Current Biology

Report

Explosive growth of secondary roads is linked to widespread tropical deforestation

Highlights

- New roads in forest frontiers enable secondary roads that amplify human impacts
- We quantify secondary road expansion and its associated forest loss across the tropics
- Secondary road impacts were orders of magnitude larger than impacts of original roads
- Conservation planning and assessment must account for secondary roads and impacts

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In brief

Environmental impacts associated with roads—such as deforestation and land clearing—are often amplified for major roads in intact ecosystems as they enable secondary road expansion. Engert et al. quantify secondary road networks linked to major roads in tropical forest frontiers and the associated forest loss and degradation.

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Explosive growth of secondary roads is linked to widespread tropical deforestation

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SUMMARY

In the tropics and beyond, roads are key proximate drivers of environmental impacts, including forest fragmentation,[1,2] fires,[3] mining,[4,5] and land clearing.[6–8] Such impacts may be amplified for the initial roads constructed in intact forests—which we term “first-cut roads”—which often promote a rash of associated secondary roads branching off the new infrastructure.[9–13] These secondary roads in turn can dramatically elevate forest and biodiversity losses.[10,14,15] Although widely seen as a conservation concern,[12,15–17] the magnitude and effects of secondary road development have not been previously quantified. Without such information, impact assessment procedures for road projects risk misjudging the level of expected forest loss, hampering decision-making.[16,18–20] Here, we quantify the environmental impacts of both first-cut and secondary roads in three of the world’s major tropical regions where high-quality road maps have recently become available: the Brazilian Amazon, the Congo Basin, and New Guinea. We identified 92 first-cut roads across our study region for which we quantified the length of adjoining secondary roads and the area of related forest loss and degradation. On average, we found 4.8, 9.8, and 49.1 km of secondary road for every kilometer of first-cut road in the Congo Basin, New Guinea, and Brazilian Amazon regions, respectively. Forest loss and degradation associated with these secondary roads was remarkably heavy, being 31.5, 22.2, and 305.2 times greater, respectively, than that directly linked with first-cut roads. Our findings provide key insights into the potential scale and extent of forest loss and degradation that will emerge with proposed roads and development corridors in tropical forests.

RESULTS

Secondary roads

First-cut roads provide an important conduit for initial human incursions into natural habitats.[21,22] In this way, they can promote substantial planned or unplanned secondary road expansion and land colonization, particularly when exports of timber, minerals, and agricultural commodities are a motivating factor[23–26] (Figure 1). Therefore, while first-cut roads may not directly cause secondary road expansion (are not ultimate drivers), they are required for secondary road expansion to occur (necessary condition) and influence the locations in which it can occur (proximate driver).[24,27] An urgent priority is hence understanding whether and how secondary roads increase the environmental impacts of first-cut roads.

Here, we identify first-cut roads in the Brazilian Amazon, the Congo Basin, and New Guinea, and then use network analyses[28] to identify and determine the lengths of their associated secondary roads (Figure S1). We identified 92 examples of first-cut roads across the continental regions using satellite imagery and existing publications (Figure 1). We then used a modified version of the location-allocation method described in Cooper[28] to identify secondary roads stemming from first-cut roads, by separating out roads that originated from existing human settlements or from other major roads (STAR Methods; supplemental information).

Location-allocation analysis is used to identify the nearest source point—in our study, source points for roads and human impacts—while accounting for variable travel speeds or travel costs over different surface types. By using network analyses to identify source points for roads and human impacts, we are able to provide a more refined assessment of the length of secondary road and the area of related forest loss and degradation than using previous methods such as distance-decay (i.e., Tulloch et al.[29]) or buffer-distance models (i.e., Spencer et al.[30]).

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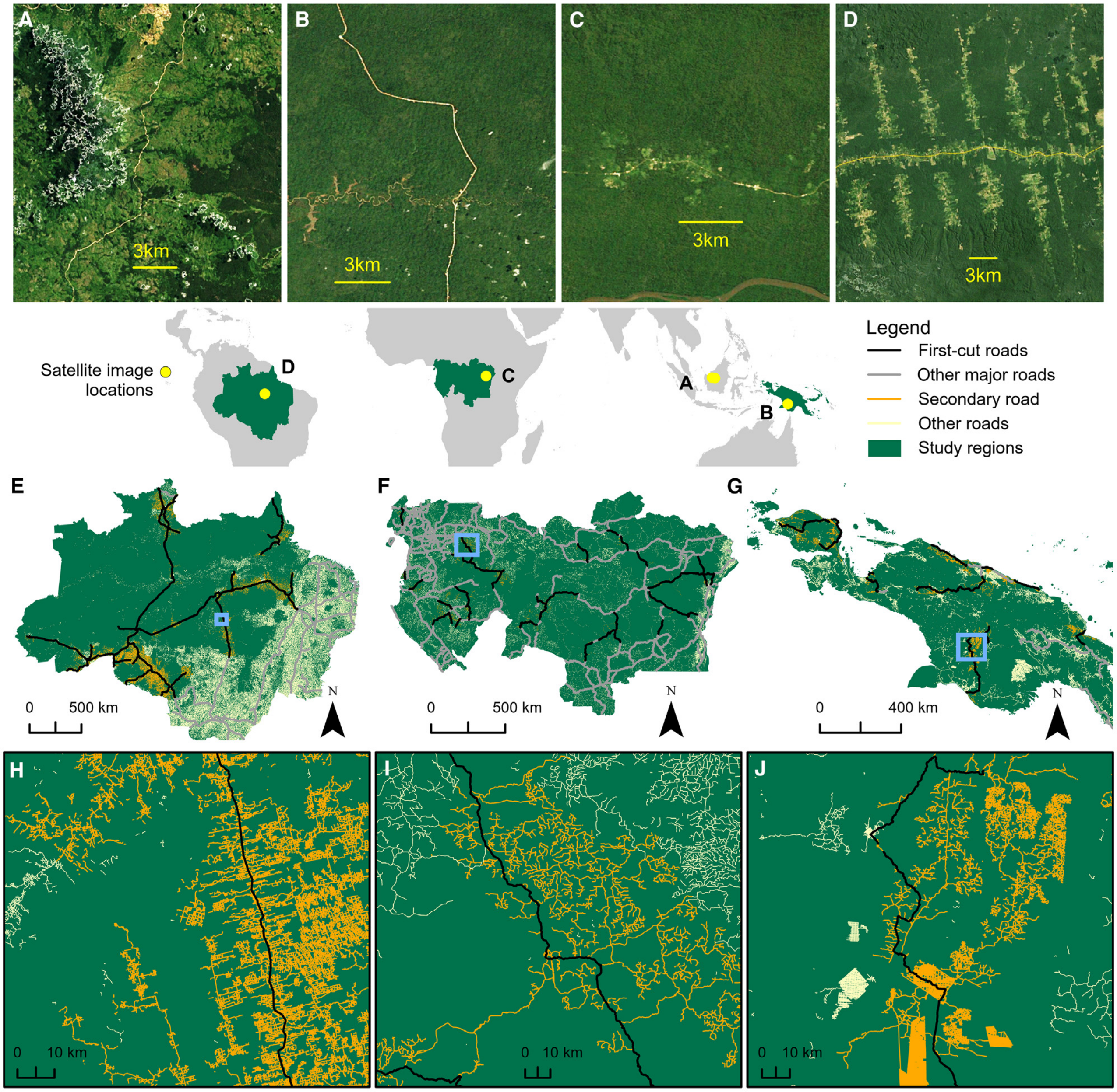

Figure 1. First-cut roads across the three continental regions assessed in this study—the Brazilian Amazon, the Congo Basin, and New Guinea

Top row shows satellite images from Google Earth (imagery circa 1984) demonstrating examples of: (A) a major road that was not considered a first-cut road due to existing anthropogenic disturbance, (B) a first-cut road in an area with no existing anthropogenic disturbance, (C) a first-cut road with minimal anthropogenic disturbance centered around the road, and (D) a first-cut road with some land colonization extending out from the road. The larger maps (E)–(G) show the study regions and locations of first-cut roads. Focal maps (H)–(J) show first-cut roads (black), secondary roads (orange), and independent roads (bright yellow) for example regions. Very dense road networks do not appear as lines but as areas because of pixel size.

