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Logging roads in tropical forests

Kleinschroth, Fritz; Gourlet-Fleury, Sylvie; Gond, Valery; Sist, Plinio; Healey, J.R.

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1 **Title**

2 **Logging roads in tropical forests: Synthesis of literature written in French and English**
3 **highlights environmental impact reduction through improved engineering**

4

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12

1 **Authors:**

2 Fritz Kleinschroth^{1,2,3*}, Sylvie Gourlet-Fleury¹, Valéry Gond¹, Plinio Sist¹, John R. Healey²

3

4 ¹CIRAD, Biens et Services des Ecosystèmes Forestiers Tropicaux, TA C 105/D, 34398

5 Montpellier Cedex 5, France.

6 ²School of Environment, Natural Resources and Geography, Bangor University, Bangor,

7 Gwynedd, LL57 2UW, UK

8 ³AgroParisTech - Centre de Montpellier, Agropolis International, 648 rue Jean-François

9 Breton, 34093 Montpellier, France

10 * Email: fritz.kln@gmail.com

11

1 **Abstract**

2 Logging roads are considered important causes of forest degradation due to direct and
3 indirect impacts on ecosystem functioning and biodiversity. Given that logging prevails in
4 tropical forests around the world, effective road management is of crucial importance to
5 reduce logging-related environmental impacts and the costs of logging operations at the same
6 time. In a review we analysed how logging roads are addressed in the literature. We
7 compared studies published over the past 65 years in the journal *Bois et Forêt des Tropiques*
8 (BFT), written mostly in French, with a range of more recent articles from the databases
9 Scopus and Web of Knowledge. Half of the articles on the subject in BFT were published
10 before 1972, while the generalist databases show a steady increase in publication rate since
11 then, reaching its present peak. From the whole body of literature, we selected 126 articles,
12 dealing with impacts and management of logging roads in tropical forests around the world,
13 for critical appraisal. Articles in BFT were characterized by a strong focus on practical issues
14 in forest road engineering, while many publications written in English were focussed on the
15 identification of impacts on forest ecosystems. Road-related environmental impacts stem
16 from the loss of forest cover during their construction, the augmentation of edge effects, soil
17 erosion and interference with wildlife, as well as their facilitation of access to the forest for
18 hunting and agricultural colonization. Based on this review we present a list of recommended
19 measures to reduce these impacts. We conclude that, despite the continuing attention paid to
20 the subject, little is known about the long-term fate of logging roads in the forest landscape.

21

1 **1. Introduction**

2 Almost half of all remaining tropical forests in the world are subject to selective logging, with
3 20% having already been logged (Asner *et al.*, 2009) and 400 million ha of natural tropical
4 forests being in the permanent timber production estate (Blaser *et al.*, 2011). Tropical forests
5 are of global importance for carbon storage, biodiversity, food provisioning and other
6 ecosystem services of great value for livelihoods. With less intact tropical forest available,
7 these pivotal functions increasingly need to be delivered by logged forests that can retain high
8 conservation values despite the logging disturbance (Edwards and Laurance, 2013;
9 Rutishauser *et al.*, 2015). However, destructive and poorly planned logging practices persist
10 throughout the tropics (Putz *et al.*, 2000, 2008) and there is an urgent need to better reconcile
11 timber extraction with biodiversity conservation (Putz *et al.*, 2012; Edwards *et al.*, 2014).

12 Globally road networks have expanded rapidly over the past century, especially in tropical
13 regions in recent years (van der Ree *et al.*, 2015). In production forests roads are the main
14 infrastructure for timber extraction. Historically, in forests adjacent to large enough rivers,
15 rafts of logs were often floated down-river, but this means of transport is decreasingly used
16 because it is slow and subject to a high rate of losses (Wilkie *et al.*, 2000). Due to their spatial
17 extent, construction and maintenance of roads is the most costly component of logging
18 operations (Holmes *et al.*, 2002; Medjibe and Putz, 2012) and also the element of logging in
19 natural forests with the greatest environmental impacts (Mason and Putz, 2001; Laurance *et*
20 *al.*, 2009). Because roads are the component of logging that is most easily detected,
21 especially by remote sensing (Figure 1), roads are frequently used as inputs for observation
22 and modelling of tropical land use and land cover change (Brandão and Souza, 2006; Laporte
23 *et al.*, 2007; Rosa *et al.*, 2014).

1 This article is a critical appraisal of the literature on the environmental impact of logging
2 roads on natural tropical forests. Recent years have seen a rapid increase in articles
3 addressing the impacts of roads on forest ecosystems. However, no previous review has
4 adequately covered both the recent literature predominantly written in English and the
5 previous French-language forestry literature, despite the long record of French science on
6 tropical forest road management. We analysed the representation of logging roads in the
7 literature over the long term with a particular focus on the question of how road-related
8 impacts on forest ecosystems can be reduced.

