observation intervals. This indicates that the differences in resolution between the satellite sensors have a stronger influence on detection of road persistence than on the detection of presence/absence of roads. It also indicates the importance of our analyses being based on data from the same (LANDSAT) sensor throughout. The length of all roads that we detected before 2005 equaled 91% of the road length in the study area in the WRI datasets. The regional geological map used in our analyses had a spatial correlation of 66% with the Dewitte et al. (2013) soil map.

There were significant differences amongst the three road categories in terms of total tree density (Kruskal Wallis $\chi^2 = 28.55$, $P < 0.001$) and woody species richness ($\chi^2 = 29.8$, $P < 0.001$). While almost completely absent on open roads, tree density and species richness were also significantly lower on revegetating than on undetectable roads (Fig. 6). Also, the dominance of the herbaceous genus *Aframomum* was significantly different amongst road categories ($\chi^2 = 19.87$, $P < 0.001$) being highest on revegetating roads, which explains the high photosynthetic activity that their detection on the LANDSAT images was based on. Though gap fraction was higher over open roads, its difference amongst road categories was not significant, indicating that major changes amongst the three categories detected through remote sensing do not result from closure of the upper canopy by in-growth of the crowns of adjacent trees but from succession of vegetation rooted on the road itself. Both road and clearing width did not differ significantly amongst the three road classes, indicating relatively constant road building practice over time and space (Fig. 6).

Modelling of road persistence

There were large changes in the spatial distribution and relative density of the open and revegetating road-categories between the seven observation intervals (Fig. 4). Of all roads in the study area, 86% were observed to be inside logging concessions. Of these, only 3% were in concessions that did not have a management plan at the end of the study (the percentage of the total concession area without a management plan was 8%).

The rate of persistence of open roads was generally low: none of the open roads present before 1997 had survived (persisted) until the last observation interval, 2010–2013, and only 2% of the open roads first observed during 1998–2005 had survived (Table 2). Of open roads first observed in 2006–2009, 61.24% persisted in this state in the subsequent 2010–2013 interval. The rate of persistence of revegetating roads was greater, with 47.22% of the revegetating roads