See also Figure S1.

We found a substantial number of secondary roads stemming from first-cut roads, with considerable variation within and among the three continental regions (Figure 2). The Congo Basin had the lowest average length of secondary road, with a mean of 4.8 km of secondary road per 1 km of first-cut road (90% confidence interval [CI] = 0.1–16.9 km). New Guinea had a higher mean length of 9.8 km (90% CI = 3.7–19.6 km), while the Brazilian Amazon had a substantially higher mean length of 49.1 km of secondary road for every 1 km of first-cut road (90% CI = 1.0–139.3 km) (Table S5).

Secondary road impacts

After identifying secondary roads stemming from first-cut roads, we were able to quantify their associated forest loss and

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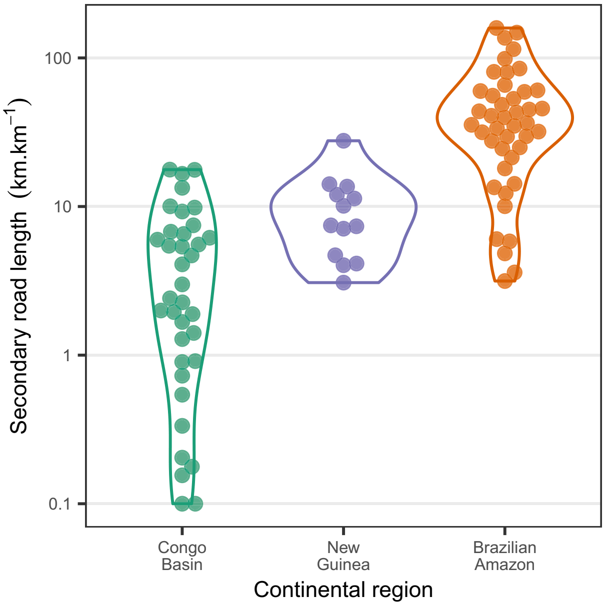

Figure 2. Length of secondary road constructed from each first-cut road in three of the world's major tropical forest frontiers

Length of secondary road for each first-cut road, normalized by first-cut road length (km.km^{-1}) and grouped by continental region.
See also Table S5.

degradation (see STAR Methods). For each of the three continental regions, we disentangled impacts arising from first-cut roads and from secondary roads, to evaluate their spatial footprints and overall environmental consequences. We separated these associated impacts into those in the construction footprint of the first-cut road (direct impacts), those associated with the first-cut road itself rather than secondary roads (indirect impacts, either <1 km from the first-cut road or closer to the first-cut road than to a secondary road), and those associated with secondary roads (secondary impacts, >1 km from the first-cut road and closer to a secondary road than a first-cut road) (Figure S1).

For all first-cut roads, the direct impacts were the smallest impact class (Figure 3). Indirect impacts were roughly an order of magnitude larger than the direct impacts in all three continental regions. Indirect impacts typically totaled 40–80 ha in area for every 1 km of first-cut road (means of 73.6 ha for the Congo Basin, 59.4 ha for the Brazilian Amazon, and 43.2 ha for New Guinea). The mean secondary impacts were even larger in extent, averaging 100.0 ha per 1 km of first-cut road for the Congo Basin, 222.0 ha for New Guinea, and 1,857.0 ha for the Brazilian Amazon (Table S6).

While secondary impacts were smallest in the Congo Basin, considering these when quantifying total first-cut road impacts resulted in a mean increase of 126.1%. The mean increase in impacts when considering secondary impacts was 399% for New Guinea and 2,826.5% for the Brazilian Amazon. Compared with the direct impacts alone, the total impacts of first-cut roads were on average 31.5 times higher in the Congo Basin, 22.2 times higher in New Guinea, and 305.2 times higher in the Brazilian Amazon. For the Brazilian Amazon and New Guinea, the total impacts of first-cut roads were correlated with the length of secondary road. This was not the case for the Congo Basin, however, where secondary road expansion is often driven by selective logging, which degrades forest but does not typically lead to widespread forest loss[31] (Figure S5).

When assessing the increase in human impacts through time, first-cut roads in the Brazilian Amazon and New Guinea show similar linear trajectories of increase (Figure S6). Such roads in the Congo Basin, however, have increased more slowly and intermittently, while accelerating in recent years. Such differences in trajectories might reflect regional differences in resource extraction intensity. Brazil and Indonesia, for instance, are major exporters of agricultural products, unlike most Congo Basin nations[32] (Figure S7).

Extent of human impacts

By classifying secondary roads and their associated impacts, we were able to determine the geographical area affected by first-cut roads and the distance over which their impacts occurred (see STAR Methods). Modeled impact extents of first-cut roads were substantially larger when considering their secondary roads and impacts than when considering only direct and indirect impacts (Figure 4). Human impacts were detectable at distances of up to 35.9, 17.7, and 68.0 km from first-cut roads in the Congo Basin, New Guinea, and the Brazilian Amazon, respectively (95% of all impacts occurred within these distances). If secondary roads are ignored, however, the impacts of first-cut roads extend just 3.9, 3.8, or 1.0 km from first-cut roads in the Congo Basin, New Guinea, and the Brazilian Amazon, respectively.

New Guinea had the smallest impact extent from roads, which is likely due to their concentration in industrial plantations and logging concessions near first-cut roads (i.e., Figure 1J). Conversely, in the Brazilian Amazon many secondary roads were largely constructed perpendicular to first-cut roads (i.e., Figure 1D). This creates a "fishbone" pattern of forest loss extending out from first-cut roads as a consequence of former government-sponsored forest colonization projects,[33] which sharply increases the spatial scale of environmental damage in the Brazilian Amazon.

DISCUSSION

Roads that penetrate frontier regions—so-called first-cut roads—can trigger a surge of secondary roads that can greatly amplify their environmental impacts. Such secondary roads are rapidly proliferating across much of the tropics, being on average 29 times greater in length than the first-cut roads from which they arose. Of even greater concern is that secondary roads are dramatically increasing the scale of forest disruption, provoking more than 150 times as much deforestation than did first-cut roads across our vast pantropical study area. We found, on average, that each kilometer of first-cut roads facilitated a total of 1,923 ha (90% CI = 192–5,149 ha) of human impacts in the Brazilian Amazon, 272 ha (76–742 ha) in New Guinea, and 186 ha (32–509 ha) in the Congo Basin.