9 **2. Methods**

10 **2.1 Literature search**

11 We used fixed search strings to generate search hits and used their number as an indication of
12 coverage of the subject. For the French-language literature, we chose to limit the search to the
13 journal Bois et Forêts des Tropiques (BFT), as it is the main publication for French-language
14 papers on this topic and it has a fully open-access archive dating back to 1947. This extensive
15 archive is not fully covered by any of the common generalist databases and merits an analysis
16 on its own. We used the search engine on the website <http://bft.cirad.fr/> which does not
17 accept Boolean operators or wildcards, therefore we successively applied the search strings:
18 “route forestière”, “piste forestière”, “route exploitation” and “piste exploitation”. For
19 comparison we used the two most well-established databases that cover the widest scope of
20 English-language literature, while focussing on peer-reviewed publications, Scopus and ISI
21 Web of Knowledge. Google Scholar is also widely used to search for scientific literature as it
22 also includes grey literature, books and reports. However, due to practical constraints a
23 systematic assessment of this source was not possible and we only used it to select some
24 influential publications outside peer-reviewed journals. In Scopus we used the search strings:

1 "logging OR forest AND road AND tropic*" and in Web of Knowledge "(logging OR forest)
2 AND road AND tropic*". According to their websites the Scopus archive dates back to 1966
3 and Web of Knowledge covers articles back to 1900, however these databases are not
4 transparent about the date since when articles from different sources are included. The total
5 number of articles obtained by search hits were 57 for BFT, 656 for Web of Knowledge and
6 463 for Scopus. The first hit for the search strings in both of the databases covering English-
7 language literature is in the year 1972. By the end of that year, 50% of all the identified
8 articles in BFT had already been published, with a peak in the number of articles on the
9 subject in the early 1950s. In Web of Knowledge and Scopus the subject was covered
10 regularly only from the 1990s onwards, with a steadily increase in the number of articles,
11 reaching almost 60 in Web of Knowledge in 2013 (Figure 2). These results are subject to bias
12 due to the large differences in structure and coverage of the databases *versus* the single
13 journal, BFT, and reflect the total number of papers published. We also emphasize that a
14 wide range of forestry journals, including BFT, are only covered by Web of Science and
15 Scopus from the 1990s onwards, therefore their earlier articles (and those from other
16 professional forestry publications) are excluded from the searches using these two databases.
17 The database CAB direct (<http://www.cabdirect.org>) has a more comprehensive coverage of
18 the professional forestry literature, but is less used. We conducted a search only for
19 comparison, which produced 704 hits using the same set of keywords as above. For a more
20 systematic approach, a much wider search string would be necessary in order to capture all
21 relevant forestry literature. Using the search string (logging OR forest*) AND (road*) AND
22 (tropic* OR ...) and for "... " (adding all tropical countries separated by OR (see Petrokofsky
23 *et al.*, 2015)) generated 2721 results in CAB direct. However, even such an extensive search
24 generates the first hits only for the year 1969, while in the year 2013 alone there were 174.
25 This partly reflects the limited coverage of older publications also in this database (earlier

1 literature is well covered by the publication “*Forestry Abstracts*”, but this could not be
2 accessed by our on-line search) but it also shows the increasing number of articles in general,
3 and on this subject in particular.

4 Notwithstanding these methodological limitations in the search for articles, our results do
5 indicate that researchers publishing in BFT addressed the subject of roads in tropical forests
6 at the earliest stages of the development of the subject. We therefore consider it of great
7 interest to include such publications in a critical appraisal comparing them with the dominant
8 literature accessed by most people who use the common generalist databases such as Web of
9 Knowledge and Scopus.

10 **2.2 Selection of articles**

11 For critical appraisal we selected 19 articles from BFT, 99 from the overall body of English-
12 language peer-reviewed publications plus 5 books and 4 reports from searches in Google
13 Scholar. Articles that addressed logging roads in tropical forests were selected by their
14 relevance for the disciplines ecology, engineering and geography. An overview of the
15 selection criteria that were used for the screening of articles is given in Table I. The term
16 “logging road” is frequently used without further definition. We included only the articles
17 reporting on roads that are built to allow wheeled vehicles to transport harvested logs from
18 the landings, where they are loaded, out of the forest. We excluded roads constructed
19 primarily for public use. The selection therefore includes primary (access) roads, which are
20 mostly build for permanent use, as well as secondary (dead-end) roads, generally built for use
21 over a limited time during a single timber harvesting operation. This definition excludes skid
22 trails designed for use by tracked vehicles, which are narrower and thus often do not form a
23 continuous opening of the canopy. Due to constraints of time and resources, the choice and
24 application of selection criteria were not independently tested by a second person, hence their
25 reproducibility might be limited.

1 The geographical focus of the articles differed between the two literatures. Whilst the French-
2 language BFT papers were mostly focused on Francophone African countries, a majority of
3 the English-language articles focused on tropical America, in particular the Amazon. Only
4 half as many English-language articles focused on Asia and again fewer on Africa, with a few
5 on tropical Australia (Figure 3).

