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ABSTRACT

Road networks are expanding in tropical countries, increasing human access to remote forests that act as refuges for biodiversity and provide globally important ecosystem services. Logging is one of the main drivers of road construction in tropical forests. We evaluated forest fragmentation and impacts of logging roads on forest resilience and wildlife, considering the full life cycle of logging roads. Through an extensive evidence review we found that for logging road construction, corridors between 3 and 66 m (median 20 m) width are cleared, leading to a loss of 0.6 to 8.0 percent (median 1.8%) of forest cover. More severe impacts are increased fire incidence, soil erosion, landslides and sediment accumulation in streams. Once opened, logging roads potentially allow continued access to the forest interior, which can lead to biological invasions, increased hunting pressure and proliferation of swidden agriculture. Some roads, initially built for logging, become converted to permanent, public roads with subsequent in-migration and conversion of forest to agriculture. Most logging roads, however, are abandoned to vegetation recovery. Given the far-reaching impacts of the roads that become conduits for human access, its control after the end of logging operations is crucial. Strategic landscape planning should design road networks that concentrate efficient forest exploitation and conserve roadless areas.

KEY WORDS

Road ecology, forest management, reduced impact logging, invasions, forest resilience, forest degradation, deforestation, pantropical

ROADS HAVE A PROMINENT ROLE IN PUBLIC PERCEPTION OF TROPICAL FOREST DESTRUCTION. Images of the fishbone-like patterns of deforestation along the Transamazonian Highway in Brazil have become one of the symbols of global deforestation threats. This may be comparable with the pictures of monotonous oil palm plantations and cattle pastures divided by a sharp line from the heterogeneous canopy of old-growth forests. Such images are a powerful visual representation of human dominance and destruction of tropical forests. However, as with all iconic images, they create the danger that a single case is used as the basis for generalizations about complex interactions occurring in tropical forest landscapes around the world – narrowing the imagination of both the public and the scientific community.

The global threats of road development are often underlined by the projection that by 2050, more than 25 million more paved road lane-km will be built worldwide, with 90% being located in non-OECD countries (Dulac 2013). It is not appropriate to apply this prediction directly to tropical forests, where predominantly unpaved roads are built, but roads are now a prevailing feature of tropical forests globally, often due to widespread selective logging activities. Remote sensing analyses have documented the expansion of logging road networks throughout the tropics (e.g. Laporte *et al.* 2007, Gaveau *et al.* 2014, Ahmed, Souza, *et al.* 2013, Kleinschroth, Healey, Gourlet-Fleury, *et al.* 2016, Arima *et al.* 2008). Annual growth rates are reported of up to 40 km of new roads per 10 000 km^2 of forest area (Brandão & Souza 2006), sometimes unconstrained by the boundaries of officially protected areas (Curran *et al.* 2004). Logging road networks, however, are highly dynamic in space and time and their impacts might differ from other types of road in tropical forests (Kleinschroth *et al.* 2015). Surprisingly, a comprehensive review of impacts for the full “life-cycle” of logging roads is largely missing.

Fifty-three percent or 400 million hectares of the natural tropical permanent forest estate comprises (timber) production forest (Blaser *et al.* 2011). In the face of such widespread logging activities in tropical forests worldwide, consensus is growing about the importance of the state of logged forests for their conservation value and the need to reduce logging impacts to maintain major ecosystem services while allowing timber extraction for economic reasons (Putz *et al.* 2012, Edwards *et al.* 2011). Logging roads have a particular role in reducing impacts of tropical logging as they are the most costly, damaging and visible part of selective logging activities. At low harvest levels (< 4 trees per ha), which are common in many tropical regions, damage from road construction is much higher than from tree felling (Gullison & Hardner 1993, Sist *et al.* 2003).

Identifying tropical forest degradation is difficult, especially on a larger scale. Roads, as the most visible indicator of human activity in tropical forests, are therefore often used as the main indicator to estimate the global extent of forest degradation (see e.g. Lewis *et al.* 2015). The underlying logic is that forest areas that are not accessible by roads are considered to be the least degraded because they provide habitat that is not immediately affected by human activities on an industrial scale (Potapov *et al.* 2008). The possibility that responsible forest management can avoid degradation is not taken into account in these approaches (Putz *et al.* 2012). “The first cut is the deepest” (Laurance *et al.* 2015) and logging roads are often the first to penetrate old-growth forests, opening what has been termed “a Pandora’s box” of environmental problems (Laurance *et al.* 2009). Road building strategies therefore advocate to concentrate road building (Laurance *et al.* 2014) and to set-aside high conservation-value forest areas from logging to keep them entirely road-free (Clements *et al.* 2014). More specific evidence, however, is needed about which impacts are directly associated with roads built for logging activities. Many publications do not make a distinction between roads built and used for logging and those for other purposes such as public transportation (e.g. Barber *et* *al.* 2014, Ahmed, Ewers *et al.* 2013, Pfaff *et al.* 2007). The majority of logging roads differ greatly from other linear forest clearings for infrastructure, in that they are used only for a certain purpose and for a limited amount of time.

Where logging takes place in industrial concessions, logging companies are often the only official users of logging road networks, which are built and maintained according to just the companies' immediate economic interests (solely to provide access to the forest for heavy machinery and to allow trucks to transport harvested trees to timber processing sites). Typically, such roads are unpaved but the investment in their engineering is based on a network hierarchy with at least two different levels: (i) a few primary roads built to permanently access the forest concession as a whole; (ii) many secondary "dead-end" roads, branching off the primary roads and only built for use in a short period of timber harvesting from a limited forest area (months to a few years) before being abandoned. Skid trails, used to extract logs by dragging them with heavy machinery from their felling site to "logging yards" (or "landing sites") on the roadside, where they are lifted onto trucks, are typically much shorter and narrower than the forest roads constructed for use by trucks, and are often under the canopy of adjacent trees. They constitute a different category of environmental impact on the forest and are not included in this review.

Habitat fragmentation is one of the main impacts of roads in tropical forests. However, there is a lack of evidence review about aspects of fragmentation related to road width, forest cover cleared for road construction, and about how animal movements are affected. To meet this need for evidence, it is crucial to assess logging roads not simply as a static component in the landscape but instead to consider their whole "life cycle". This includes the intense activity during the construction phase, the main primary use phase (often timber extraction), followed by alternative fates such as road abandonment followed by gradual recovery of forest cover *versus* maintenance of the road as a more permanent landscape feature due to continuing use, sometimes associated with upgrade to a public road. Given the dynamic nature of tropical forests and the complexity of current degradation and conversion processes, information is scarce about the relative importance and persistence of each phase in the road life-cycle. We evaluated the short- and long-term impacts of logging roads on tropical forest vegetation, fauna, soil and hydrology by addressing the following questions: (1) To what extent are logging roads fragmenting forests by dissecting formerly connected forests into smaller units? (2) How do roads affect forest resilience and wildlife populations? (3) How long-lasting are each of these impacts in dynamic tropical forest environments? (4) How commonly do roads built for logging undergo a transition to public roads that can eventually lead to large-scale deforestation? (5) How can such impacts be reduced through preventative or *post hoc* interventions?