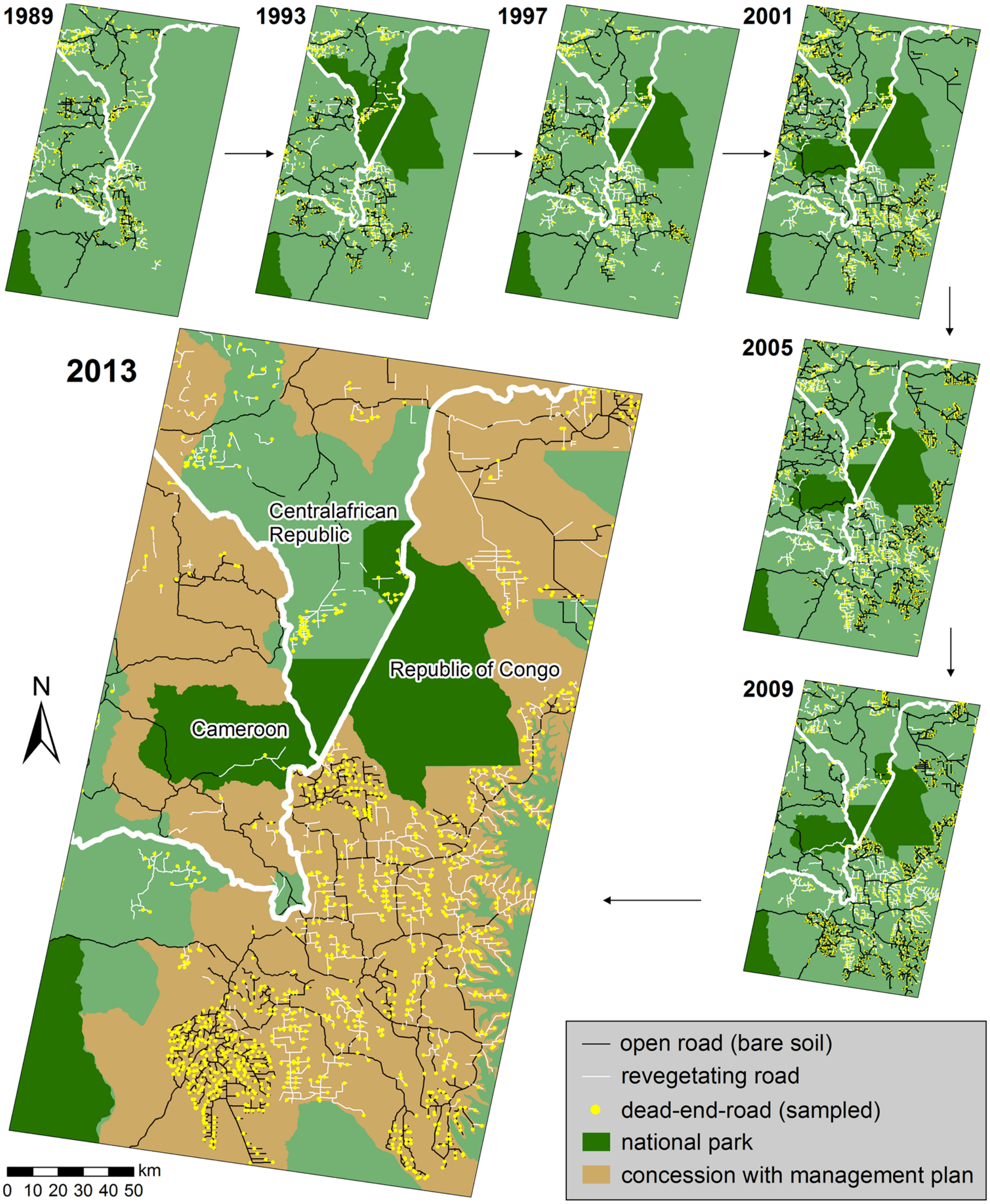

Fig. 4. Maps of the logging road network at the end of each four-year observation interval. Open roads (with bare soil) are shown in black, revegetating roads in white; country borders are bold white; national parks have a dark green shading, areas with approved management plans have a brown shading. To make sure that only secondary road segments were included in the analyses, exclusively dead end roads (terminal branches) were sampled (marked with a small yellow dot).

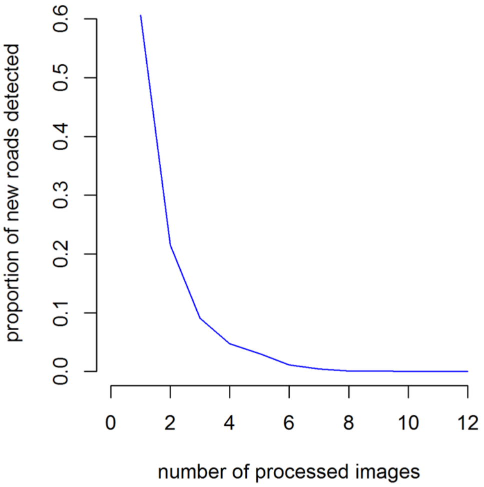

Fig. 5. Contribution of each image that was added iteratively to the number of detected road segments on average per observation interval.

present in 1990–1993 surviving until 2010–2013 (Table 2). The rate of persistence of revegetating roads first observed in each subsequent time interval then increased continuously, which implies that there were no major changes in the survival time (i.e., lifespan) of revegetating roads over the study period (Table 2). Six percent of all roads have been observed as re-opened, of which 54% could subsequently be observed in the revegetating state. Re-opened roads showed similar patterns in terms of persistence as those observed for the first time, with a lower probability of surviving until the 2010–2013 interval for those re-opened in 2006–2009 (33.33%; Table 2).

The Kaplan Meier median persistence of roads in the open state was 4 (4–4) (median with range of 95% confidence interval, CI, in parentheses) years, whereas median persistence of roads in the