6 **3. Critical appraisal**

7 **3.1 Technical advice for forest exploitation**

8 The very first article in BFT that mentioned roads in Central African forests (Steinmann,
9 1948), was written with the connotation of adventure in exploring the forest as unknown
10 territory in order to gain access to forest resources in the French colonies. Over the next few
11 years the articles in BFT became very specific in giving technical advice for road planning,
12 building and maintenance in order to ensure efficient logging operations. Detailed
13 descriptions of machines used for construction, maintenance and transport were given
14 (Tuffier, 1954; Le Ray, 1958) but also a wide range of recommendations for road engineering
15 were presented and discussed. Of major importance here was the construction of roads
16 adapted to the landscape, e.g. fitting a road into the terrain, contouring the shape of the road
17 surface, implementing drainage systems and designing river crossings (Allouard, 1954a; Le
18 Ray, 1956, 1960; Esteve and Lepitre, 1972a). Decades later, and without making reference to
19 these articles, several very similar ideas and recommendations were presented in a book in
20 English on forest road operations in the tropics (Sessions, 2007), showing that most of these
21 engineering principles introduced more than 60 years previously are still considered to be
22 “good” practice. Early articles also considered the planning strategy of the overall road
23 network and the optimization of the layout, with maps and schematic plans given as examples
24 (Allouard, 1954b; Krzeszkiewicz, 1959; Le Ray, 1959). The average skidding distance of

1 1 km in Central Africa, which is the main variable that influences road spacing in the
2 landscape, has not changed since then (*personal observation*). These articles were based on
3 the primarily objective of maximizing the number of trees that can be reached with the least
4 effort and costs for road building. However, they also mentioned that these measures would
5 help to reduce the extent of damage to the forest. For most subsequent articles on this subject,
6 in other journals (e.g. Gullison and Hardner, 1993; Dykstra and Heinrich, 1996; Johns *et al.*,
7 1996; FAO & ATIBT, 1999; Picard *et al.*, 2006; Schulze and Zweede, 2006), the primary
8 objective changed towards environmental impact reduction, but the recommended practices
9 remained very similar.

10 **3.2 Direct impacts of roads on tropical forests**

11 We found few detailed analyses of the ecological impacts of logging roads in articles
12 published in BFT. Estève (1983) quantified the destruction of forest cover for logging-related
13 infrastructure in Central Africa and South America and concluded that, with only 5%
14 destruction, the ecological value of the forest remained largely unchanged. In an African
15 logging concession, roads and log landing sites accounted for only 0.8% of the forest area
16 (Durrieu de Madron *et al.*, 2000). However, the majority of the English-language articles
17 published over the last 25 years give a strongly contrasting perspective, describing a variety
18 of road-related threats to forest ecosystems with potentially detrimental effects to their
19 ecological functioning at various scales. The amount of forest cover cleared (Figure 4), and
20 thus biomass lost, for road building has been raised as an issue in terms of local-scale impacts
21 (Olander *et al.*, 1998; Gideon Neba *et al.*, 2014). However, strong regional differences are
22 reported, with a notably high average value of 17% stand disturbance by roads and skid trails
23 in Malaysia (Pinard *et al.*, 2000).

1 Even if only a small proportion of the forest cover is cleared for road building (as in most of
2 Central Africa and Amazonia), negative effects might reach much further. Edge effects can
3 lead to the death of big trees (Laurance, 2000) and the desiccation of forests due to enhanced
4 evapotranspiration in adjacent forest areas (Goosem, 2007; Briant *et al.*, 2010; Fraser, 2014;
5 Kunert *et al.*, 2015). Together with large amounts of debris (left behind after clearing) as a
6 potential fuel, roads can thus increase the vulnerability of the forest to fires (Uhl and
7 Kauffman, 1990; Nepstad *et al.*, 2001).

8 Road construction drastically changes the forest habitat, not only by removing vegetation but
9 also by altering soil functions through removal of top soil, application of external materials
10 and heavy mechanical compaction (Donagh *et al.*, 2010). The most severe effect of soil
11 exposure and compaction is often erosion (Malmer and Grip, 1990; Douglas, 2003), which in
12 combination with heavy tropical rainfall can remain a problem for more than ten years after
13 logging (Clarke and Walsh, 2006). This results in the loss of soil material on and around
14 roads and the accumulation of sediment in streams and rivers (Gomi *et al.*, 2006; Ziegler *et*
15 *al.*, 2007; Negishi *et al.*, 2008). Together with other hydrological impacts, e.g. damming of
16 water courses through inadequately constructed river crossings, this can lead to serious
17 deterioration of the ecosystem by changing the physical and chemical characteristics of the
18 water (Trombulak and Frissell, 2000; Bruijnzeel, 2004; Connolly and Pearson, 2007). This
19 can have a direct impact on local communities who depend on the ecosystem service of clean
20 drinking water from streams (Mandle *et al.*, 2015). Many of these articles examining road-
21 related impacts also present possible mitigation measures that we discuss in detail below.

22 Roads in forests directly interfere with animal populations through road kill (Laurance *et al.*,
23 2009; Clements *et al.*, 2014) but also by influencing their movement and behaviour (Chazdon
24 *et al.*, 2009; Lees and Peres, 2009; Hoeven, 2010). Negative effects of roads have been
25 shown on small mammals (Malcolm and Ray, 2000), birds (Develey and Stouffer, 2001);

1 Laurance and Gomez, 2005), elephants (Blake *et al.*, 2008) and dung beetles (Hosaka *et al.*,
2 2014). This has been associated with habitat changes and human activity, but increased noise
3 levels can also have an impact (Laurance, 2015). However, roadsides and abandoned roads
4 can also attract animals due to higher abundance of herbs as food sources, as has been shown
5 for gorillas (Matthews and Matthews, 2004). Puddles and ditches resulting from compacted
6 soils on logging roads have been reported to be a suitable reproduction site for turtles (Ernst
7 *et al.*, 2014). An overview of the varying effects of roads on different groups of species is
8 given by van Vliet and Nasi (2007) showing, for example, that elephants are more frequently
9 found in proximity to roads and settlements, while certain wild ungulates show strong
10 patterns of road avoidance.