METHODS

Given the relatively wide scope of this evidence review, we considered all literature dealing with the impacts of roads initially built for logging in tropical forests around the world. We conducted a comprehensive database search in Web of Science and CAB-direct, using the keywords: “logging” AND “road*” AND “impact” AND “tropic*”. This generated 156 results for Web of Science and 393 for CAB Direct. In an iterative process, we broadly selected relevant publications based on title and abstract. These selected papers led to further sources through backward tracking (based on their reference lists) and forward tracking (based on subsequent papers in which they have been cited). Other reviews on related subjects (Kleinschroth, Gourlet-Fleury, *et al.* 2016, Laurance *et al.* 2009, Hawthorne *et al.* 2011, Picard *et al.* 2012) proved to be particularly useful in identifying additional publications. All these references were added to our existing literature database (see data availability statement below), covering more than 1300 publications related to road ecology and tropical forest management. This database allowed comprehensive full text searching – in addition to that enabled by online search engines. We searched all documents for the keywords “logging” and “road”. All selected documents then underwent a critical appraisal of the methods and results used in each study. Inclusion criteria were that they must present original evidence of impacts based on empirical methods or first-hand observations. The relevant information was extracted and grouped into thematic categories. In parallel, we extracted quantitative results for all road width measurements of logging roads and the proportion of forest area that had been cleared for road building (i.e. disturbed area as a percentage of overall logged area).

The search strategy resulted in 178 publications that were used to provide the evidence for further review. Overall, the analysed studies showed strong contrasts in the methods used, with a dominance of anecdotical observations made on individual roads. Given these empirical limitations and strong differences in focus, we did not apply any weighing between the studies. The quantitative results are therefore only indicative. Many sources do not document how exactly they measured road corridor width, but the most straightforward way on the ground is to measure the distance between the stems of the two closest trees on either side of the road track (Figure 1). We did not include measurements entirely based on remote sensing, as optical sensors (in contrast to LIDAR) only allow the estimation of canopy opening from above. Evidence reviews based on published literature carry a risk of publication bias (Huntingdon 2011), due to failure of researchers to publish non-significant or non-anticipated results. We have no evidence for such publication bias but noted that most of the published studies reported negative effects of roads on the forest.

RESULTS AND DISCUSSION

FRAGMENTATION IMPACTS. —The first and most obvious road impact is linear clearing of forest cover. Road tracks (Figure 1) used by logging vehicles had a median reported width of 6.4 m (primary roads) and 5.1 m (secondary roads). The range of track widths is relatively small (3 m to 7.9 m, Table 1) but most logging road construction involves the felling of trees in much wider corridors than just the road track itself. This is due to traffic safety reasons and in order to let the sun dry the road surface after rain (Sessions 2007). Overall medians for full corridor width are 24.85 m for primary and 15.1 m for secondary roads but there are strong regional contrasts. Few measurements are available for Asia, but secondary logging roads in tropical America (range 3 – 10.5 m) have generally narrower corridors than in Africa (15.1 – 66.6 m, Table 1).

The proportion of forest that is cleared for road construction depends on both road length density and road width. The most commonly used reference area for this proportion is the total logged area, for example that delimited by annual logging blocks. The global median percentage is 1.7 percent of the forest area, with the range of values being 0.6–8 percent in America, 0.74–6.4 percent in Africa and 3.3–4.8 percent in Asia (Table 2). The full clearing of forest for road construction leads to carbon emissions from destroyed biomass. A study in East Kalimantan, Indonesia estimated road construction to account for 14% of all logging-related carbon emissions (Griscom *et al.* 2014). These calculations account for the damage that road construction causes to trees adjacent to the corridor (Iskandar *et al.* 2006, Johns *et al.* 1996, Jackson *et al.* 2002). In a Central African study, the biomass recovered through forest regrowth on road tracks abandoned at least 15 years previously accounted for only 6% of the initial amount (Kleinschroth, Healey, Sist, *et al.* 2016).

IMPACTS ON SOIL AND HYDROLOGY. —The construction of logging roads is accompanied by the exposure of subsoil, as topsoil is mostly scraped away. Traffic and machine use cause additional compaction of the soil on the road track (Woodward 1996). This soil degradation can have important consequences *in situ* and *ex situ*. *In situ* effects are increased bulk density (Donagh *et al.* 2010, Guariguata & Dupuy 1997) and reduced soil respiration (Takada *et al.* 2015), which affect the "soil natural capital", reducing ecosystem services of nutrient retention and cycling, soil formation and primary productivity. Such supporting services are of great importance for vegetation recovery on the road track, thus determining the time duration of many other road impacts. In combination with steep terrain and high rainfall, soil exposure and compaction lead to increased rates of surface water runoff (Douglas 2003, Ziegler *et al.* 2007), which can result in severe erosion (Clarke & Walsh 2006, Sidle *et al.* 2004) and high rates of sediment export (Negishi *et al.* 2008). Sediment has far reaching *ex situ* consequences on aquatic habitats in down-slope streams. Greatly enhanced sediment yields have been quantified in Malaysian streams, with levels 14 times higher after logging than before, thus affecting water quality and streamflow through accumulation of sediment and wood debris (Gomi *et al.* 2006).

After abandonment, road track soils can remain compacted for a long time. In a study in Costa Rica, three out of four roads were still compacted >10 years after abandonment (Guariguata & Dupuy 1997). In Central Africa, abandoned road tracks showed a 36% decrease in compaction after 15 years but this was still 55% higher than the level of the adjacent forest (Kleinschroth, Healey, Sist, *et al.* 2016). Regarding erosion and hydrology it is notable that most studies (with the exception of some reports from Guyana by Steege *et al.* 1996) have been conducted in South-East Asia, especially Malaysia, where logging intensities are particularly high and the steep terrain is more prone to erosion than in the lowland basins of the Congo and the Amazon rivers. In Sabah, erosion, sediment transport and landslides show episodic peaks for a long time after logging, depending on the occurrence of extreme weather events (Douglas *et al.* 1999, Sidle *et al.* 2006). Early studies that compared sediment yields before and one year after logging showed contradictory results ranging between 3.6 times higher values (Douglas *et al.* 1992) and no difference at all (Douglas *et al.* 1993). However, a longer-term study showed that sediment sources 21 years after logging were mainly road-linked (Walsh *et al.* 2011). The effects of gullying, landslides and collapses of roadfill material contribute to the long-term degradation of soils and watercourses in heavily logged forest areas (Chappell *et al.* 2004). Road crossings of watercourses can make a large contribution to the sediment load, as bridge abutments are often simply filled with soil that erodes over time as slopes revert back to their angle of repose (Wells 2002). Although sediment production from road surfaces can be reduced by 86% within one year due to establishment of a herb layer (Negishi *et al.* 2006), recovering vegetation is estimated to take 20 years to reach a sufficient root strength that to prevent landslides on roads in steep terrain (Sidle *et al.* 2006).