Differences among regions

Secondary roads and their associated impacts varied greatly among regions, being highest in the Brazilian Amazon and lowest

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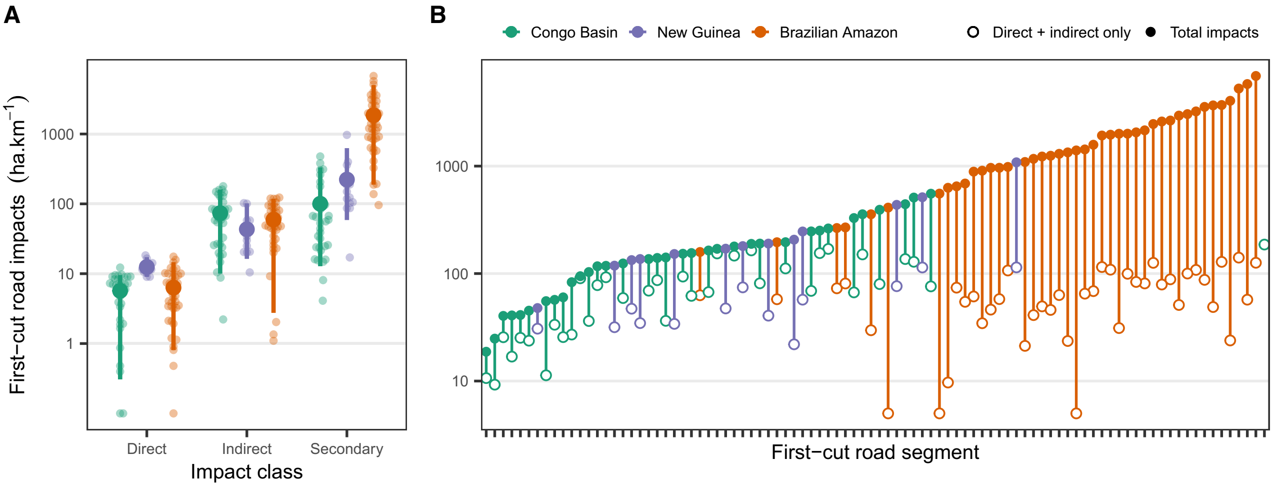

Figure 3. Human impacts facilitated by first-cut roads

(A) Mean impacted area (ha) for first-cut roads by impact class and continental region (bars indicate 5%–95% quantile range).

(B) Comparison between impact area when considering only direct and indirect impacts and when considering secondary impacts also (total impacts); longer lines indicate greater secondary impacts.

In (A), large dots represent mean values, and lines indicate the 5%–95% interquartile range.

See also Table S6 and Figures S5 and S7.

in the Congo Basin region. Such differences may reflect local environmental, political, or socioeconomic factors. New Guinea, for example, has steep mountainous regions that limit road construction and land conversion,[34,35] and first-cut roads in these areas had lesser impacts than did those in the flat lowlands. Conversely, the vast, flat basins of the Brazilian Amazon and Congo permit relatively easy and inexpensive road building, except in extensive flood-prone areas[36] where navigable rivers are often used for transportation (i.e., Reed and Miranda[37]).

Beyond their environmental differences, our three study regions also have many political, historical, and socioeconomic dissimilarities. High rates of forest loss in Brazil, for instance, have been driven by commodity agriculture and livestock production to supply international and domestic markets[38–41] (Figure S7). Notably, many of Brazil's current first-cut roads were built during the military dictatorship period of the 1960s and 1970s for the explicit purpose of promoting land colonization and commodity agriculture.[23]

Conversely, deforestation from large-scale agriculture is rare in the Congo Basin, which currently produces only modest agricultural exports.[32,38] Much of the forested land in the Congo is being used for industrial selective logging, which often generates dense networks of forest roads and degrades forests but leads to little outright deforestation[31,42,43] (Figure S5). However, the period over which reliable data is available also constrains these analyses. Certain areas in Central Africa were key production regions for oil palm and rubber during the former colonial period, but these areas are by now largely human-dominated and can no longer be assessed as "frontier" regions due to limited satellite imagery time frames.[44,45]

In New Guinea, road impacts were highly variable but generally lower than those in the Brazilian Amazon, as a consequence of the island's historically low levels of development. However, first-cut roads in New Guinea are currently promoting large areas of commodity agriculture (Figure S7). Beyond this, new megaprojects—such as massive palm oil and food estate projects in Indonesian Papua intended to supply domestic and export markets—are expected to increase road building and deforestation in the near future.[34,35]

Proliferating first-cut roads

Globally, new investments in roads and extractive industries are creating an unprecedented wave of first-cut roads in forested regions, especially in lower-income nations where development pressures are often intense.[21,46] Vast expanses of new roads are expected by mid-century from major infrastructure schemes such as China's Belt and Road Initiative,[47] the Programme for Infrastructure Development in Africa,[48] the Initiative for the Integration of Regional Infrastructure in South America,[49] and national programs in Indonesia,[35,50] Malaysia,[51] and Papua New Guinea,[34] among others. Many proposed road projects will penetrate areas with exceptional environmental and societal values, such as protected areas, key biodiversity areas,[52,53] and indigenous territories,[54] and may enable extensive networks of secondary roads and their associated forest loss and degradation.

The Congo Basin and New Guinea are expected to see rapid increases in industrial palm oil and pulpwood plantations and logging concessions.[55–57] In the Congo Basin, such concessions will likely be spurred by large-scale development corridors[48,52] that are likely to enable further secondary road expansion and forest loss. Similarly, New Guinea has a number of proposed development corridors, highways, and extractive industry megaprojects that are likely to dramatically expand secondary roads and forest disruption.[34,35] Large infrastructure projects in these and other tropical regions[49,50,58] are expected to imperil hundreds of conservation areas, intact-forest tracts, and indigenous territories while leading to globally significant carbon emissions.[49,51,52,54,59]

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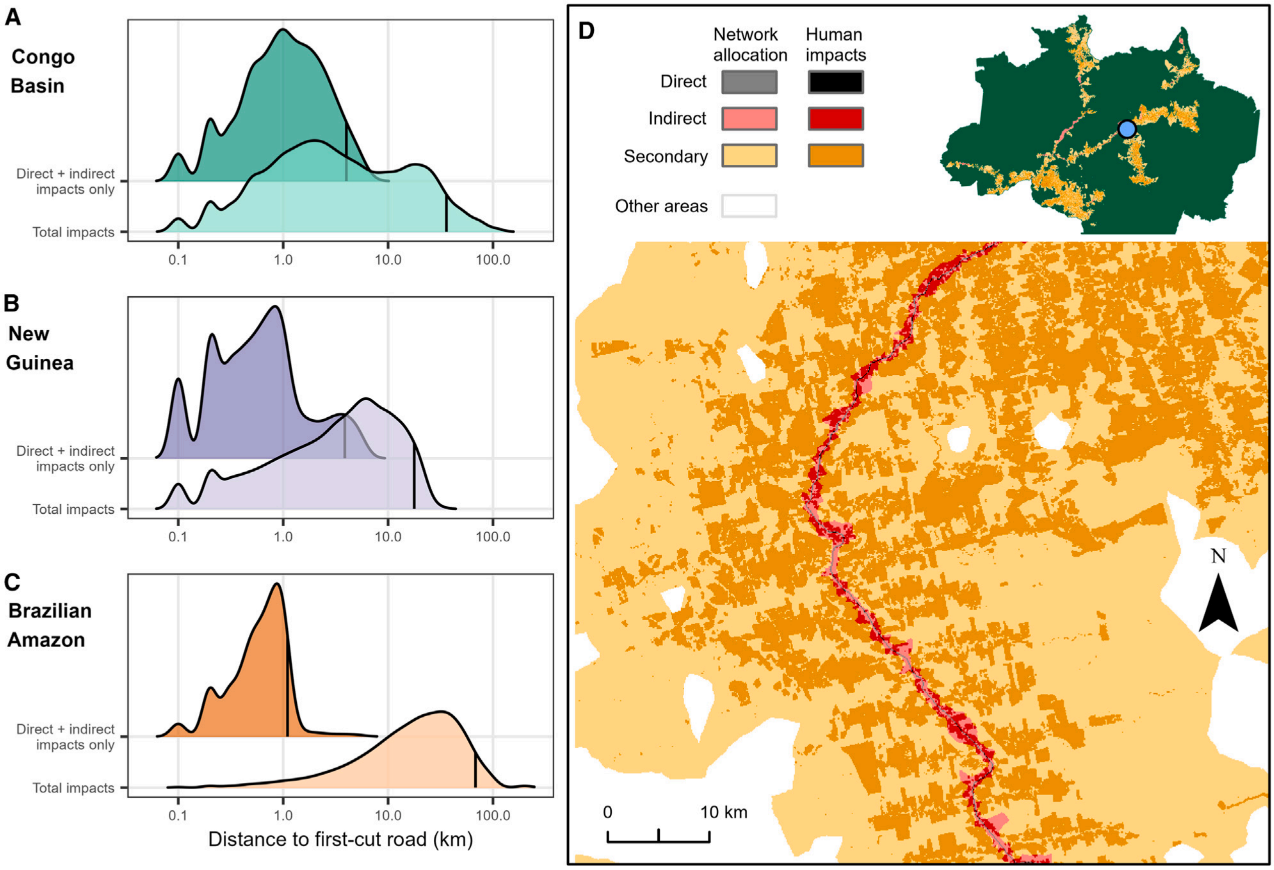