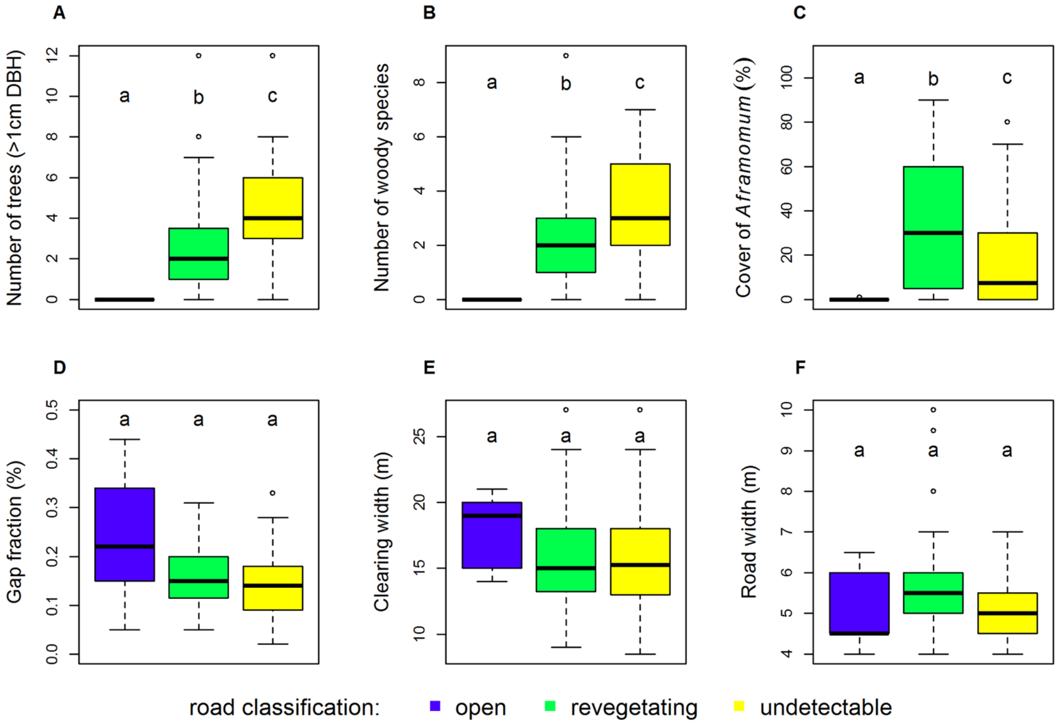

Fig. 6. Boxplots for field measurements carried out in February and March 2014 in 5x5 m plots on roads detected from LANDSAT 8 OLI images (dated 27 January 2014, 8 March 2014 and 31 March 2014) in the three different categories open (blue), revegetating (green) and undetectable (yellow). Variables are (A) tree density, (B) number of woody species, (C) cover of dominant herbs from the genus *Aframomum*, (D) gap fraction on hemispherical photographs, (E) clearing width and (F) road width. Small letters indicate significant differences between the categories based on the Kruskal-Wallis rank sum test with a Bonferroni-corrected pairwise Mann-Whitney U test for post hoc comparison.

Table 2. Number of secondary logging road segments observed for the first time during each observation interval and the probability for these road segments to survive in the same state until the last observation interval (2010–2013).

Interval of first observation	New roads observed	Roads disappeared†	Roads survived‡	Survival (%)
Open roads				
1990-1993	70	70	0	0
1994-1997	87	87	0	0
1998-2001	242	241	1	0.41
2002-2005	189	186	3	1.59
2006-2009	178	69	109	61.24
2010-2013	324	0	324	100
Revegetating roads				
1990-1993	144	76	68	47.22
1994-1997	156	74	82	52.56
1998-2001	138	47	91	65.94
2002-2005	78	22	56	71.79
2006-2009	151	41	110	72.85
2010-2013	169	0	169	100
Re-opened roads				
1990-1993	0	0	0	0
1994-1997	14	14	0	0
1998-2001	24	24	0	0
2002-2005	24	24	0	0
2006-2009	12	8	4	33.33
2010-2013	24	0	24	100
Revegetating re-opened roads				
1990-1993	0	0	0	0
1994-1997	2	2	0	0
1998-2001	5	5	0	0
2002-2005	15	13	2	13.33
2006-2009	15	4	11	73.33
2010-2013	16	0	16	100

Note: The results are separated between road categories in two states (classified as open or revegetating) that each are again separated based on whether they were observed for the first time (top two sections of table) or have been re-opened after the previous road had disappeared (lower two sections of table).

† Road segments that could no longer be classified to be in the same state in the images of the final observation interval.

‡ Road segments observed in the same state until and including the final observation interval.

revegetating state was 20 years (CI not applicable; Table 3). Mean persistence of open roads showed very little variation with substrate: 4.15 ± 0.14 (mean ± SE) years on rich substrates and 4.23 ± 0.22 on poor substrates. In contrast, revegetating roads showed a 4.6-year longer persistence on poor substrates (21.30 ± 0.32) than on rich substrates (16.70 ± 1.18; Table 3). Re-opened roads showed a median persistence of 8 (4–12 CI) years, which was markedly longer on poor substrates (16 years, CI not applicable) although this was based on a low number of observations. Re-opened roads persisted for 12 (8–12 CI) years in the revegetating state.

Given that most open roads persisted for a shorter time than the four-year observation interval, the spatial variation in persistence of roads in this open state was too low to be used convincingly as a response variable in a Cox proportional hazard model. We also observed large differences between the three substrate fertility classes in their distributions along the gradients of altitude and distance to settlement: the distributions for poor and rich substrates were generally similar to each other, with those of intermediate substrates being more distinct for both gradients. Therefore we excluded the intermediate substrates from the subsequent statistical analyses.