11 **3.3 Indirect impacts of roads on tropical forests**

12 Arguably the biggest threat resulting from logging roads in the tropics is that they grant
13 access to the forest interior for other land uses. The presence of roads facilitates illegal and
14 uncontrolled logging activities (Obidzinski *et al.*, 2007, Laurance and Balmford, 2013) and
15 the probability of logged areas being deforested is highly dependent on distance from major
16 roads (Asner *et al.*, 2006). This is mostly because logging roads are used successively for
17 encroachment by farmers who colonize new areas for slash-and-burn agriculture (Johns *et al.*,
18 1996; Reid and Bowles, 1997; Mertens and Lambin, 2000; Pfaff *et al.*, 2007). However, this
19 process varies depending on human population density, soil quality and topography (Cropper
20 *et al.*, 1999), as well as market access and tenure regulations (Chomitz and Gray, 1996), and
21 is often linked with official re-designation of roads for public use or even large-scale
22 programs with incentives for colonization (Nepstad *et al.*, 2001; Barber *et al.*, 2014). With
23 increasing disturbance intensity this can lead to feedback loops resulting in deforestation or
24 severe degradation at larger scales (Laurance *et al.*, 2002; Malhi *et al.*, 2014).

1 In the absence of appropriate landscape planning, over the long-term some roads initially
2 built for logging have developed into major public roads and can even be linked with the
3 conversion to large-scale agro-industrial agriculture and pastoralism. This has been reported
4 for Latin America and South-East Asia for cattle grazing, soy-bean production and oil-palm
5 plantations (Reid and Bowles, 1997; Fearnside, 2007; Laurance and Balmford, 2013).
6 However, the reason why logged forests become vulnerable to such conversions can only
7 indirectly be attributed to the presence of roads. It is more linked with the loss in short-term
8 economic value and a widespread underestimation of the ecological importance of production
9 forests (Gaveau *et al.*, 2013; Edwards *et al.*, 2014).

10 A less visible form of forest degradation resulting from roads is the depletion of wildlife
11 populations through unregulated hunting that has even resulted in “empty” forests (Redford,
12 1992; Robinson *et al.*, 1999; Laurance *et al.*, 2006; Poulsen *et al.*, 2011). In Central Africa
13 especially, bushmeat provides the most important source of protein for most forest-dependent
14 communities, making hunting an essential activity for human nutrition that has been practiced
15 for a long time (Figure 5). However, the presence of extensive road networks has led to a
16 process of specialization of market hunters linked to a longer transport chain and increased
17 quantities of extracted bushmeat being supplied to meet the increasing demand in urbanized
18 areas further away from the forest (Wilkie *et al.*, 1992, 2000; Nasi *et al.*, 2008). Even logging
19 vehicles are frequently used to transport hunters, weapons and game, thus increasing the
20 radius of defaunation around settlements deeper into the forest (Poulsen *et al.*, 2009).

21 Roads can also facilitate biological invasions in tropical forests. Dispersal by trucks and other
22 logging vehicles has been shown to be the main driver for the spread of exotic tree
23 (Padmanaba and Sheil, 2014), ant (Walsh *et al.*, 2004) and grass (Veldman and Putz, 2010)
24 species.

1 **3.4 Reducing the impacts of logging roads**

2 The potential problems with roads in tropical forests have long been appreciated from a forest
3 management perspective (as evidenced in the BFT articles reviewed above) and so there has
4 been a parallel set of publications focused on the development of engineering techniques
5 designed to minimise these problems. These are well represented in both the French- and
6 English-language literatures (Table II).

7 Improved road planning, construction and maintenance has been a central element in the
8 development of reduced-impact logging (RIL) guidelines (Pinard *et al.*, 1995) and in the
9 FAO model code of forest harvesting practice (Dykstra and Heinrich, 1996). Effective road
10 planning in order to reduce residual stand damage and loss of biomass, as described in BFT
11 in the 1950s, was included as a key component of RIL (Putz *et al.*, 2008). Another important
12 recommendation is to reduce the clearing width of road corridors (Sist, 2000). Especially in
13 Central Africa, there is still a widespread belief among forest managers that forest clearing on
14 both sides of the road is necessary to let the sun dry the road surface (Sessions, 2007).

15 However, it has already been emphasized by Allouard (1954b) that a well-maintained and
16 drained road does not require a wide open canopy. Also, the need to build roads fitted to the
17 topography in order to avoid soil erosion on the road surface (Negishi *et al.*, 2008) has long
18 been articulated (Le Ray, 1956).

19 With a stronger focus on biodiversity conservation, the set of impact-reduction measures has
20 recently been augmented. This includes the declaration of set-asides from logging in high
21 conservation-value areas as well as measures to reduce the fragmenting effect of roads on
22 animal habitats (Goosem, 2007; Clements *et al.*, 2014). Given the problems with hunting and
23 encroachment, control of access has been identified as a crucial aspect of road management.
24 This requires guarded barriers at strategic points in the permanent road network but also the

1 closure of roads after harvest (Mason and Putz, 2001; Applegate *et al.*, 2004; Bicknell *et al.*,
2 2015). However, wherever local communities do not accept such measures, it becomes
3 difficult for logging operators to enforce them (Figure 6).