Figure 4. Relative density of human impacts by distance from first-cut roads for each continental region

(A–C) Relative density distributions of human impacts as a function of distance to first-cut roads in the three study regions are shown: (A) the Congo Basin, (B) New Guinea, and (C) the Brazilian Amazon.

(D) Map demonstrating the difference in impacted areas when considering secondary impacts. The "total impacts" distribution includes direct impacts, indirect impacts, and impacts associated with secondary roads. Impacts are aggregated across all first-cut roads. Vertical lines on density plots show 95% quantile values.

See also Figure S6.

Impact assessment and policy implications

Environmental impact assessment (EIA) procedures for road projects often focus on their direct effects[17,22,60–62] while ignoring their extensive secondary impacts, which can be massive in scope. For example, an EIA for a mining road in Sumatra, Indonesia suggested that 424 ha of forest would be lost during road construction—a far smaller total than the 3,000–6,000 ha of forest loss expected by scientists and activists.[20] While it is currently possible to estimate the indirect environmental impacts of first-cut roads (i.e., Engert et al.[20]), as yet there are no spatially resolved methods for modeling their often substantial secondary impacts.[29,52]

Infrastructure projects such as new roads can improve socioeconomic opportunities for rural and indigenous communities[63,64] but may also increase the vulnerability of such communities to land invasions, violence, and resource theft.[65–67] Refined estimates of the impacts of first-cut roads presented here could be used to inform future impact assessment procedures and identify projects with substantial environmental and socioeconomic risks that should be avoided.[49,62,68,69]

In this study, we used a novel mapping strategy to assess the source of ~3.85 million km of roads across the world's major tropical forest regions. This approach yielded a massive dataset; had we relied on human observers to manually classify these same roads, we would have needed an estimate of ~18,000 person-h,[8] a challenging figure. Clearly, road networks are temporally dynamic and can vary markedly in their lifespan and ecological impacts.[31,43,70] Further studies of frontier road dynamics are a top priority given the daunting scale and pace of their environmental and societal impacts.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Jayden E. Engert (engert_ecospatial@outlook.com).

Materials availability

This study did not generate new unique reagents.

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Data and code availability

- New Guinea road data have been deposited at Zenodo and are publicly available as of the date of publication at https://doi.org/10.5281/zenodo.14762338.
- Congo Basin road data have been deposited at ETH Research Collection and are publicly available as of the date of publication at https://www.research-collection.ethz.ch/handle/20.500.11850/342221.
- The Brazilian Amazon roads data reported in this study cannot be deposited in a public repository because they are copyrighted under the PrevisIA platform (https://previsia.org.br). To access the data, contact Dr. Carlos Souza Jr. at souzajr@imazon.org.br.
- Travel cost layers have been deposited at Zenodo and are publicly available as of the date of publication at https://doi.org/10.5281/zenodo.14762338.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.E.E. and W.F.L.; resources, J.E.E., C.M.S., F.K., F.Y.I., S.P.C., J.B., and I.N.; methodology, J.E.E.; analysis, J.E.E.; writing – original draft, J.E.E. and W.F.L.; writing – review & editing, J.E.E., W.F..L, C.M.S., F.K., and D.J.B.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
- METHOD DETAILS
  - ○ Identifying first-cut roads
  - ○ Network analyses
  - ○ Travel time
  - ○ Classifying human settlements
  - ○ Identifying secondary roads
  - ○ Classifying human impacts

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2025.02.017.

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REFERENCES

1. Goosem, M. (2007). Fragmentation impacts caused by roads through rainforests. Curr. Sci. *93*, 1587–1595.
2. Laurance, W.F., Camargo, J.L.C., Fearnside, P.M., Lovejoy, T.E., Williamson, G.B., Mesquita, R.C.G., Meyer, C.F.J., Bobrowiec, P.E.D., and Laurance, S.G.W. (2018). An Amazonian rainforest and its fragments as a laboratory of global change. Biol. Rev. Camb. Philos. Soc. *93*, 223–247.
3. Nepstad, D., Carvalho, G., Cristina Barros, A., Alencar, A., Paulo Capobianco, J., Bishop, J., Moutinho, P., Lefebvre, P., Lopes Silva, U., and Prins, E. (2001). Road paving, fire regime feedbacks, and the future of Amazon forests. Forest Ecol. Manag. *154*, 395–407.
4. Asner, G.P., Llactayo, W., Tupayachi, R., and Luna, E.R. (2013). Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring. Proc. Natl. Acad. Sci. USA *110*, 18454–18459.
5. Edwards, D.P., Sloan, S., Weng, L., Dirks, P., Sayer, J., and Laurance, W.F. (2014). Mining and the African environment. Conserv. Lett. *7*, 302–311.
6. Busch, J., and Ferretti-Gallon, K. (2017). What drives deforestation and what stops it? A meta-analysis. Rev. Environ. Econ. Policy *11*, 3–23.
7. Sales, M., De Bruin, S., Herold, M., Kyriakidis, P., and Souza, C., Jr. (2017). A spatiotemporal geostatistical hurdle model approach for short-term deforestation prediction. Spat. Stat. *21*, 304–318.
8. Engert, J.E., Campbell, M.J., Cinner, J.E., Ishida, Y., Sloan, S., Supriatna, J., Alamgir, M., Cislowski, J., and Laurance, W.F. (2024). Ghost roads and the destruction of Asia-Pacific tropical forests. Nature *629*, 370–375.
9. Fearnside, P.M., and de Alencastro Graça, P.M.L. (2006). BR-319: Brazil's Manaus-Porto Velho Highway and the Potential Impact of Linking the Arc of Deforestation to Central Amazonia. Environ. Manag. *38*, 705–716.
10. Fearnside, P.M. (2007). Brazil's Cuiabá- Santarém (BR-163) Highway: The Environmental Cost of Paving a Soybean Corridor Through the Amazon. Environ. Manag. *39*, 601–614.
11. Perz, S., Brilhante, S., Brown, F., Caldas, M., Ikeda, S., Mendoza, E., Overdevest, C., Reis, V., Reyes, J.F., Rojas, D., et al. (2008). Road building, land use and climate change: prospects for environmental governance in the Amazon. Philos. Trans. R. Soc. Lond. B Biol. Sci. *363*, 1889–1895.
12. Laurance, W.F., Goosem, M., and Laurance, S.G.W. (2009). Impacts of roads and linear clearings on tropical forests. Trends Ecol. Evol. *24*, 659–669.
13. Laurance, W.F., Peletier-Jellema, A., Geenen, B., Koster, H., Verweij, P., Van Dijck, P., Lovejoy, T.E., Schleicher, J., and Van Kuijk, M. (2015). Reducing the global environmental impacts of rapid infrastructure expansion. Curr. Biol. *25*, R259–R262.
14. Barber, C.P., Cochrane, M.A., Souza, C.M., Jr., and Laurance, W.F. (2014). Roads, deforestation, and the mitigating effect of protected areas in the Amazon. Biol. Conserv. *177*, 203–209.
15. Fearnside, P.M. (2015). Highway construction as a force in the destruction of the Amazon forest. In Handbook of Road Ecology (Wiley), pp. 414–424.
16. Fearnside, P.M. (1987). Deforestation and international economic development projects in Brazilian Amazonia. Conserv. Biol. *1*, 214–221.
17. Johnson, C.J., Venter, O., Ray, J.C., and Watson, J.E.M. (2020). Growth-inducing infrastructure represents transformative yet ignored keystone environmental decisions. Conserv. Lett. *13*, e12696.
18. Holden, C. (1987). World Bank launches new environment policy: bringing the environment to the center of policy concerns will take some doing, given the powerful influence of conventional economic thinking. Science *236*, 769.
19. Laurance, W.F., Cochrane, M.A., Bergen, S., Fearnside, P.M., Delamônica, P., Barber, C., D'Angelo, S., and Fernandes, T. (2001). Environment. The future of the Brazilian Amazon. Science *291*, 438–439.
20. Engert, J.E., Ishida, F.Y., and Laurance, W.F. (2021). Rerouting a major Indonesian mining road to spare nature and reduce development costs. Conserv. Sci. Pract. *3*, e521.
21. Laurance, W.F., Clements, G.R., Sloan, S., O'Connell, C.S., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., et al. (2014). A global strategy for road building. Nature *513*, 229–232.