The selected best Cox proportional hazard model for revegetating roads included three explanatory variables: geological substrate, altitude and distance to settlement (Table 4). Slope and rainfall were excluded during variable selection. Road persistence was significantly longer on poor compared with rich substrates ($P < 0.001$) and road persistence was shorter with higher altitude ($P < 0.001$). The distance to nearest settlement was associated with increasing persistence of revegetating roads ($P = 0.005$).

Table 3. Kaplan-Meier survival time (persistence) measured in four-year-intervals for secondary logging road segments, differentiated by road state and substrate nutrient content type based on classification of geology.

				Survival time (years)	
Road state	Substrate type	Observations	Events†	Mean ± SE‡	Median (95% CI)§
Open	All	1090	653	4.2 ± 0.11	4 (4–4)
	Rich	309	165	4.15 ± 0.14	4 (4–4)
	Intermediate	507	392	4.25 ± 0.25	4 (4–4)
	Poor	274	96	4.23 ± 0.22	4 (4–4)
Revegetating	All	836	260	18.69 ± 0.44	20 (NA)
	Rich	230	100	16.7 ± 1.18	16 (16–20)
	Intermediate	439	100	18.4 ± 0.71	NA
	Poor	167	60	21.3 ± 0.32	NA
Re-opened	All	98	70	7.2 ± 0.93	8 (4–12)
	Rich	61	36	7.23 ± 0.86	8 (4–12)
	Intermediate	25	24	4 ± 0	4 (NA)
	Poor	12	10	15.27 ± 0.87	16 (NA)
Revegetating re-opened	All	53	24	11.6 ± 0.95	12 (8–12)
	Rich	24	19	11.4 ± 0.87	12 (8–12)
	Intermediate	22	2	15.8 ± 2.68	14 (NA)
	Poor	7	3	12 ± 0	12 (NA)

Note: Results are separated as described in the notes of Table 2.

† Shift from the open to the revegetating state or from the revegetating state to disappearance.

‡ Mean values (with standard errors) are restricted due to skewedness of the data.

§ Median values are shown with the range of the 95% confidence intervals, wherever applicable. NA denotes cases where calculation was not applicable due to a low proportion of observations with events occurring.

DISCUSSION

The persistence of scars in forest cover resulting from secondary logging roads is limited. These roads are temporary elements in the landscape that vary in the timespan of their threat to the forest ecosystem. Open roads are considered worst for environmental damage and poor delivery of ecosystem services (Wilkie et al. 2000, Laurance et al. 2009), but open roads mostly persisted for less than four years. This indicates that spontaneous re-vegetation follows road abandonment without major delays. Revegetating roads persisted in that state more than four times as long as open roads but they are assumed to have already recovered some of their capacity to deliver ecosystem services and to be on a trajectory towards full forest recovery. However, we found contrasts in the duration of re-vegetation processes that indicate strong site-specific differences in the rate of forest recovery on roads. As already hypothesized by Gourlet-Fleury et al. (2011) for logged forest, the recovery of forest cover through regeneration on roads was delayed on resource-poor substrates. These findings highlight the importance of considering site conditions determined by substrate fertility for the planning of logging operations.

Recovery of vegetation cover on logging roads has occurred continuously over the past 28 years: the earlier a road was abandoned, the lower is the probability that it is still detectable as a road today. The observed sequence of road-states from open through revegetating to undetectable, represents a successional trajectory in which bare soils first become colonized by dominant herbaceous species that are then overgrown by an increasing density of trees, with increasing species diversity. Previously, abandoned logging roads have been identified as long-lasting corridors, characterized by uniform floristic patterns (Guariguata and Dupuy 1997). We found evidence that the time-span that these corridors are detectable depends on site factors. By limiting our analyses to dead-end secondary logging roads we greatly reduced the potential for differences in road-use frequency to influence the results. This allows us to make a powerful use of the novel approach of analyzing roads as human infrastructure to determine the major factors limiting the rate of forest recovery after logging through natural regeneration processes. We do not have any further information about differences in road construction but given the remoteness of the whole study area combined with our own field observations, we are confident that all these dead-end roads were built in a similar way, without any surfacing operations

Table 4. Results of a Cox Proportional Hazard survival analysis for secondary logging road segments in the revegetating state.