Streams are often physically altered wherever they are crossed by logging roads with inadequately constructed or maintained bridges or culverts, thus damming up the stream and creating artificial ponds. A particular problem is caused when road bridges and culverts constructed with logs collapse into streams after road abandonment (Chappell *et al.* 2004). Recovery of stream water quality can be delayed by many years if sediment is temporarily stored behind channel obstructions and released periodically (Douglas 1999). Obstruction of streams has negative consequences for animal species that depend on fast flowing water and surrounding vegetation that is intolerant of waterlogging, but at the same time it creates new habitats for other species (Schmidt *et al.* 2015).

WEAKENED FOREST RESILIENCE. —Road impacts in forests can extend to a much greater area than just the corridor cleared for road construction. Edge effects may reach far into the adjacent forest, through desiccation resulting from exposure to wind and higher tree transpiration rates next to the open corridor (Kunert *et al.* 2015). Such desiccation effects may make an important contribution to the correlation between roads and fire occurrence (Nepstad *et al.* 1999, Adeney *et al.* 2009). Tree debris, accumulated at the roadside during road construction, may act as additional fuel for such fires (Laurance & Useche 2009). Roads may also influence fire regimes through increased fire ignition as a result of human activities that occur in the transportation corridor (Franklin & Forman 1987, Brando *et al.* 2014). On the other hand, to fight fires, road access is needed (Francis E. Putz, pers. comm.). Road-related fire-risk also decreases over time as shown by Siegert *et al.* (2001) for the exceptional fires that raged in Borneo during 1997-98. Sixty-five percent of the area within a 1000 m buffer around recently established logging roads was burned. In contrast, for old logging roads used at least six years earlier, the burnt area was only 16 percent.

There are substantial dangers of positive feedbacks between logging roads, fire occurrence and invasions of grasses and lianas (Veldman *et al.* 2009). In their function as corridors, logging roads can facilitate biological invasions. For example logging trucks have been shown to act as dispersal vectors for exotic grasses in Bolivia (Veldman & Putz 2010). Also, in South-East Asia, road construction and subsequent swidden agriculture facilitate the invasion of pyrogenic grasses such as the cogon grass, *Imperata cylindrica* (Putz & Romero 2015). Shrubs have also been reported to spread along logging roads (Padmanaba & Sheil 2014). The establishment of many invasive plants is favoured by the open canopy above the road (Costa & Magnusson 2002). Consequently the exotic herb species *Chromolaena odorata*, which is very abundant along open roads in central Africa, disappeared shortly after road abandonment due to growth of taller shading species (Kleinschroth, Healey, Sist, *et al.* 2016). In the Congo Basin, recent El Niño-related fire events showed a clear positive correlation with the abundance of Marantaceae herbs (Verhegghen *et al.* 2016). These indigenous herbs show long-lasting high abundance on abandoned logging roads (Kleinschroth, Healey, Sist, *et al.* 2016), which may explain many (but not all) observed fire outbreaks being located near permanent or recently abandoned logging roads in this region (Verhegghen *et al.* 2016).

Some studies also document negative impacts of animal invasions of forests along roads. The exotic little red fire ant, *Wasmannia auropunctata*, is reported to spread along logging roads in Gabon, potentially harming the vision of large mammals through its stings (Walsh *et al.* 2004) and forest anuran communities in Brunei were severely disturbed by the road-facilitated immigration of the predatory greater swamp frog, *Limnonectes ingeri* (Konopik *et al.* 2013).

WILDLIFE IMPACTS: "LANDSCAPES OF FEAR" AND DEFAUNATION. —Logging roads can have strong impacts on animal population dynamics. While in Australia public roads in rainforests have been associated with high numbers of road kill (Goosem 1997), we did not find any empirical studies that document large numbers of animals killed by logging road traffic. The more important impact of logging roads is that they can fragment animal habitats causing a change in animal behaviour. Open forest roads form a different habitat in terms of microclimate, and may expose animals to potential predators (Thiollay 1997) and a strongly increased likelihood of encounters with hunters. Roads thus present strong peaks in the "landscape of fear" for wildlife (Laundré *et al.* 2010). Forest specialist and understorey birds in particular are reported to avoid edges created by roads and not to cross them (Lees & Peres 2009, Laurance *et al.* 2004, Develey & Stouffer 2001, Laurance 2004). However, in a study by Laurance & Gomez (2005), radio-tracked birds only refrained from crossing roads when they were in open corridors of > 250 m width, which is uncommonly wide for logging roads (see above). It is therefore equivocal how far the sheer presence of a logging road inhibits animals of most species from crossing it. A study in Cameroon using track plots filled with substrates where animals leave traces that can later be associated with a species, suggest that duikers and apes might avoid crossing logging roads (Hoeven 2010). Correlations between reduced animal population densities and proximity to roads have been found to be linked to increased rates of hunting on and around roads (Van Vliet & Nasi 2008). That hunting is the main factor has also been confirmed through studies comparing roads outside and inside areas where hunting is effectively prevented. Examples are a fenced oil concession (Laurance *et al.* 2006) and large national parks, where inside the protected areas roads did not affect animal movement patterns, while outside they did (Blake *et al.* 2008).

Unregulated hunting is now imperilling vertebrate species throughout the tropics (Bennett *et al.* 2002). This has even led to the widespread reporting of “empty” forests (Redford 1992) that look intact from the outside but are actually depleted of major components of their wildlife populations through hunting (Bennett & Robinson 2000, Poulsen *et al.* 2011, Laurance *et al.* 2006). Increased levels of hunting have been noted near logging roads throughout the tropics (Theuerkauf *et al.* 2001, Laurance *et al.* 2006, Wong & Linkie 2013, Hall *et al.* 1997, Thiollay 1997, Brodie *et al.* 2015). In Central Africa especially, bushmeat provides the most important source of protein for most forest-dependent communities, who have been hunting for a long time (Nasi *et al.* 2008). The presence of extensive road networks, however, has allowed the development of a new type of livelihood, that of specialized market hunters. Improved accessibility has extended the reach of the transport chain, which has led to increased quantities of extracted bushmeat being supplied to meet the increasing demand in urbanized areas further away from the forest (Wilkie *et al.* 2000). Logging company employees and other people settling around logging camps are further driving the demand for bushmeat (Bennett & Gumal 2001). Logging vehicles are frequently used to transport hunters, weapons and game, thus increasing the radius of defaunation around settlements deeper into the forest (Poulsen *et al.* 2009, Robinson *et al.* 1999).