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22. Laurance, W.F., and Arrea, I.B. (2017). Roads to riches or ruin? Science *358*, 442–444.
23. Frohn, R.C., Dale, V.H., and Jimenez, B.D. (1990). Colonization, Road Development and Deforestation in the Brazilian Amazon Basin of Rondonia. No. ORNL/TM-11470) (Oak Ridge National Lab. [ORNL]).
24. Geist, H.J., and Lambin, E.F. (2002). Proximate causes and underlying driving forces of tropical deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. BioScience *52*, 143–150.
25. Seibert, J. (2011). More continuity than change? New forms of unfree labor in the Belgian Congo, 1908-1930. In Humanitarian Intervention and Changing Labor Relations (Brill), pp. 369–386.
26. Rodney, W. (2018). How Europe Underdeveloped Africa (Verso Books).
27. Brennan, A. (2003). Necessary and Sufficient Conditions (Stanford Encyclopedia of Philosophy). https://plato.stanford.edu/entrieS/necessary-sufficient/.
28. Cooper, L. (1963). Location-allocation problems. Oper. Res. *11*, 331–343.
29. Tulloch, A.I.T., Gordon, A., Runge, C.A., and Rhodes, J.R. (2019). Integrating spatially realistic infrastructure impacts into conservation planning to inform strategic environmental assessment. Conserv. Lett. *12*, e12648.
30. Spencer, K.L., Deere, N.J., Aini, M., Avriandy, R., Campbell-Smith, G., Cheyne, S.M., Gaveau, D.L.A., Humle, T., Hutabarat, J., Loken, B., et al. (2023). Implications of large-scale infrastructure development for biodiversity in Indonesian Borneo. Sci. Total Environ. *866*, 161075.
31. Kleinschroth, F., Laporte, N., Laurance, W.F., Goetz, S.J., and Ghazoul, J. (2019). Road expansion and persistence in forests of the Congo Basin. Nat. Sustain. *2*, 628–634.
32. Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos Lima, M.G., Baumann, M., Curtis, P.G., De Sy, V., et al. (2022). Disentangling the numbers behind agriculture-driven tropical deforestation. Science *377*, eabm9267.
33. Alves, M.T.R., Piontekowski, V.J., Buscardo, E., Pedlowski, M.A., Sano, E.E., and Matricardi, E.A.T. (2021). Effects of settlement designs on deforestation and fragmentation in the Brazilian Amazon. Land Use Policy *109*, 105710.
34. Alamgir, M., Sloan, S., Campbell, M.J., Engert, J., Kiele, R., Porolak, G., Mutton, T., Brenier, A., Ibisch, P.L., and Laurance, W.F. (2019b). Infrastructure expansion challenges sustainable development in Papua New Guinea. PLoS One *14*, e0219408.
35. Sloan, S., Campbell, M.J., Alamgir, M., Engert, J., Ishida, F.Y., Senn, N., Huther, J., and Laurance, W.F. (2019a). Hidden challenges for conservation and development along the Trans-Papuan economic corridor. Environ. Sci. Policy *92*, 98–106.
36. Douven, W., and Buurman, J. (2013). Planning practice in support of economically and environmentally sustainable roads in floodplains: the case of the Mekong delta floodplains. J. Environ. Manage. *128*, 161–168.
37. Reed, E., and Miranda, M. (2007). Assessment of the mining sector and infrastructure development in the Congo Basin region, *27* (World Wildlife Fund, Macroeconomics for Sustainable Development Program Office). https://wwf.panda.org/wwf_news/?99440/Assessment-of-the-Mining-Sector-and-Infrastructure-Development-in-the-Congo-Basin-Region.
38. Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., and Hansen, M.C. (2018). Classifying drivers of global forest loss. Science *361*, 1108–1111.
39. Pendrill, F., Persson, U.M., Godar, J., and Kastner, T. (2019a). Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environ. Res. Lett. *14*, 055003.
40. Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S., and Wood, R. (2019b). Agricultural and forestry trade drives large share of tropical deforestation emissions. Glob. Environ. Change *56*, 1–10.
41. Hoang, N.T., and Kanemoto, K. (2021). Mapping the deforestation footprint of nations reveals growing threat to tropical forests. Nat. Ecol. Evol. *5*, 845–853.
42. Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S., and Goetz, S.J. (2007). Expansion of industrial logging in Central Africa. Science *316*, 1451.
43. Kleinschroth, F., Healey, J.R., Sist, P., Mortier, F., and Gourlet-Fleury, S. (2016). How persistent are the impacts of logging roads on Central African forest vegetation? J. Appl. Ecol. *53*, 1127–1137.
44. Marchal, J. (2017). Lord Leverhulme's Ghosts: Colonial Exploitation in the Congo (Verso Books).
45. Wong, G.Y., Holm, M., Pietarinen, N., Ville, A., and Brockhaus, M. (2022). The making of resource frontier spaces in the Congo Basin and Southeast Asia: A critical analysis of narratives, actors and drivers in the scientific literature. World Dev. Perspect. *27*, 100451.
46. Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., and Hall, J.W. (2019). Infrastructure for sustainable development. Nat. Sustain. *2*, 324–331.
47. Ascensão, F., Fahrig, L., Clevenger, A.P., Corlett, R.T., Jaeger, J.A.G., Laurance, W.F., and Pereira, H.M. (2018). Environmental challenges for the Belt and Road Initiative. Nat. Sustain. *1*, 206–209.
48. Thorn, J.P.R., Bignoli, D.J., Mwangi, B., and Marchant, R.A. (2022). The African Development Corridors Database: a new tool to assess the impacts of infrastructure investments. Sci. Data *9*, 679.
49. Vilela, T., Malky Harb, A., Bruner, A., Laísa da Silva Arruda, V., Ribeiro, V., Auxiliadora Costa Alencar, A., Julissa Escobedo Grandez, A., Rojas, A., Laina, A., and Botero, R. (2020). A better Amazon road network for people and the environment. Proc. Natl. Acad. Sci. USA *117*, 7095–7102.
50. Alamgir, M., Campbell, M.J., Sloan, S., Suhardiman, A., Supriatna, J., and Laurance, W.F. (2019). High-risk infrastructure projects pose imminent threats to forests in Indonesian Borneo. Sci. Rep. *9*, 140.
51. Sloan, S., Campbell, M.J., Alamgir, M., Lechner, A.M., Engert, J., and Laurance, W.F. (2019). Trans-national conservation and infrastructure development in the Heart of Borneo. PLoS One *14*, e0221947.
52. Laurance, W.F., Sloan, S., Weng, L., and Sayer, J.A. (2015). Estimating the environmental costs of Africa's massive "development corridors". Curr. Biol. *25*, 3202–3208.
53. Sloan, S., Bertzky, B., and Laurance, W.F. (2017). African development corridors intersect key protected areas. Afr. J. Ecol. *55*, 731–737.
54. Estrada, A., Garber, P.A., Gouveia, S., Fernández-Llamazares, Á., Ascensão, F., Fuentes, A., Garnett, S.T., Shaffer, C., Bicca-Marques, J., Fa, J.E., et al. (2022). Global importance of Indigenous Peoples, their lands, and knowledge systems for saving the world's primates from extinction. Sci. Adv. *8*, eabn2927.
55. Pallares, G., and Ngeunga, M. (2021). DRC: A Polluting Palm Oil Business is Shaming European Development Banks (InfoCongo). https://infocongo.org/en/drc-a-polluting-palm-oil-business-is-shaming-european-development-banks/.
56. Blaise, A. (2023). Asian demand for timber to intensify pressure on Central Africa's forests (Forest News). https://forestsnews.cifor.org/80672/asian-demand-for-timber-to-intensify-pressure-on-central-africas-forests?fnl=.
57. Bokanga, M. (2024). Congo: The Next Frontier for the Palm Oil Industry. In Elaeis guineensis - New Insights (IntechOpen).
58. Kaszta, Ż., Cushman, S.A., Htun, S., Naing, H., Burnham, D., and Macdonald, D.W. (2020). Simulating the impact of Belt and Road initiative and other major developments in Myanmar on an ambassador felid, the clouded leopard, *Neofelis nebulosa*. Landsc. Ecol. *35*, 727–746.
59. Houghton, R.A., House, J.I., Pongratz, J., Van Der Werf, G.R., Defries, R.S., Hansen, M.C., Le Quéré, C., and Ramankutty, N. (2012). Carbon emissions from land use and land-cover change. Biogeosciences *9*, 5125–5142.
60. Karlson, M., Mörtberg, U., and Balfors, B. (2014). Road ecology in environmental impact assessment. Environ. Impact Assess. Rev. *48*, 10–19.
61. Jaeger, J.A.G. (2015). Improving Environmental Impact Assessment and Road Planning at the Landscape Scale. In Handbook of Road Ecology, R. van der Ree, D.J. Smith, and C. Grilo, eds. (John Wiley & Sons), pp. 32–42.