Explanatory variable	Parameter estimate†	Hazard ratio ± SE	*P* value
Poor substrate‡	−0.622	0.537 ± 0.168	<0.001***
Altitude	0.362	1.436 ± 0.068	<0.001***
Distance to nearest settlement	−0.446	0.640 ± 0.160	0.005**

Notes: n = 397, number of events = 160, re-opened road segments and intermediate substrates were excluded from the analysis.

† Positive parameter estimate values indicate higher hazard for a road to disappear, i.e., shorter survival times (decrease in persistence); negative values vice versa.

‡ Substrate nutrient content type based on classification of geology. For this factorial variable the reference level was set to the most abundant factor (rich substrate).

having taken place.

We found forest recovery to be slower on resource-poor substrates. Slow regeneration of tropical forests on soils of poor quality is a well-known general issue (Finegan 1996, Crk et al. 2009). However, this has only recently arisen as a concern in the Congo Basin (Gourlet-Fleury et al. 2011) where it has not yet been taken into account in forest management practices (N. Bayol *personal communication*). Large parts of the southern CAR and the northern Republic of Congo are characterized by "Carnot" sandstone, producing resource-poor soils associated with dense, slow-growing forest types (Fayolle et al. 2012, Gond et al. 2013; Fig. 1). Here, a new logging frontier has been opened only since 2000 (Laporte et al. 2007; Fig. 4). This logging boom in the far north of Republic of Congo had its peak in about 2004, so it is not yet possible to draw conclusions about persistence of most of the relatively new roads in this area. However, our results lead to concern that they may revegetate as slowly as those roads created earlier on similar substrates in CAR.

Our results show that secondary logging roads persisted for a shorter time at higher altitudes. However, neither topographic slope nor rainfall improved the statistical model. Given that the available topographic and climatic data are very coarse, it is possible that small-scale variations in either of the variables do influence natural regeneration on roads. However, the effect of altitude on detectability of roads might also be linked with forest structure which is likely to differ with altitude in the study area. Revegetating roads persisted in this state for a longer time when they were located further away from settlements. Given the consistency in the management of forest concessions, the duration of use of logging roads is similarly short throughout the forest of the study area. Therefore the Von Thünen model, where forest degradation decreases with rising transportation costs to the market (Chomitz and Gray 1996, Angelsen 2007), does not seem to apply to the rate of forest recovery on these roads. Instead, our findings could be a result of the variation in logging history across the study area which may be linked with distance to settlement. The forest landscapes on resource-rich soils in the western part of the study area that have a longer history of disturbance and higher settlement density (and thus shorter average distance to settlement) are likely to have a greater abundance of fast-growing, light-demanding tree species (Sheil and Burslem 2003). The abundance of these species in the forest might accelerate the process of forest regrowth on abandoned roads, reducing the contrast between road and forest faster than in less disturbed forest landscapes. In contrast, in the east of the study area (northern Republic of Congo) there is a shorter logging history and lower settlement density (and thus higher average distance to settlement). In contrast to other places where the proximity to less disturbed forests promotes faster recovery after disturbance (Chazdon 2003), here the rate of detected forest recovery on roads (based on the contrast with the surrounding forest) may be slower because of a lower density of fast-growing pioneer species in the surrounding forest (*personal observations*).

Given the longer persistence of logging roads on resource-poor substrates, careful road planning as part of sustainable forest management needs to take such local site conditions into account. Reduced impact logging (RIL) is usually associated with lower densities of harvested trees (Medjibe and Putz 2012) to enable sufficient regeneration of timber species. However, if this results in an extensification of logging over a larger area requiring an expansion of the road network into vulnerable sites, there may be no net gain (Gullison and Hardner 1993, Schneider 1995). Instead, a reduction of total harvest area by concentrating logging operations in areas identified as more productive combined with silvicultural intensification (Fredericksen and Putz 2003) needs to be considered for the Congo Basin area. This would allow less productive areas to be protected for conservation without, or with a reduction in, timber harvesting. This "land sparing" over "land sharing" strategy has been advocated for logging activities by Edwards et al. (2014). A way to achieve sustainable intensification in more productive areas in the Congo Basin is the diversification of harvested species (Karsenty and Gourlet-Fleury 2006) and the implementation of post-logging silviculture (Gourlet-Fleury et al. 2013).