Little is known about the persistence of hunting impacts after logging road abandonment and for how long transport for commercial hunting remains possible. Hunters on motorcycles might only be able to use logging roads up to 10 years after abandonment due to collapsed bridges and vegetation recovery (Kleinschroth, Healey, Sist, *et al.* 2016). Roads often continue to be used as footpaths after the end of logging activities, but evidence of the effects of such footpaths on animal populations is ambiguous. Hall et al. (1997) showed that footpaths are avoided by elephants (*Loxodonta africana*) in Democratic Republic of Congo, while Brodie et al. (2015) showed no effect on mammal abundances of trails on abandoned logging roads.

Human disturbance of habitats and animal populations can lead to changes in the overall animal community structure. Changes in species richness and composition have been shown for dung beetles inside road corridors (Hosaka *et al.* 2014, Yamada *et al.* 2014) and for nocturnal animals within approximately 30 m on either side of road edges (Laurance *et al.* 2008). An impact on bird communities has been proposed by Mason (1996) and Thiollay (1997) but could not be confirmed by Develey & Stouffer (2001). Also, for butterfly communities, no evidence of community changes could be found (Willott *et al.* 2000).

While some roads provide a barrier to animal movement, others function as corridors positively “facilitating” it. Animals may be attracted by roads as they provide connections, orientation and food: Pumas (*Puma concolor*) and jaguars (*Panthera onca*) have been identified as “trail walkers” on old logging roads in Belize (Harmsen *et al.* 2010); african civets (*Civettictis civetta*) have been reported to use logging roads as preferred pathways and hunting grounds in Africa (Ray & Sunquist 2001) and leopards (*Panthera pardus*) are reported to make 20% of their movements following human paths (Jenny 1996). Also elephants (*Loxodonta africana*) feed on secondary vegetation growing on roadsides (Nummelin 1990, Barnes *et al.* 1997) and after road abandonment, recovering vegetation provides a food source welcomed by gorillas (*Gorilla gorilla gorilla*) (Matthews & Matthews 2004). Puddles, which frequently develop in ruts and compacted tracks of logging roads, provide surrogate habitats for anuran communities (Ernst *et al.* 2016).

FOREST CONVERSION IMPACTS. —The issue of human invasion of tropical forest land is central to the issue of whether logged forests become degraded or not (Laurance 2001). In their function as access routes into formerly inaccessible forests, logging roads may not only facilitate illegal logging (Obidzinski *et al.* 2007) and hunting (Wilkie *et al.* 1992), but also conversion of forest land to agriculture. The construction of logging roads is often seen as the first step in a sequence of increasing human impact on tropical forests that starts with selective exploitation of forest resources and then leads to forest degradation and eventually deforestation by conversion to agricultural land (Figure 2). In general, conversion of tropical forests to agriculture can be divided into (i) small-scale encroachment through colonization by individual families carrying out swidden agriculture for subsistence or local markets for agricultural products and (ii) large-scale plantations of commercial crops for national or international markets, both in planned (according to legal requirements) and unplanned ways.

In Amazonia, a clear correlation has been shown between proximity to a road and deforestation (Laurance *et al.* 2002). The expansion of the secondary road network (in large parts considered an unofficial or illegal activity; Barber et al. 2014) is often driven by the logging sector (Arima *et al.* 2005, Perz *et al.* 2007). Such roads have then been shown to provide entry points to the forest for settlers seeking land (Uhl & Vieira 1989, Veríssimo *et al.* 1995). According to remote sensing analyses, logging occurs within 25 km of detectable roads, and also the probability of logged forests being deforested is four-times higher than for unlogged (Asner *et al.* 2006). Spatially explicit examples of logging roads in Brazil that have been unofficially used for colonization are the Transiriri and the Transtutuí roads near Uruará (Arima *et al.* 2005) and other secondary roads in the state of Pará, such as north of São Félix do Xingu (Mertens *et al.* 2002). Linear patterns of deforestation along logging roads have also been observed in Central Africa (Mertens & Lambin 2000) and South-East Asia (Kavanagh *et al.* 1989), emphasizing that logging roads can open up access to forests for conversion in a wide range of contexts.

Not all logging roads necessarily lead to an influx of subsistence farmers (Kummer & Turner II 1994). Kleinschroth, Healey & Gourlet-Fleury (2016) showed that only 12% of roads in a > 100,000 km^2 Central African forest area subject to commercial logging remained open for more than 15 years. All other (mostly secondary) logging roads were transient, showing a median persistence of less than four years before recovery of vegetation cover (Kleinschroth *et al.* 2015). Forest areas in Africa with low human population density are generally not 'opened-up' through conversion to agriculture following logging road construction (Wunder 2005). According to the von Thünen model (Angelsen 2007) it is mostly access to markets that increases the likelihood of forest land being converted to agriculture. Logging operations might not be followed by in-migration at all in remote areas with poor soils that are sparsely populated (Chomitz & Gray 1996). Putz & Romero (2015) note that in Indonesia swidden farmers continue to use abandoned logging roads after they have become impassable by vehicles, independently of the proximity to formal markets. The time window for first colonization of forest by small-scale agriculturalists making use of abandoned logging roads may, however, be restricted to the first five years after logging (Walker & Smith 1993). After that, the recovery of forest biomass makes forest conversion too costly. Generally, logging with its associated road construction cannot in itself be seen as the sole cause of encroachment by agriculturalists, as this often depends on official re-designation of the roads for public use or even large-scale government programs providing incentives for colonization (Nepstad *et al.* 2002, Barber *et al.* 2014, Alvarez & Naughton-Treves 2003). Governmental infrastructure development plans often simply exploit the opportunity provided by the previous construction of logging roads (Putz & Romero 2015).