62. Juffe-Bignoli, D., Burgess, N.D., Hobbs, J., Smith, R.J., Tam, C., Thorn, J.P.R., and Bull, J.W. (2021). Mitigating the impacts of development corridors on biodiversity: a global review. Front. Ecol. Evol. *9*, 683949.
63. Hettige, H. (2006). When Do Rural Roads Benefit the Poor and How? An In-Depth Analysis Based on Case Studies (Asian Development Bank).
64. Clements, G.R., Aziz, S.A., Bulan, R., Giam, X., Bentrupperbaumer, J., Goosem, M., Laurance, S., and Laurance, W.F. (2018). Not everyone wants roads: Assessing indigenous people's support for roads in a globally important tiger conservation landscape. Hum. Ecol. *46*, 909–915.
65. Davis, M. (2002). Late Victorian Holocausts: el Niño Famines and the Making of the Third World (Verso Books).
66. Hecht, S.B., and Cockburn, A. (2010). The Fate of the Forest: Developers, Destroyers, and Defenders of the Amazon (University of Chicago Press).
67. Laltaika, E.I., and Askew, K.M. (2021). Modes of dispossession of indigenous lands and territories in Africa. In Lands of the Future: Anthropological Perspectives on Pastoralism, Land Deals and Tropes of Modernity in Eastern Africa, E.C. Gabbert, F. Gebresenbet, J.G. Galaty, and G. Schlee, eds. (Berghahn Books), pp. 99–122.
68. Laurance, W.F. (2018a). Conservation and the global infrastructure tsunami: Disclose, debate, delay! Trends Ecol. Evol. *33*, 568–571.
69. Laurance, W.F. (2018b). If you can't build well, then build nothing at all. Nature *563*, 295.
70. Ahmed, S.E., Souza, C.M., Riberio, J., and Ewers, R.M. (2013). Temporal patterns of road network development in the Brazilian Amazon. Reg. Environ. Change *13*, 927–937.
71. Botelho, J., Jr., Costa, S.C.P., Ribeiro, J.G., and Souza, C.M., Jr. (2022). Mapping roads in the Brazilian Amazon with artificial intelligence and Sentinel-2. Remote Sens. *14*, 3625.
72. OpenStreetMap contributors (2022). OpenStreetMap Data Extracts (GeoFabrik). https://download.geofabrik.de/.
73. Allen, G.H., and Pavelsky, T.M. (2018). Global extent of rivers and streams. Science *361*, 585–588.
74. Jarvis, A. (2008). Hole-filed seamless SRTM data. http://srtm.csi.cgiar.org.
75. Gumbricht, T., Román-Cuesta, R.M., Verchot, L.V., Herold, M., Wittmann, F., Householder, E., Herold, N., and Murdiyarso, D. (2017). Tropical and subtropical wetlands distribution version 2 (Center for International Forestry Research [CIFOR]). https://data.cifor.org/dataset.xhtml?persistentId=doi:10.17528/CIFOR/DATA.00058.
76. ESA (2017). Land Cover CCI Product User Guide Version 2 Tech. Rep. maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf.
77. Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., et al. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. BioScience *51*, 933–938.
78. Rose, A., McKee, J., Sims, K., Bright, E., Reith, A., and Urban, M. (2021). LandScan Global 2020 (Oak Ridge National Laboratory).
79. Vancutsem, C., Achard, F., Pekel, J.F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., and Nasi, R. (2021). Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. Sci. Adv. *7*, eabe1603.
80. Haklay, M., and Weber, P. (2008). Openstreetmap: User-generated street maps. IEEE Pervasive Comput. *7*, 12–18.
81. El-Ashmawy, K.A. (2016). Testing the positional accuracy of OpenStreetMap data for mapping applications. Geod. Cartogr. *42*, 25–30.
82. Brovelli, M.A., and Zamboni, G. (2018). A new method for the assessment of spatial accuracy and completeness of OpenStreetMap building footprints. ISPRS Int. J. Geo Inf. *7*, 289.
83. Zhou, Q., and Lin, H. (2019). Investigating the completeness and omission roads of OpenStreetMap data in Hubei, China by comparing with Street Map and Street View. Preprint at arXiv.
84. Voss, P.R., and Chi, G. (2006). Highways and population change. Rural Sociol. *71*, 33–58.
85. Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., et al. (2018). A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature *553*, 333–336.
86. Nunes, C.A., Berenguer, E., França, F., Ferreira, J., Lees, A.C., Louzada, J., Sayer, E.J., Solar, R., Smith, C.C., Aragão, L.E.O.C., et al. (2022). Linking land-use and land-cover transitions to their ecological impact in the Amazon. Proc. Natl. Acad. Sci. USA *119*, e2202310119.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Major road locations	This paper, STAR Methods	https://www.openstreetmap.org/
New Guinea roads	Engert et al.[8]	See Table S1; https://doi.org/10.5281/zenodo.14762338
Congo Basin roads	Kleinschroth et al.[31]	https://www.research-collection.ethz.ch/handle/20.500.11850/342221?locale-attribute=de
Brazilian Amazon roads	Botelho et al.[71]	https://previsia.org.br/
Supplemental roads	OpenStreetMap[72]	https://www.openstreetmap.org/
Waterways	Allen and Pavelsky[73]	https://zenodo.org/records/1297434#.YfGIXf7MLcu
Topographic slope	Jarvis[74]	http://srtm.csi.cgiar.org
Wetlands	Gumbricht et al.[75]	https://data.cifor.org/dataset.xhtml?persistentId=doi:10.17528/CIFOR/DATA.00058
Remotely-sensed vegetation type	ESA[76]	https://www.esa-landcover-cci.org/
WWF Ecoregion	Olson et al.[77]	https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world
Open Street Map buildings	OpenStreetMap contributors[72]	https://www.openstreetmap.org/
Human population density	Landscan[78]	https://landscan.ornl.gov/
Human impacts	Vancutsem et al.,[79] Table S4	https://forobs.jrc.ec.europa.eu/TMF
Software and algorithms		
R software	N/A	https://www.r-project.org/
ArcGIS	N/A	https://www.arcgis.com/index.html