Further research, taking into account the spatial distribution of the road network, is needed to determine whether or not existing roads should be re-opened for subsequent timber harvests and how such a more intensively used but overall smaller road network would affect the forest landscape and its ecosystem function. During the study period, we detected very few re-opened roads, although this is considered a common practice in managed concessions during subsequent cycles of logging operations, usually as the lowest cost option (N. Bayol, *personal communication*). According to Karsenty and Gourlet-Fleury (2006), the very first cut of selective logging is mainly focused on the "cream", i.e., the most valuable, internationally traded species. Only if the expected timber yield justifies the high transport costs would this be followed by a second cut, e.g., because a market for less well known species has developed (Karsenty and Gourlet-Fleury 2006). Although the duration of the study period and the number of samples are both low, our results do already indicate that re-opened roads persisted for longer in the open state but shorter in the revegetating state, compared with new roads. Both might be a sign of an increased level of forest degradation: initially it takes longer until vegetation cover is established (e.g., due to a higher level of soil compaction), then the recovering vegetation on the road soon becomes very similar to the surrounding forest that has been degraded to a greater extent through repeated logging.

Our analyses show a very dynamic secondary logging road network that appears only for a relatively short time. It is therefore difficult to use logging roads in the Congo Basin as static indicators of forest degradation and fragmentation. Recent studies (Bell et al. 2012, Brandt et al. 2014) have used road networks in the Congo Basin to quantify the extent of logging activities in relation to forest management and forest concession ownership. Taking road persistence into account could strongly enhance the accuracy of such analyses. This should be accompanied by further field-based vegetation inventories to quantify species composition, rate of recovery of biomass and forest stature on and adjacent to logging roads in relation to the time of their abandonment. The highly dynamic nature of forest roads (with a low level of persistence) appears much more complex than is assumed in standard measures of habitat patch fragmentation. This calls for the development of new tools to quantify the fragmentation impact of non-permanent roads in forest landscapes.

Conclusions

We have presented the assessment of temporal dynamics in logging road networks as a tool to characterize differences in recovery of forest vegetation in areas of contrasting environment and with different disturbance histories. Our results suggested that substrate-related site factors are slowing down the progress of succession on logging roads. This informs better planning of forest management to accelerate recovery of forest on roads. The influence of substrate fertility on the rate of forest regeneration needs to be included in management of sustainable logging practices. In areas of resource-poor substrate, where roads recover more slowly, there should be a presumption against construction of new roads because the capacity of these areas to sustain repeated cycles of logging without degradation of the forest landscape is low.

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LITERATURE CITED

Ahmed, S. E., A. C. Lees, N. G. Moura, T. A. Gardner, J. Barlow, J. Ferreira, and R. M. Ewers, 2014. Road networks predict human influence on Amazonian bird communities. Proceedings of the Royal Society B 281:20141742.

Albertz, J., and R. Tauch. 1994. Mapping from space: Cartographic applications of satellite image data. GeoJournal 32:29–37.

An, L., and D. G. Brown. 2008. Survival analysis in land change science: Integrating with GIScience to address temporal complexities. Annals of the Association of American Geographers 98:323–344.

Angelsen, A. 2007. Forest cover change in space and time: Combining the von Thünen and forest transition theories. World Bank Policy Research Working Paper 4117:1–43.

Applegate, G., F. E. Putz, and L. K. Snook. 2004. Who pays for and who benefits from improved timber harvesting practices in the tropics? Lessons learned and information gaps. CIFOR, Bogor, Indonesia.

Asner, G., M. Keller, R. Pereira, and J. Zweede. 2002. Remote sensing of selective logging in Amazonia: Assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis. Remote Sensing of Environment 80:483–496.

Bayol, N., B. Demarquez, C. De Wasseige, R. Eba, J. Fisher, R. Nasi, X. Rossi, M. Steil, and C. Vivien. 2012. Forest management and the timber sector in Central Africa. *In* C. de Wasseige, P. de Marcken, N. Bayol, F. Hiol Hio, P. Mayaux, B. Desclée, R. Nasi, A. Billand, P. Defourny, and R. Eba'a Atyi, editors. The forests of the Congo Basin: state of the forest 2010. Publications Office of the European Union, Luxembourg.

Bell, A. R., R. L. Riolo, J. M. Doremus, D. G. Brown, T. P. Lyon, J. Vandermeer, and A. Agrawal. 2012. Fragmenting forests: the double edge of effective forest monitoring. Environmental Science & Policy 16:20–30.

Bivand, R., and N. Lewin-Koh. 2014. maptools: Tools for reading and handling spatial objects. R package version 0.8-30. http://cran.r-project.org/package=maptools

Boulvert, Y. 1996. Etude geomorphologique de la Republique Centrafricaine: carte a 1: 1000000 en deux feuilles Ouest et Est. ORSTOM Editions, Paris, France.