In the Amazon logging can lead to feedback loops facilitated by roads, as logging activities attract a growing population and the presence of more people justifies more roads (Fearnside 1985). The attraction of human settlement generally results in an expansion of deforestation or severe forest degradation, eventually making way for the development of large-scale agro-industrial crop and livestock agriculture (Fearnside 1987). Logging reduces the immediately exploitable natural capital of forests, and thus their short-term value, providing an important economic incentive for conversion to cattle pasture, soy-bean or oil-palm crop land in Latin America and South-East Asia (Veríssimo et al. 1995, Uhl & Vieira 1989, Reid & Bowles 1997, Laurance & Balmford 2013). Thus, in the absence of appropriate land use planning, road construction can facilitate an expansion of the area converted to other land uses (Chomitz & Gray 1996). These problems are characteristic of areas where logging and agricultural frontiers are not clearly separated. As frequently observed in Amazonia, in the absence of appropriate planning controls, loggers and ranchers collaborate in road construction for timber exploitation followed by forest conversion to pasture (Schneider *et al.* 2000). Suggested measures to combat conversion of forest along logging roads include communicating evidence to policy makers of the value retained by logged forests for delivery of ecosystem services and conservation of biodiversity (Gaveau et al., 2013; Edwards et al., 2014), providing incentives through certification schemes, and stricter regulation of the granting of logging concessions (Oliveira *et al.* 2007).

The extent to which all or parts of the Trans-Amazonica or other highways in the Brazilian Amazon were initially built as logging roads and subsequently developed into major public roads is not documented. Nonetheless, the vast majority of public roads in tropical forest areas are likely to have started as logging roads (Francis E. Putz, pers. comm.), providing a lower cost option for increased public access. Loggers (conscious of the large costs involved) build roads where they are needed and where roadbuilding is feasible - the same criteria of feasibility apply to public road building, though the needs may be different. In the available literature, however, increased logging is often described as the consequence rather than the cause of road building and paving (Carvalho *et al.* 2001, Nepstad *et al.* 2001, Fearnside 2007, Johns *et al.* 1996), with the construction of roads providing a subsidy from the government to the timber industry (Uhl *et al.* 1997). Mertens et al. (2002) advocate the differentiation of numerous processes and actors in the case of Brazil: primary roads are usually built by the state, while secondary road networks are often constructed by loggers, miners or dedicated colonization organisations. Roads built for a certain economic purpose are then regularly abandoned by their initial builders but then improved by colonists. Construction of new roads by large ranchers spontaneously colonising forest areas is the exception (Binswanger 1991) but once the process has started, these roads are sometimes subsequently used and extended by logging companies (Mertens *et al.* 2002). Uhl et al. (1997) documented these processes for the logging of “terra firme” forest, without forest management plans. Big companies, which have enough capital to invest in constructing their own roads, can operate relatively independently of existing road networks. Their business model is focused on highly selective logging restricted to the most valuable mahogany (*Swietenia macrophylla*) trees over large areas. In forest areas where such high-value tree species do not occur or have already been logged, this model is not commercially viable, so logging is restricted to areas where there are government-constructed roads. Here, high-intensity logging is often carried out by less-well-capitalised, small-scale local enterprises, followed by individuals using only a chainsaw who take the leftover trees. This cascade of uncontrolled exploitation, resulting from the initial road construction, generally leads to severe forest degradation and may pave the way for subsequent conversion to agriculture.

Logging road impacts also have an anthropological dimension. For Amazonia, concern has arisen that logging roads could provide unwanted access by outsiders to the land of indigenous communities, thus destroying their traditional way of life (Veríssimo *et al.* 1995, Uhl & Vieira 1989). In contrast, however, there is a more widespread (but often neglected) demand from rural communities in tropical forest areas for improved access through new or better roads. In Central Africa, for example, Tiani et al. (2005) reported a positive perception by local communities of new road connections, facilitating access to health care and education. Protecting the health of people living along roads does, however, require the management of road surface quality in a way that limits the risk of respiratory diseases from dust raised by heavy logging vehicles (Cerutti *et al.* 2014).

ROAD PLANNING AS A COMPONENT OF SUSTAINABLE FOREST MANAGEMENT. —Road construction is one of the most costly components of selective logging operations (Holmes *et al.* 2002, Medjibe & Putz 2012). Therefore, investment in road construction and management depends on the capital of logging companies (Gaveau *et al.* 2009). Best practice engineering guidelines for logging road construction in tropical forests have been published since the 1950's (reviewed by Kleinschroth, Gourlet-Fleury, *et al.* 2016). There have been few notable developments in road engineering over this period, despite increased concern about the need to reduce negative environmental impacts. The bigger issue is that the existing best practice recommendations are rarely implemented, throughout the tropics (Putz *et al.* 2000).

A landmark publication setting out recommendations for improved road planning, construction and maintenance is the FAO model code of forest harvesting practice (Dykstra & Heinrich 1996), which played a crucial role in the development of reduced-impact logging (RIL) guidelines (Pinard *et al.* 1995). The need for effective planning of road networks before they are constructed, in order to reduce residual stand damage, loss of biomass and damage to soil and watercourses, is a key component of RIL (Putz *et al.* 2008, Sist 2000). One component of this planning is to minimize road length density by optimizing the layout to reach the resource via the shortest path (Gullison & Hardner 1993, Picard *et al.* 2006). However, there is a potential trade-off between roads that are short and straight and those that are fitted to the topography to avoid steep slopes and the buffer zones of water courses (Negishi *et al.* 2008, Le Ray 1956), and even avoid large individual trees that are planned to be retained (Malcolm & Ray 2000). Overall, carefully planned road networks have been shown to reduce forest damage by 40% compared with unplanned existing practice (Johns *et al.* 1996). Planning road networks that best combine minimisation of environmental damage with economic efficiency requires high quality engineering based on accurate topographical and edaphic/geotechnical information. Generally-available remotely-sensed imagery is not sufficient for accurate road planning, but imagery that penetrates the forest canopy down to ground level (in particular LiDAR) offers the prospect of a step-change improvement (Putz & Romero 2015).

The width of road corridors from which trees are cleared is another important dimension for limiting environmental impact (Sist 2000). Forest canopy cover is commonly cleared on both sides of the road to increase the rate of sun drying of the road surface after rain (Sessions 2007). However, depending on road orientation the width required to effectively achieve this can be quite narrow due to the high angle of the sun in the tropics (Wells 2002). The better a road is maintained and drained (e.g. through a parabolic camber throughout) the smaller can be the canopy opening needed to keep the surface sufficiently dry (Allouard 1954). In areas with notable rainfall seasonality restricting log extraction from core forest areas to the dry season would allow the use of low maintenance roads under a closed canopy. Reducing the width of the road corridor does increase the risk of vehicle collisions with wildlife, therefore it should be accompanied by enforced speed limitations (Sessions 2007). Canopy bridges (achieved by large trees whose crowns meet across the road being retained unfelled) and infrastructure installed to increase the connectivity of animal habitats (e.g. tunnels below the road surface) are also recommended as a means of increasing the potential for wildlife to safely cross road corridors (Goosem 2007).