4 Since RIL standards have been published, numerous studies have been carried out comparing
5 the effectiveness of RIL with that of conventional logging, generally emphasizing the
6 usefulness of such measures including road building standards (Healey *et al.*, 2000; Pereira *et*
7 *al.*, 2002; Feldpausch *et al.*, 2005; Ezzine de Blas and Ruiz Pérez, 2008; Medjibe and Putz,
8 2012).

9 Forest regeneration after exploitation is of crucial importance for sustainable forest
10 management (Karsenty and Gourlet-Fleury, 2006; Zimmermann and Kormos, 2012). Given
11 that most secondary logging roads are only temporarily used, they do provide a potential site
12 for tree regeneration after abandonment (Figure 7). However, especially in areas where high
13 volumes of timber are harvested such as the dipterocarp forests of South-East Asia, reduced
14 levels of regeneration have been reported on abandoned roads and skid trails due to
15 unfavourable soil conditions (Pinard *et al.*, 1996, 2000; Zang and Ding, 2009). Also, in more
16 urbanized areas, lower levels of forest recovery have been recorded with proximity to roads
17 (Crk *et al.*, 2009). In contrast, for regions with low intensity logging regimes, logging roads
18 and strip clear cuts have been associated with enhanced levels of regeneration of light-
19 demanding timber species (Hartshorn, 1989; Fredericksen and Mostacedo, 2000; Nabe-
20 Nielsen *et al.*, 2007; Swaine and Agyeman, 2008). Road edges, those areas that have been
21 cleared during road construction to let the sun dry the surface, are particularly suitable
22 microhabitats for recruitment of timber species (Guariguata and Dupuy, 1997; Doucet, 2004).

23 **3.5 Characterizing the spatial distribution and coverage of logging roads**

1 Highly selective logging at low densities, as occurs in most of Central Africa and Amazonia,
2 is a form of cryptic disturbance which, in contrast to full deforestation, can only be detected
3 marginally or not at all with conventional remote sensing techniques on larger scales (Peres *et*
4 *al.*, 2006). Due to their linearity and connectedness, roads are the only components of such
5 logging activities that are detectable on medium- to high-resolution satellite images. Articles
6 in BFT were among the first to make use of this finding and suggested the use of logging
7 roads as indicators of the extent of logging disturbance in tropical forests (Gond *et al.*, 2003;
8 Mayaux *et al.*, 2003; Bourbier *et al.*, 2013). Despite some technical drawbacks (de Wasseige
9 and Defourny, 2004), it is now the *de facto* standard across all tropical regions to use roads as
10 indicators for human dominance of tropical forests (Asner *et al.*, 2004a, 2004b, 2009; Souza
11 *et al.*, 2005; Laporte *et al.*, 2007; Hirschmugl *et al.*, 2014; Gaveau *et al.*, 2014). The spatial
12 distribution, i.e. the extent and density, of road networks can be used to model human
13 influences on tropical forests at larger scales (Mertens *et al.*, 2001; Arima *et al.*, 2008; Bell *et*
14 *al.*, 2012; Ahmed *et al.*, 2013b, 2013a, 2014). It also served as an important input to define
15 the intactness of forest landscapes (Potapov *et al.*, 2008) and the identification of priority
16 road-free areas at a global scale (Laurance *et al.*, 2014).

17 **4. Contrasting trends in the literature**

18 Assessment of the literature included in this review reveals two main underlying agendas for
19 these studies that can be roughly classified into conservation approaches *versus* forest
20 management approaches. Dominant parts of the recent literature found in the generalist
21 databases Web of Knowledge and Scopus are focussed on the negative impacts of industrial-
22 type logging and reinforce the long-standing bad reputation of export-driven timber
23 harvesting in tropical countries (Bowles *et al.*, 1998). Only recently, facing the overwhelming
24 occurrence of logging in tropical forests, have publications started to address the ecological
25 value of logged forests that shows the need for them to be protected from further conversion

1 into oil-palm plantations or other agricultural land (e.g. Edwards *et al.* 2011). Conversely,
2 almost all the reviewed articles in BFT adopted a much more pragmatic approach, without
3 openly expressing any doubts about the continuation of logging activities. The history of BFT
4 cannot be disentangled from French colonial history and its' founding institution, the Centre
5 Technique Forestier Tropical (CTFT). The initial colonial motivation of efficiently
6 organizing forest exploitation in overseas forests was later translated into development
7 cooperation (Bonneuil and Kleiche, 1993). However, no change occurred in the adherence to
8 the traditional principles of sustainable forestry and the aim to promote this in collaboration
9 with a range of stakeholders in the field. Irrespective of the motivations behind the historical
10 literature, it contains a high standard of engineering recommendations and the resulting
11 practices mostly persist to the present day. Knowledge of this historical legacy from the
12 literature is crucial in understanding the development of today's logging practices. Lessons
13 learned in the 1950s should not be forgotten, but rather fed into modern evaluation and
14 improvement of logging activities.