Bourbier, L., G. Cornu, A. Pennec, C. Brognoli, and V. Gond. 2013. Large-scale estimation of forest canopy opening using remote sensing in Central Africa. Bois et Forets des Tropiques 315:3–9.

Brandão, A. O., and C. M. Souza. 2006. Mapping unofficial roads with Landsat images: a new tool to improve the monitoring of the Brazilian Amazon rainforest. International Journal of Remote Sensing 27:177–189.

Brandt, J. S., C. Nolte, J. Steinberg, and A. Agrawal. 2014. Foreign capital, forest change and regulatory compliance in Congo Basin forests. Environmental Research Letters 9:044007.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer, New York, New York, USA.

Chazdon, R. L. 2003. Tropical forest recovery: legacies of human impact and natural disturbances. Perspectives in Plant Ecology, Evolution and Systematics 6:51–71.

Chazdon, R. L. 2014. Second growth: The promise of tropical forest regeneration in an age of deforestation. University of Chicago Press, Chicago, Illinois, USA.

Chen, J., X. Zhu, J. E. Vogelmann, F. Gao, and S. Jin. 2011. A simple and effective method for filling gaps in Landsat ETM+ SLC-off images. Remote Sensing of Environment 115:1053–1064.

Chomitz, K. M., and D. A. Gray. 1996. Roads, land use, and deforestation: a spatial model applied to Belize. World Bank Economic Review 10:487–512.

Crawley, M. J. 2005. Statistics: An introduction using R. John Wiley & Sons, Chichester, UK.

Crk, T., M. Uriarte, F. Corsi, and D. Flynn. 2009. Forest recovery in a tropical landscape: what is the relative importance of biophysical, socioeconomic, and landscape variables? Landscape Ecology 24:629–642.

De Wasseige, C., and P. Defourny. 2004. Remote sensing of selective logging impact for tropical forest management. Forest Ecology and Management 188:161–173.

Dewitte, O., et al. 2013. Harmonisation of the soil map of Africa at the continental scale. Geoderma 211-212:138–153.

Edwards, D. P., et al. 2014. Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Global Change Biology 20:183–91.

Fayolle, A., B. Engelbrecht, V. Freycon, F. Mortier, M. Swaine, M. Réjou-Méchain, J.-L. Doucet, N. Fauvet, G. Cornu, and S. Gourlet-Fleury. 2012. Geological substrates shape tree species and trait distributions in African moist forests. PLoS ONE 7:e42381.

Finegan, B. 1996. Pattern and process in neotropical secondary rain forests: the first 100 years of succession. Trends in Ecology & Evolution 11:119–24.

Fraser, B. 2014. Carving up the Amazon. Nature 509:418–419.

Fredericksen, T. S., and F. E. Putz. 2003. Silvicultural intensification for tropical forest conservation. Biodiversity and Conservation 12:1445–1453.

Gazel, J. 1956. Carte geologique 1:1 000 000 du Cameroun. Planche 1-B-Sud. Direction des Mines et de la Géologie du Cameroun, Yaoundé, Cameroon.

Gond, V., A. Fayolle, A. Pennec, G. Cornu, P. Mayaux, P. Camberlin, C. Doumenge, N. Fauvet, and S. Gourlet-Fleury. 2013. Vegetation structure and greenness in Central Africa from Modis multi-temporal data. Philosophical Transactions of the Royal Society B 368:20120309.

Gourlet-Fleury, S., et al. 2011. Environmental filtering of dense-wooded species controls above-ground biomass stored in African moist forests. Journal of Ecology 99:981–990.

Gourlet-Fleury, S., F. Mortier, A. Fayolle, F. Baya, D. Ouédraogo, F. Bénédet, and N. Picard. 2013. Tropical forest recovery from logging: a 24 year silvicultural experiment from Central Africa. Philosophical Transactions of the Royal Society B 368:20120302.

Guariguata, M. R., and J. M. Dupuy. 1997. Forest regeneration in abandoned logging roads in lowland Costa Rica. Biotropica 29:15–28.

Guariguata, M. R., and R. Ostertag. 2001. Neotropical secondary forest succession: changes in structural and functional characteristics. Forest Ecology and Management 148:185–206.

Gullison, R. E., and J. J. Hardner. 1993. The effects of road design and harvest intensity on forest damage caused by selective logging: empirical results and a simulation model from the Bosque Chimanes, Bolivia. Forest Ecology and Management 59:1–14.

Healey, J. R., C. Price, and J. Tay. 2000. The cost of carbon retention by reduced impact logging. Forest Ecology and Management 139:237–255.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978.