Reducing the impacts of roads on forest biodiversity as a component of sustainable forest management requires the implementation of measures to prevent increased hunting and agricultural colonization following logging (Laurance 2001). Control of access to roads during and after logging is crucial (Bicknell *et al.* 2015), and requires both guarded barriers at strategic points in the permanent road network and the closure of logging roads (= “putting roads to bed”) after harvest (Mason & Putz 2001, Applegate *et al.* 2004). The corridor of closed roads can be used to promote forest recovery, e.g. enrichment planting or other measures to promote the natural regeneration of timber trees (Kleinschroth, Healey, Sist, *et al.* 2016). Such tree plantations may also provide a psychological barrier against land colonization by swidden farmers (Putz & Romero 2015). Consideration should, nonetheless, be given to reopening roads that had been closed at the end of the previous logging operation for subsequent harvest operations in order to avoid the construction of new roads in the same area, or as a cost-effective alternative to opening up new forest areas for logging (Figure 3, Kleinschroth, Healey & Gourlet-Fleury 2016). If forest managers focus their management activities around a well-planned network of logging roads they can reduce both costs and unintended subsequent impacts (Putz & Romero 2015).

To achieve sustainable forest management, companies that hold logging concessions should be held responsible for careful management of the quality and accessibility of their road networks. There is an argument that the infrastructure of tropical production forests should be managed like that of temperate forests, with a well-planned network of maintained permanent roads for management access (Francis E. Putz, pers. comm.). Here, roads are used not just during logging operations but also for interim monitoring, fire control and silvicultural interventions such as enrichment planting and thinning. These advantages, however, need to be weighed up against the risks of access for illegal hunting and encroachment that is often unregulated due to the institutional constraints in many tropical countries. Weak governance and lack of law enforcement also means that we cannot rely on protected forest areas to achieve conservation objectives. Therefore it is crucial to maximize the conservation value of the surrounding matrix of logged forest (Clark *et al.* 2009) by keeping it free of permanently accessible road that cause the fragmentation of forest habitat and a reduction in roadless space. The strategic planning of where to place permanent and temporary roads in the overall forest landscape is therefore crucial for achieving the best compromise between retaining access for ongoing forest management, while minimising long-term fragmentation and degradation in the highest priority areas for biodiversity conservation (Kleinschroth *et al.* 2017). The debate about "land sharing *versus* land sparing" also applies in the context of tropical timber production. The question here is in which areas should timber be harvested through separate one-off operations using temporary road infrastructure versus installing permanent road infrastructure (with its greater costs of initial capital and ongoing maintenance) to allow the forest to be managed for continuing higher timber yields, i.e. "sustainable intensification" (Putz & Ruslandi 2015). Such intensification in appropriate areas could help to ensure the protection of intact forests and roadless areas elsewhere, thus achieving the goal of land-sparing-logging (Edwards *et al.* 2014), as anticipated by the scenarios of Healey *et al.* (2000). For such protection of intact forests to be effective, region-wide landscape planning would be necessary.

LOGGING ROADS AS FOREST HABITAT COMPONENTS. —Forest road corridors can be associated with five elementary functions: filter or barrier, conduit, source, sink and habitat

(Forman 2003). The habitat type provided by logging roads is otherwise relatively rare in tropical forests (except along river channels or on very steep slopes subject to landslides), with its bare soil and greatly elevated light availability, which have been shown to increase leaf and fruit production in woody plants growing adjacent to road corridors (Johns 1988). Abandoned logging roads can even contribute to forest habitat diversity, which can increase some components of biodiversity, as shown for temperate forests (Coffin 2007). Wherever vegetation establishment is not prevented by severe soil degradation or continued road use, there is good potential for gradual recovery of ecosystem services, including provision of timber following tree regeneration. In regions with low intensity timber harvesting, enhanced levels of regeneration of light-demanding timber species have been observed on abandoned logging roads (Fredericksen & Mostacedo 2000, Nabe-Nielsen *et al.* 2007, Swaine & Agyeman 2008, Kleinschroth, Healey, Sist, *et al.* 2016). The road edge zone on either side of the track, from which trees are cleared during road construction, is a particularly suitable microhabitat for recruitment of timber species (Guariguata and Dupuy, 1997; Doucet, 2004). In contrast, in areas where soils are vulnerable to severe soil compaction or capping of the surface, especially where forests are subject to high-intensity timber harvesting such as the dipterocarp forests of South-East Asia, reduced levels of tree regeneration have been reported on abandoned roads and skid trails (Pinard et al., 1996, 2000; Zang and Ding, 2009). Here, plants that can colonise degraded soils, such as certain fern species, may play an important role in ameliorating soil conditions and facilitating gradual forest recovery through vegetation succession. In their study in Peninsular Malaysia, Negishi *et al.* (2006) estimated that it would take up to 40 years for ferns to ameliorate substrate conditions sufficiently to enable taller plant species to establish a canopy that out-shades the ferns. Generally, the composition of vegetation recovering on abandoned logging roads may differ from that of old-growth forest for a long time, even if tree species diversity can reach comparable levels after 15 years (Kleinschroth, Healey, Sist, et al. 2016, but see Guariguata & Dupuy 1997).

OUTLOOK. —We have identified major knowledge gaps concerning long-term impacts of logging roads. While there have been many studies of the immediate impacts of logging roads on animal community composition and movement, little is known about how this affects wildlife populations over the long-term. Much depends on how the barrier-effect and road-related threats such as poaching develop over time, and their impact on genetic diversity and exchange within populations. Given the practical limitations of field studies and the physical limits of remote sensing information, other innovative technologies should be tested for inclusion in scientific studies. There is already a rapid expansion in the use of camera traps and other electronic animal tracking devices in tropical forests (Harmsen *et al.* 2010, Vanthomme *et al.* 2013), which could be deployed in the study of road impacts. An example of more innovative approaches is the Rainforest Connection project (https://rfcx.org/) that places solar-powered smartphones equipped with software that can filter different audio-signals in rainforest canopies. These devices are programmed to send an alert when they record the sound of motors such as those of chainsaws or motorbikes, indicating illegal activities, and they could be used as a cost-effective method of monitoring poaching.