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

We identified examples of ‘first-cut’ roads across the worlds major tropical forest ‘frontiers’: the Amazon and Congo Basins and the island of New Guinea. A road was considered a ‘first-cut’ road if it met the following criteria:

1. The road was considered a ‘major’ road such as a national highway, motorway, or primary road;
2. The road was constructed in a landscape that had not yet experienced significant human invasion and modification.

We identified 92 ‘first-cut’ roads across our study region: 13 in New Guinea, 33 in the Congo Basin, and 46 in the Brazilian Amazon. For each first-cut road, we identified secondary road which had been constructed from the first-cut road as a source and calculated the length of said secondary road. We then delineated and classified human impacts (forest loss and degradation) associated with the first-cut road itself and the connected secondary road.

All data used are detailed in the key resources table.

METHOD DETAILS

Our study methodology consists of four key steps: (1) identifying first-cut roads; (2) developing network analyses; (3) identifying and measuring secondary road length; and (4) classifying and quantifying human impacts (Figure S1).

Our study area covers the island of New Guinea, Congo Basin, and Brazilian Amazon (Figure 1). The study area was selected based on complete coverage of recent, high-quality road data. For the spatial unit of analysis, travel time and network analyses were conducted at 1 ha resolution, and human impacts were also quantified at this spatial resolution. The analyses did not include an explicit temporal component, though human impact data was based on landcover changes identifiable in satellite imagery that started in circa 1985, and first-cut roads were included that were constructed within the last ∼100 years.

Identifying first-cut roads

To identify first-cut roads and classify and quantify their secondary road and impacts on forest loss and degradation we selected study regions that complied with three key criteria: (1) have high-quality, updated road maps available, (2) have experienced large-scale anthropogenic landscape conversion predominantly within recent decades, and (3) have experienced rapid land

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colonization and conversion within this period or are expected to in the future. Based on these criteria, we identified the Brazilian Amazon, Congo Basin, and island of New Guinea as important study regions.

We defined "first-cut roads" as major roads (trunk roads, motorways, highways, or primary roads) that were constructed in landscapes that had not yet experienced significant human invasion and modification. Therefore, major roads that were constructed in landscapes that had already experienced notable human modification, for example conversion for perennial agriculture, were not considered first-cut roads. For New Guinea and the Congo Basin, major roads were identified using the aforementioned road classes in the Open Street Map database. Open Street Map data is compiled from a variety of sources including official government data, data provided by non-governmental organisations, and an open-source global mapping community.[80] While Open Street Map data has been shown to be incomplete in some regions (i.e. Engert et al.[8]), it typically achieves a high degree of spatial precision[81,82] and often more complete in the major road classes from which we drew 'first-cut' roads (i.e. Zhou and Lin[83]). For the Brazilian Amazon we considered national highways with BR classification to be major roads, which included some "secondary" roads in frontier regions (i.e. BR-230). We determined which major roads could be considered 'first-cut roads' using satellite imagery accessed through Google Earth (Figure 1) and published information (i.e. Fearnside[10]), and hence focused on roads constructed in the last 100 years. These major roads were then separated into discrete "first-cut road" units by splitting at intersections and existing human settlements. To exclude small line segments and small link roads, first-cut roads were excluded from analyses if they were less than 40km long. Our dataset included 13 first-cut roads in New Guinea, 33 in the Congo Basin, and 46 in the Brazilian Amazon.

Network analyses

We used network analyses, specifically a form of location allocation analysis,[28] to identify both secondary roads and related deforestation and forest degradation. Location allocation analysis is a modified version of Euclidean allocation that includes a friction surface to identify the nearest source point while accounting for variable travel speeds or travel costs over different surface types. In our assessment, we created a travel cost layer for use as the friction surface, and considered settlements and major roads to be source points for minor roads, and settlements, all roads, and rivers to be source points for human impacts. As road expansion and forest loss and degradation are primarily dependent on human populations and enabled by roads, our network analyses required accurate information on road networks and human settlements.

Firstly, we developed high-accuracy road and settlement maps using the best available data for each region. For roads in New Guinea we used the "ghost roads" dataset described in Engert et al.[8]; for the Brazilian Amazon we used the AI-detected road dataset described in Botelho et al.[71]; and for the Congo Basin we used the road dataset described in Kleinschroth et al.[31] As both Engert et al.[8] and Kleinschroth et al.[31] relied on inconsistent freely-available satellite imagery, they were also supplemented with the most recent Open Street Map data by selecting and appending any OSM roads not included in the aforementioned datasets. All roads that were not classed as major roads as above (BR- designated roads in the Brazilian Amazon; trunk, motorway, highway, or primary road classes in New Guinea and the Congo Basin) were considered 'minor' roads from which we identified secondary roads. Our human settlement layer was created using both Landscan population density maps[78] and Open Street Map building locations[72] to account for any gaps in either of these datasets (supplemental information). As with the road data, Open Street Map building data is incomplete in many regions, but often includes buildings not present in official government data (i.e. Brovelli and Zamboni[82]) or remotely-sensed population density maps (from visual inspection).