15 **5. Identification of knowledge gaps**

16 We have reviewed a large body of literature about logging roads in tropical forests, mostly
17 focussing on immediate direct and indirect environmental impacts and on management
18 techniques designed to mitigate these. However, given the history of more than half a century
19 of industrial-scale logging operations it is somewhat surprising that the long-term fate of
20 logging road networks remains unknown, with insufficient attention paid to road
21 abandonment and subsequent forest recovery. This may be linked to the fact that large
22 formerly-logged areas in Latin America and South East Asia are now deforested. However, in
23 Central Africa this is not the case. Here, only a small proportion of logging road networks is
24 maintained in a constantly open state due to the costs and the obligation for many forest
25 concessions to close secondary roads after exploitation. Little is known about the persistence

1 of road networks in the overall forest landscape or about the long-term successional trajectory
2 on abandoned forest roads, especially in Central Africa. Such long-term characterization of
3 forest road networks can help in the development of much needed strategies for post-logging
4 silviculture and should be taken into account when determining forest degradation based on
5 road networks, for example in the context of the REDD+ programme (reducing emissions
6 from deforestation and forest degradation).

7 We feel that current definitions of intactness or roadlessness of forest landscapes do not do
8 justice to the complexity of the interactions between roads and forests when they are simply
9 based on the application of a fixed buffer distance around all roads. A new understanding of
10 the temporal and spatial dynamics of forest road networks is urgently needed for initiatives
11 that try to reconcile forest certification with the protection of intact forest landscapes. The
12 long-term management of road networks should provide a crucial step towards the anticipated
13 goal of supra-regional landscape planning across the tropics (Lewis *et al.*, 2015).

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3 road runoff generation in a logged catchment in Peninsular Malaysia. *Earth Surface*
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1 **Tables**

2 Table I: Inclusion and exclusion criteria for articles to be considered for critical appraisal,
 3 listed in hierarchical order.

	Inclusion criteria	Exclusion criteria
Language	English, French (only in <i>Bois et Forêts des Tropiques</i>)	Any other language, other journals in the French language
Object	Roads and road networks	
Location	Pan-tropical (Central and South America, Africa, South-East Asia, Australia)	Non-tropical
	Closed canopy tropical forests used for timber exploitation	Tree plantations after clearcutting, woodlands, savannas, wetlands
Principal utilization	Wheeled vehicles transporting timber	Skidding (log yarding), public transportation
Type	Primary roads: permanently maintained, providing principal access to the forest Secondary roads: mostly dead-end roads, connecting logging sites with primary roads, abandoned after use	
Questions and applications	Forest engineering: Layout, design, construction, maintenance, management Ecology: interactions with wildlife and forest ecosystems, direct and indirect impacts, persistence, impact reduction GIS and remote sensing: detection, characterization, spatial distribution	Mention roads only as one of many factors in connection with forest degradation and deforestation Logging impacts that are not directly linked with roads (e.g. timber species population and recruitment issues) Purely concerning economic and social development or land use policy

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- 1 Table II: Logging-road-related environmental problems and measures to mitigate such
- 2 impacts. Each measure is only listed once, although it could also be useful in the context of
- 3 other problems. A selection of the most relevant references is given for each measure.

Road-related environmental problems	Measures to reduce impacts	References
Forest clearing for road construction (carbon emissions, loss of habitat)	Minimize road length by optimizing the layout (to reach the resource via the shortest path)	Le Ray, 1959; Gullison and Hardner, 1993; Johns <i>et al.</i> , 1996; Picard <i>et al.</i> , 2006; Schulze and Zweede, 2006
	Minimize road length by finding the optimal ratio between lengths of roads and skid trails	Krzeszkiewicz, 1959; Dykstra and Heinrich, 1996; Sessions, 2007
	No road construction in high conservation-value areas	Sist <i>et al.</i> , 1998; Healey <i>et al.</i> , 2000; Durrieu De Madron <i>et al.</i> , 2011
	Allow changes in road alignment to avoid large trees	Le Ray, 1959; Sessions, 2007
Edge effects: desiccation, wind exposure, death of large trees	Reduce the width of forest clearing for road construction (on average 10 m, taking solar angle and exposure to wind into account)	Allouard, 1954b; Dykstra and Heinrich, 1996; Sist, 2000; Laurance and Gomez, 2005; Feldpausch <i>et al.</i> , 2005; Laurance <i>et al.</i> , 2009
Soil erosion (and the deterioration of water quality through sedimentation)	Adapt road routing to the topography (location on top of ridges and across slopes)	Allouard, 1954a; Le Ray, 1956; Esteve and Lepitre, 1972b; Pinard <i>et al.</i> , 1995; Dykstra and Heinrich, 1996
	Limit the road gradient and the length of downhill runs	Allouard, 1954b; Le Ray, 1956; Sessions, 2007; Ziegler <i>et al.</i> , 2007; Negishi <i>et al.</i> , 2008
	Ensure drainage through road camber, roadside ditches and cross-drains	Allouard, 1954b; Le Ray, 1956; Dykstra and Heinrich, 1996; Sist <i>et al.</i> , 1998; Sessions, 2007; Putz <i>et al.</i> , 2008
	Stabilize the road surface with laterite	Allouard, 1954a; Sessions, 2007
	Fitting road alignment to the terrain and good engineering practice to protect slopes (e.g. minimise high risk excavations of side slopes, and stabilise excavations where they cannot be avoided)	Allouard, 1954a; Le Ray, 1956; Dykstra and Heinrich, 1996; Sessions, 2007