The most common way to assess human impact on tropical forests over a large scale is by using roads as indicators (Laporte *et al.* 2007, Asner *et al.* 2009, Lewis *et al.* 2015). However, this approach does not differentiate between types of roads, although they can differ hugely in the severity and duration of impact that they indicate. Therefore, more effort is needed to understand and disentangle the impacts of roads depending on their location and connectivity in the overall network, the purposes that they are used for, how they are managed and maintained, and for how long they persist. There is a lack of quantification of the proportion of roads that have enabled long-term human encroachment *versus* those that have not, becoming impassable due to washouts of bridges and culverts, and recolonization by forest vegetation. For roads that have led to long-term forest degradation or conversion to agriculture, it would be important for forest policy to know what proportion were initially built for logging *versus* other purposes. This evidence would enable testing of whether road construction for logging invariably leads to subsequently illegal forest exploitation. It would also indicate whether and where there is a need to focus actions to prevent this occurring, in places where legal logging is allowed to continue.

CONCLUSIONS. —The indirect impacts of logging roads on occurrence of fire, deterioration of water quality, conversion to agriculture and increased hunting are much more severe than the direct impacts of road construction and planned use on forest cover, soil and wildlife, as these are limited in persistence and in the surface area that they affect. To reduce the subsequent indirect impacts, road access management is therefore crucial. For many tropical countries, however, it remains questionable how successful the enforcement of access restrictions can be, given the high demands for bushmeat and agricultural land. One solution to this problem is to intensify road construction and timber harvesting in suitable areas with high production potential, while sparing other areas of high conservation value from any new road construction.

In the nexus of roads, hunting and deforestation it is generally difficult to determine if roads are endogenous or exogenous factors (Lambin *et al.* 2003). The question is, do roads affect just the precise location or also the overall quantity of forest conversion and hunting? So far, it seems that the construction of roads reduces the costs of such activities, thus making them affordable for more people. It remains unclear, however, what alternative sources of nutrition and livelihood are available for growing rural populations, and which productive land can be used to provide them. Much depends on the direction of transformations in society and how people's interaction with their natural environment changes, including forest conversion planned by governments. Poor governance, human population growth, migration and dependence on markets (from local to international) make this direction very hard to predict.

Roads are becoming an increasingly common component of tropical forests around the world. Given the great importance of logged forests for biodiversity conservation and carbon storage, and the high potential risks associated with the presence of roads, large-scale road planning needs to be placed near the top of the forest policy agenda. Monitoring the spatio-temporal dynamics of roads in tropical forests will provide crucial evidence for the goal of "development without destruction" (Lewis *et al.* 2015) through large-scale landscape planning. Its implementation is likely to require much more effective management of the accessibility of forest roads than is generally the case currently.

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DATA AVAILABILITY STATEMENT

Library entries for the full pre-selected literature database will be made available on DRYAD digital repository in *.bib, *.ris and *.xml formats.

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TABLES

TABLE 1: Widths of primary and secondary logging roads in tropical forests, separated between road track (the surface on which vehicles travel) and corridor (full width of forest cleared including on both sides of the track).

Track width (m)		**Corridor width (m)**		**Country/ Continent**	**Forest certifi-cation**	**Reference**
Primary	**Secondary**	**Primary**	**Secondary**			
6.6		24.7		Bolivia		Gullison & Hardner (1993)
5.2	4.6	13.3	10.5	Bolivia		Jackson et al. (2002)
	3.6		5.5 (5.3–5.7) [a]	Brazil		Johns *et al.* (1996)
4.3	5.1	10.1	9.8	Brazil		Feldpausch *et al.* (2005)
		12.5	3.0	Brazil		Uhl & Vieira (1989)
	3.3 (3.0–3.5) [a]		5.8 (5–6.5) [a]	Costa Rica		Guariguata & Dupuy (1997)
7		17		Cameroon		Hoeven (2010)
		25	20	Cameroon		Gideon Neba *et al.* (2014)
	5.3		17.2	Cameroon		Kleinschroth, Healey, Sist, *et al.* 2016), unpublished material
7.9	6.4			Central African Republic		Malcolm & Ray (2000)
6.4	5.1			Central African Republic		Durrieu de Madron *et al.* (2000)
6.8		22.6		Gabon		Medjibe *et al.* (2013)
	4.1		15.1	Gabon	FSC	Medjibe *et al.* (2013)
	7.9		66.6	Gabon	None	Medjibe *et al.* (2013)
		40	25	Republic of Congo		FAO (1995)
	7.7		25.3	Republic of Congo		Kleinschroth, Healey, Sist, *et al.* (2016), unpublished material

		30	20	Central Africa		Estève (1983)
3·49				Malaysia		Ziegler *et al.* (2007)
		32.75		Indonesia	FSC	Griscom *et al.* (2014)
		31.78		Indonesia	None	Griscom *et al.* (2014)
5.5	4	17.4	6.8	America[b]		
7.2	6	28.5	40.9	Africa[b]		
3.5		32.3		Asia[b]		
6.4	5.1	24.9	15.1	Global[c]		
5.8	5.26	24.1	19.3	Global[d]		

[a] Mean and range (in brackets) of values given in the paper

[b] Mean summarized for values of the respective continent

[c] Median summarized for all values

[d] Mean summarized for all values

TABLE 2: Proportion of the overall surface area of the forest (reference area defined for each study) cleared for road building.

Proportion of forest area cleared for road building	**Country/ Continent**	**Reference area**	**Reference**
1%	Brazil	"Overall logged area"	Feldpausch *et al.* (2005)
8%	Brazil	"Total logged forest area"	Uhl & Vieira (1989)
1.05%	Bolivia	"Section of logged area"	Gullison & Hardner (1993)
2.1%	Bolivia	"Harvesting block"	Jackson *et al.* (2002)
1.3 (0.6–2)%	Brazil	"Total area of four harvest blocks"	Asner *et al.* (2002) Pereira *et al.* (2002)
0.7%	Belize	"One-year logging coupe"	Arevalo *et al.* (2016)
2%	Cameroon	"Annual allowable cut area"	Gideon Neba *et al.* (2014)
0.74%	Cameroon	"Average across seven logging concessions"	Kleinschroth, Healey, Sist, *et al.* (2016)
0.8%	Central African Republic	"Annual allowable cut area"	Durrieu de Madron *et al.* (2000)
6.4%	Gabon	"Logged section of overall forest area"	White (1994)
1.7%	Republic of Congo	NA	FAO (1995)
0.8%	Republic of Congo	"Average across four logging concessions"	Kleinschroth, Healey, Sist, *et al.* (2016)
1.84 (1.3–2.4)%	Central Africa [a]	NA	Estève (1983)
4 (3.3–4.7)%	Indonesia [a]	"Logging unit"	Pinard *et al.* (2000)
4.8%	Malaysia	"Logging compartment"	Johns (1988)
0.6–8%	America [b]		
0.74–6.4%	Africa [b]		
3.3–4.8%	Asia [b]		
1.7%	Global [c]		
2.48%	Global [d]		