Jones, A., et al. 2013. Soil atlas of Africa. European Commission, Publications Office of the European Union, Luxembourg.

Karsenty, A., I. Drigo, M. Piketty, and B. Singer. 2008. Regulating industrial forest concessions in Central Africa and South America. Forest Ecology and Management 256:1498–1508.

Karsenty, A., and S. Gourlet-Fleury. 2006. Assessing sustainability of logging practices in the Congo Basin's managed forests: the issue of commercial species recovery. Ecology and Society 11:26.

Kleinbaum, D. 2012. Survival analysis: A self learning text. Springer, New York, New York, USA.

Laporte, N. T., J. A. Stabach, R. Grosch, T. S. Lin, and S. J. Goetz. 2007. Expansion of industrial logging in Central Africa. Science 316:1451.

Laurance, W. F., M. Goosem, and S. G. W. Laurance. 2009. Impacts of roads and linear clearings on tropical forests. Trends in Ecology & Evolution 24:659–69.

Liu, X. 2012. Survival analysis: models and applications. John Wiley & Sons, Hoboken, New Jersey, USA.

Malcolm, J. R., and J. C. Ray. 2000. Influence of timber extraction routes on Central African small-mammal communities, forest structure, and tree diversity. Conservation Biology 14:1623–1638.

Medjibe, V. P., and F. E. Putz. 2012. Cost comparisons of reduced-impact and conventional logging in the tropics. Journal of Forest Economics 18:242–256.

Nasi, R., A. Billand, and N. van Vliet. 2012. Managing for timber and biodiversity in the Congo Basin. Forest Ecology and Management 268:103–111.

Negishi, J. N., R. C. Sidle, A. D. Ziegler, S. Noguchi, and A. R. Nik. 2008. Contribution of intercepted subsurface flow to road runoff and sediment transport in a logging-disturbed tropical catchment. Earth Surface Processes and Landforms 1191:1174–1191.

Newman, M. E., K. P. McLaren, and B. S. Wilson. 2014. Assessing deforestation and fragmentation in a tropical moist forest over 68 years; the impact of roads and legal protection in the Cockpit Country, Jamaica. Forest Ecology and Management 315:138–152.

Orstom. 1967. Carte geologique 1:2,000,000 du Congo. Atlas du Congo, Planche VIII. Service cartographique de l'ORSTOM, Paris, France.

Putz, F., P. Sist, T. Fredericksen, and D. Dykstra. 2008. Reduced-impact logging: Challenges and opportunities. Forest Ecology and Management 256:1427–1433.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Richards, J. A. 2012. Remote sensing digital image analysis: an introduction. Springer, Berlin, Germany.

Ruiz Perez, M., D. Ezzine de Blas, R. Nasi, J. Sayer, M. Sassen, C. Angoue, N. Gami, O. Ndoye, G. Ngono, and J. Nguinguiri. 2005. Logging in the Congo Basin: A multi-country characterization of timber companies. Forest Ecology and Management 214:221–236.

Schneider, R. R. 1995. Government and the economy on the amazon frontier. Environment Paper 11. World Bank, Washington, D.C., USA.

Sessions, J. 2007. Forest road operations in the tropics. Springer, Berlin, Germany.

Sheil, D., and D. F. R. P. Burslem. 2003. Disturbing hypotheses in tropical forests. Trends in Ecology & Evolution 18:18–26.

Therneau, T. 2014. A package for survival analysis in S. R package version 2.37-7. http://cran.r-project.org/package=survival

van Zyl, J. J. 2001. The shuttle radar topography mission (SRTM): a breakthrough in remote sensing of topography. Acta Astronautica 48:559–565.

White, F. 1983. The vegetation of Africa: a descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa. Unesco., Paris, France.

Wilkie, D., E. Shaw, F. Rotberg, G. Morelli, and P. Auzel. 2000. Roads, development, and conservation in the Congo Basin. Conservation Biology 14:1614–1622.

WRI and MDDEFE. 2012. Atlas forestier interactif du Congo. Version 3.0. Document de Synthese. World Resources Institute & République du Congo Ministère de l'economie forestière et du développement durable, Washington, D.C., USA.

WRI and MEFCP. 2010. Atlas forestier interactif de la République centrafricaine. Version 1.0: Document de synthèse. World Resources Institute & Ministère des eaux forêts chasse et pêche de la République centrafricaine, Washington, D.C., USA.

WRI and MINFOF. 2012. Interactive forest atlas of Cameroon. Version 3.0. Overview Report. World Resources Institute & Ministère des Fôrets et de la Faune Cameroun, Washington, D.C., USA.