Road-related environmental problems	Measures to reduce impacts	References
Physical alteration of streams	Limit amount of stream crossings	Le Ray, 1959; Clarke and Walsh, 2006
	Apply good engineering practice in building culverts, bridges and fords	Allouard, 1954a; Douglas, 2003; Sessions, 2007
	Place buffer zones around streams and wetlands	Pinard <i>et al.</i> , 1995; Sist <i>et al.</i> , 1998; Applegate <i>et al.</i> , 2004
Road kill and behaviour change of animals	Set and control speed limits	Allouard, 1954b; Laurance <i>et al.</i> , 2006, 2009; Sessions, 2007
	Ensure overhead canopy connections (green bridges)	Goosem, 2007; Sessions, 2007
	Set up road crossing infrastructure (signs, speed bumps, bridges, culverts)	Laurance <i>et al.</i> , 2009; Clements <i>et al.</i> , 2014
	Respect habitats of endangered species in road planning	van Vliet and Nasi, 2007; Clements <i>et al.</i> , 2014
	Limit number and weight of logging vehicles	Allouard, 1954b; Sessions, 2007
	Adapt roadside vegetation to animal preferences	Hoeven, 2010
Facilitation of hunting	Control access to currently used roads	Mason and Putz, 2001; van Vliet and Nasi, 2007; Edwards <i>et al.</i> , 2014b
	Close secondary roads after harvest with physical barriers and removal of stream crossings	Sist <i>et al.</i> , 1998; Applegate <i>et al.</i> , 2004; van Vliet and Nasi, 2007; Bicknell <i>et al.</i> , 2015a
	Prohibit the transport of hunters and bushmeat with logging vehicles	Robinson <i>et al.</i> , 1999; Wilkie <i>et al.</i> , 2000; Poulsen <i>et al.</i> , 2009
Agricultural colonization	Plan and regulate land-uses, provide alternatives for settlers	Dykstra and Heinrich, 1996; Chomitz and Gray, 1996; Mertens and Lambin, 2000; Laurance <i>et al.</i> , 2014

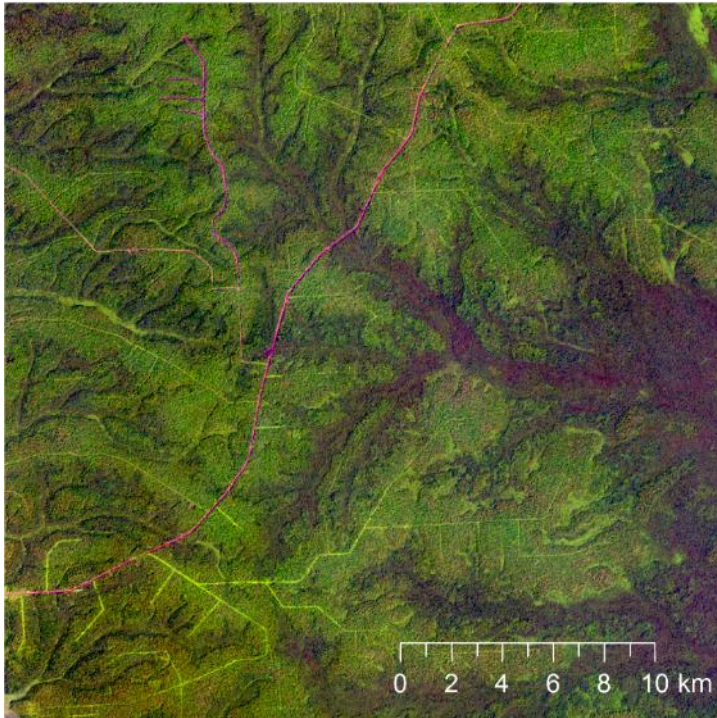
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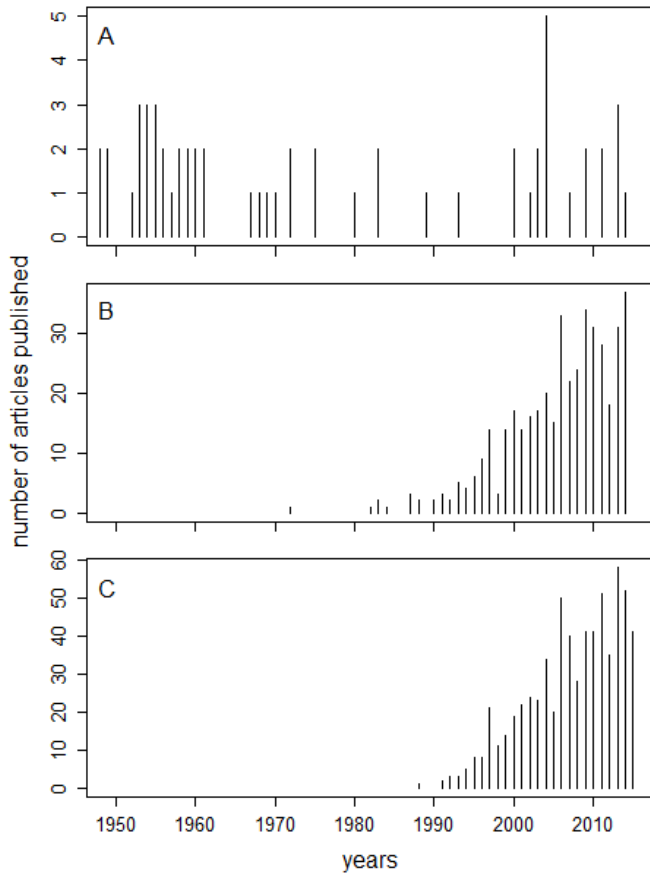
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1 **Figures**