[a] Mean and range (in brackets) of values given in the paper

[b] Range (minimum and maximum values) summarized for respective continent

[c] Median summarized for all values

[d] Mean summarized for all values

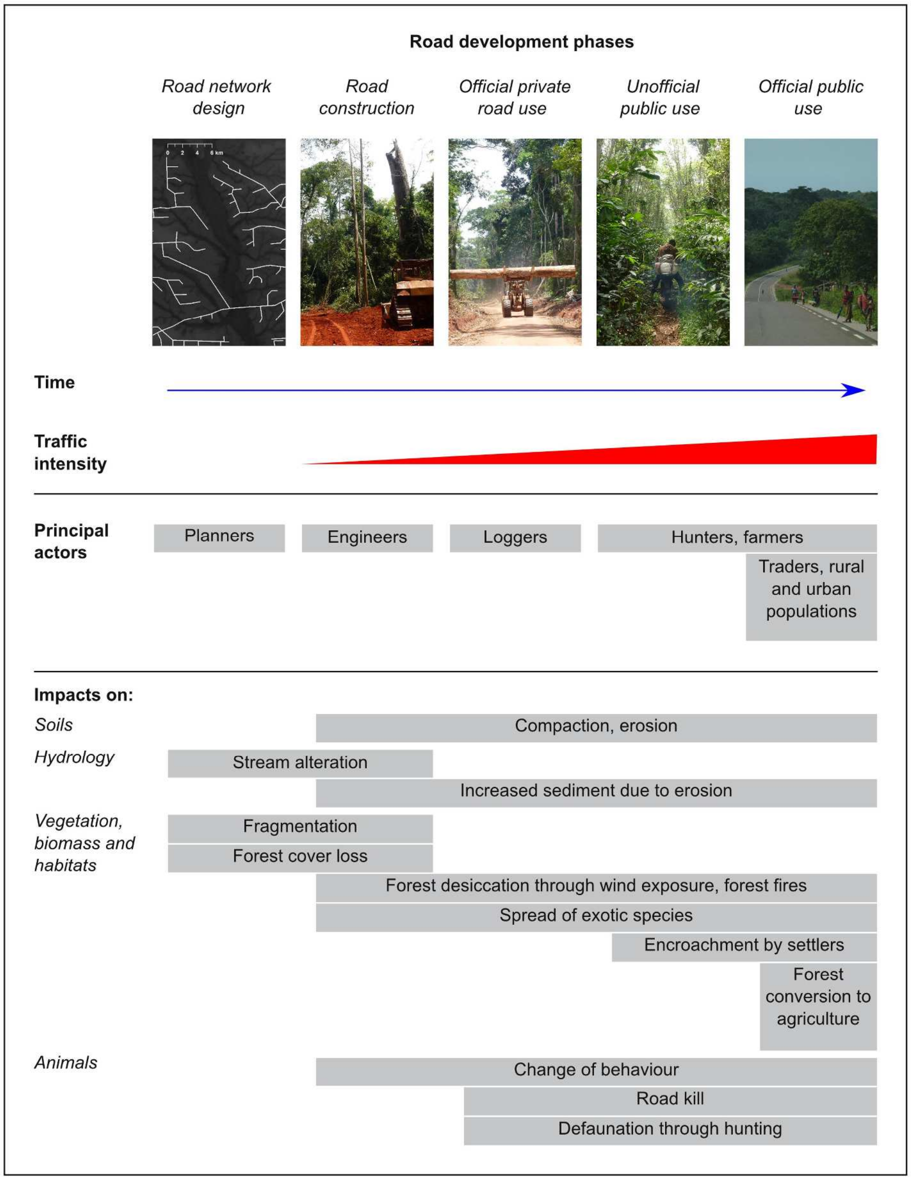
FIGURE LEGENDS

FIGURE 1: Example of a secondary logging road in Republic of Congo annotated with cross-section measures and their respective names used in the text.

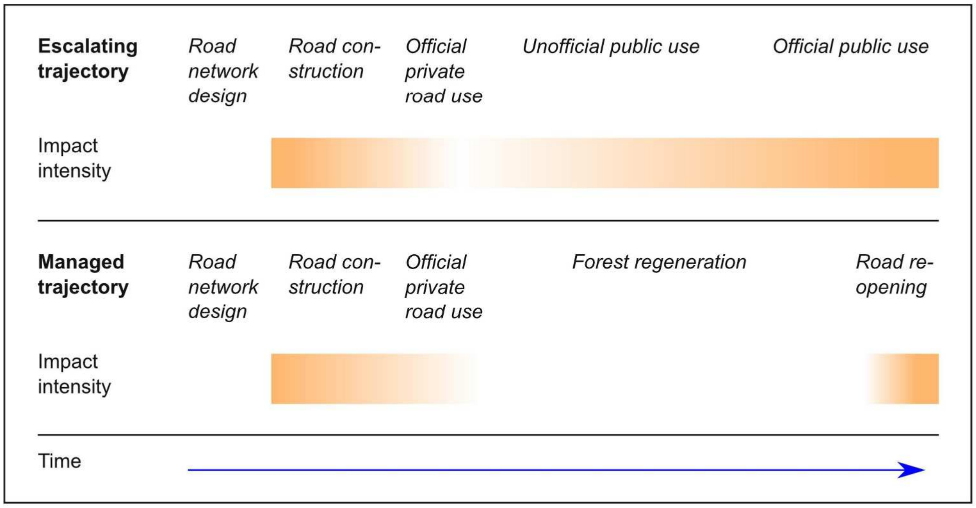
FIGURE 2: Conceptual model of the temporal evolution of logging roads, principal actors, potential impacts linked to each phase and measures to mitigate them.

FIGURE 3: Comparison of the impact intensity of two hypothetical logging road development trajectories, depending on follow-up use (see Figure 2) or successful closure after logging until the next logging cycle. A darker shading of the orange bar indicates higher impact intensity, based on an estimated accumulation of impacts described in the main text.

Example of a secondary logging road in Republic of Congo annotated with cross-section measures and their respective names used in the text.
Figure 1
207x206mm (300 x 300 DPI)



Conceptual model of the temporal evolution of logging roads, principal actors, potential impacts linked to each phase and measures to mitigate them.
Figure 2
222x285mm (300 x 300 DPI)



Comparison of the impact intensity of two hypothetical logging road development trajectories, depending on follow-up use (see Figure 2) or successful closure after logging until the next logging cycle. A darker shading of the orange bar indicates higher impact intensity, based on an estimated accumulation of impacts described in the main text.

Figure 3

211x112mm (300 x 300 DPI)