2

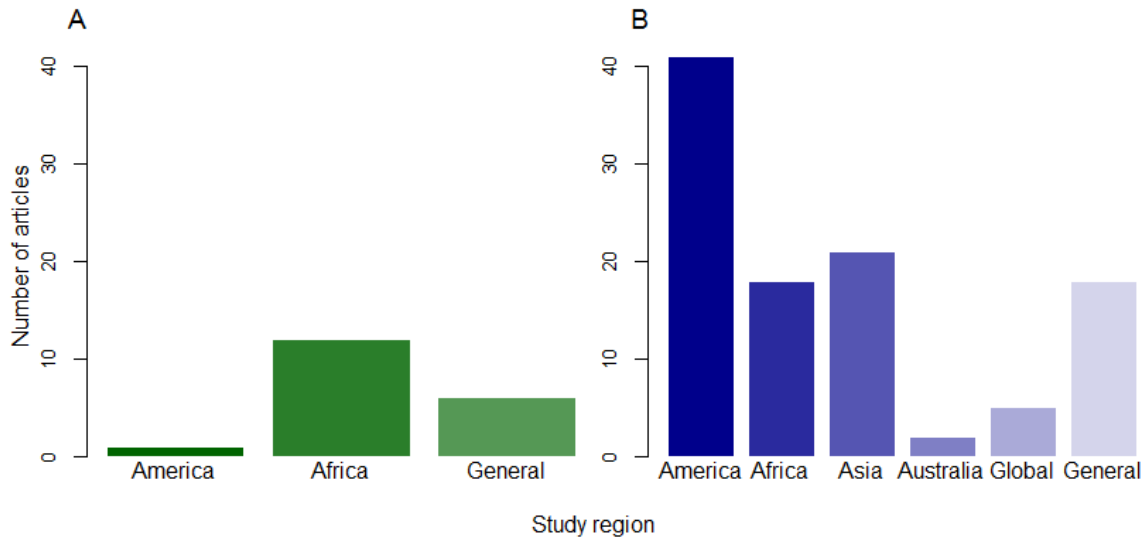
3 Figure 1. Logging roads in the Northern Republic of Congo. Red colour indicates bare soils
4 as on currently used roads; bright green indicates high photosynthetic activity as on
5 abandoned roads with recovering vegetation. Extract of a LANDSAT 8 image, dated 7th
6 January 2015.



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2 Figure 2: Number of articles obtained by search hits for logging roads in tropical forests
 3 (exact search strings are given in the text) in the databases of (A) *Bois et Forêts des*
 4 *Tropiques*, (B) Scopus and (C) ISI Web of Knowledge.

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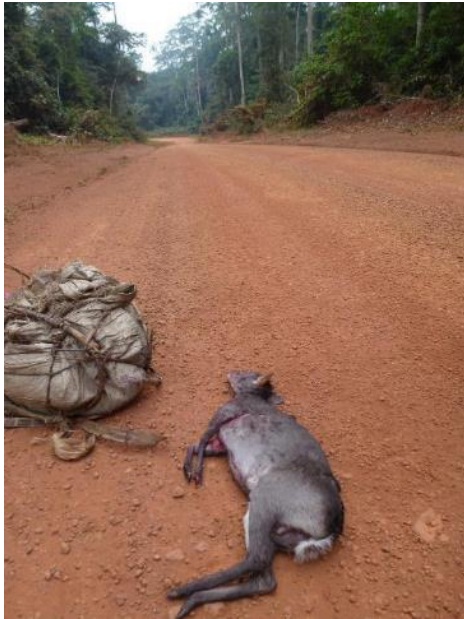


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 2 Figure 3. Regional focus of articles (number of articles per continent, if applicable) selected
 3 for critical appraisal, comparing articles in *Bois et Forêt des Tropiques* (A) with the English
 4 language literature (B). Global = Analyses carried out on a pantropical or global scale,
 5 General = General relevance without specific geographical reference.



6
 7 Figure 4. Newly constructed logging roads in south east Cameroon and northern Republic of
 8 Congo. Left: Primary road making permanent access to the forest. Right: secondary (dead-
 9 end) road built for temporary use to collect timber from log landings (here stored on the road
 10 side).

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2 Figure. 5. Hunted duiker along a logging road in Cameroon.



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4 Figure 6: Attempts to control access to the logging road network in a forest concession in
5 Cameroon. Left: Guarded barrier at the forest edge. Right: Logs placed on a secondary road
6 after harvest to block the access have been burned by hunters to gain access by motorcycle.

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2 Figure 7. Abandoned logging roads, closed with a log to block access one year after
3 exploitation in south east Cameroon (left) and with dense herb cover and regenerating trees
4 14 years after abandonment in northern Republic of Congo (right).

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