We then used the high-accuracy road maps to identify discrete, inter-connected road networks. To do this, we created road presence raster layers at 1 -km resolution and identified discrete networks of connected roads using the Region Group tool with 8-cell neighbourhood in Arcmap 10.8. We chose the 1 -km resolution to account for small gaps in road shapefiles that may occur due to slight inaccuracies in mapping or road detection. The discrete networks were then converted from raster to polygons, and we identified those that were within 2 -km of a first-cut road and considered these to be connected to the first-cut road. This 2 -km distance was selected to account for small gaps in road shapefiles that may be due to mapping inaccuracies or gaps introduced in the data cleaning steps. Secondary roads could henceforth only be identified from those road networks connected to a first-cut road.

As first-cut-road-associated land-colonisation may result in the development of new human settlements, we then classified human settlements as either dependent on first-cut roads, or independent of first-cut roads. Independent settlements are those that were present before the first-cut road was constructed (supplemental information) or are not connected to the first-cut road by minor road networks, while dependent settlements are those connected to the first-cut road and established after its construction (supplemental information). While existing settlements may increase in size and population due to the increased access provided by a first-cut road,[84] we opted to ignore this effect in order to provide a more conservative estimate of the impacts of first-cut roads.

These initial data preparation steps allowed us to develop a robust network analysis workflow to identify secondary roads and impacts. For the network analyses, we considered human settlements and major roads to be source points for minor roads; and settlements, roads, and rivers to be source points for forest loss and degradation. To account for differences in travel cost over different surface types, we created a travel time map to use as a friction surface (Tables S1–S3). The travel time map was created using a modified version of the methods outlined in Weiss et al.[85] and Engert et al.[20] that estimates travel time based on pre-clearing vegetation cover, topography, waterways, and roads. Travel times from source locations were created using the Cost Distance tool in Arcmap 10.8.

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Travel time

To estimate travel time for the study regions (New Guinea, Brazilian Amazon, Congo Basin) we used a method developed from an adaption of Weiss et al.[85] and Engert et al.[20] Our adapted travel time map used information on vegetation type, slope, road locations, and waterways (Tables S1 and S2). Contrary to Weiss et al.,[85] we did not use information on current land-cover type or anthropogenic land-cover types, rather we attempted to estimate travel times prior to conversion to anthropogenic land-uses. To accomplish this, we created a map of pre-human-modification vegetation types (Table S3) using a variety of published spatial datasets. Travel times for roads were taken from the reported maximum travel speed in OpenStreetMap when available, and estimated based on road class when maximum speed was not available (Table S2). All travel speeds and travel times were converted to minutes per meter travel time before creating the maps.

In order to develop network allocation models to identify the sources of both minor roads and human impacts (deforestation and degradation), we developed three separate travel time maps. The first map, used to identify the source of minor roads, was created while excluding major roads in order to identify the travel time to minor roads if the major roads were not present (major roads used as a source, rather than a component of the map). The second and third maps, used to identify the source of human impacts, included all road types (major and minor). The second map was created to identify sources of human impacts associated with land-based travel (roads and settlements as sources) and hence considered waterways to be a barrier to movement. Finally, the third map was created to identify sources of human impacts associated with water-based travel and hence considered waterways to be conduits of movement.

Classifying human settlements

We created maps of human settlements by combining Landscan population density maps[78] with Open Street Map building locations.[72] Settled cells were identified from Landscan maps by rescaling the map to 1 ha resolution and reclassifying the population density map as either settled (1) or not settled (0) using a cut-off of 4 people per hectare. We then identified settlements (defined as groups of settled cells) by calculating the proportion of cells within a 1km neighbourhood that were settled and classifying all areas with >20% of the neighbourhood settled as a 'settlement'. Similarly, we converted Open Street Map building locations to a building presence layer at 1 ha resolution, and classified all areas with more than 20% of cells containing buildings within a 1 km neighbourhood as being settlements.

To identify settlements dependent on first-cut roads, we first used the network analyses to identify settlements that were both (1) linked to first-cut roads through the road network, and (2) more accessible by first-cut roads than other major roads. We then used satellite imagery (including high-resolution imagery and timeseries Landsat imagery) accessed through Google Earth, information available from published sources and grey literature (e.g. Wikipedia), and expert assessment from paper authors, to identify which of these settlements appeared after the construction of the nearest first-cut road and which appeared before (Figure S2). High resolution and Landsat imagery was used to confirm settlement locations and Landsat timeseries imagery was used alongside published and grey literature to identify time of emergence. Settlements that were connected to the first-cut road, more accessible via first-cut road than other major roads, and that appeared after first-cut road construction were considered dependent on the first-cut road, all other settlements were considered independent (Figure S3).

Identifying secondary roads

We used the above outlined network analyses to identify secondary roads stemming from first-cut roads. We considered secondary roads to be those minor roads that were (1) part of a network directly connected to the first-cut road, (2) had a lower travel time (by 20 mins or more) from first-cut roads than from independent settlements, and (3) had a lower travel time from first-cut roads than from other major roads. We therefore created travel time maps using as starting points (1) first-cut roads, (2) other major roads, and (3) independent settlements, and calculated the minimum travel time for each minor road across each of the three travel time maps using the Zonal Statistics tool in Arcmap 10.8. This allowed us to identify minor roads for which the travel time was lower from first-cut roads than from other major roads or independent settlements. We conducted visual inspections across the road networks to ensure these classifications were reasonable. After identifying secondary roads, we determined their first-cut road source using the Cost Allocation tool in Arcmap 10.8, and summed the total length of secondary-road for each first-cut road.

Classifying human impacts

We used a similar process to classify impacts as was used to classify secondary road. To identify 'human impacts', we first classified Vancutsem et al.[79] land-cover change data as 'human impacted' or not at the original raster resolution (Table S4), then aggregated to 1 ha resolution by calculating the proportion of each cell that had experienced human impacts. The Vancutsem et al.[79] dataset captures a wide range of impacts including complete deforestation, logging, and fires, and we developed a classification scheme that aimed to separate human impacts from natural disturbances, such as river inundation. The Vancutsem et al.[79] dataset, which assesses Landsat imagery for the period 1982-2021, also includes various classes of 'forest regrowth' which they classify as a form of forest degradation and which we used to identify forest loss or degradation that either subsequently regrew or occurred before this period. As many of the major roads constructed in the Brazilian Amazon and Congo Basins were constructed prior to 1982, the inclusion of this class was important for accurately quantifying the scale of impacts. A limitation of the Vancutsem et al.[79] dataset is a lower ability to detect selective logging, which is a major driver of road network expansion in the Congo Basin.[31] Additionally,

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accuracy in detecting non-forest land cover types was higher for Africa than Latin America or Asia,[79] hence human incursions may be slightly underestimated for this region.

The new 1-ha cells were considered to be impacted if the proportion of the area with some ‘human impact’ was >10%. This 10% threshold was set in order to further exclude cells that were more likely to be impacted through some stochastic natural process than through human action. The use of this threshold and the ~19% omission error rate of the Vancutsem et al.[79] transition data suggests that our estimates of forest loss and degradation are likely to be an underestimate. While the environmental effects of ‘human impacts’ differ between impact types (i.e. short-term degradation versus persistent deforestation[86]), we considered impacts to be equal as the main aim was to assess the extent and scale of area affected. We also recorded the year in which the majority of impacts occurred for each 1 ha cell (the year that had the greatest percentage of impacts within each cell) to assess changes through time.

To disentangle first-cut-road-associated impacts from other human impacts we identified impacted cells that had a lower travel time to first-cut roads and their secondary roads than (1) independent settlements and their connected roads, (2) other major roads and their associated roads, (3) all other roads (networks not connected to settlements or major roads), and (4) rivers and other navigable waterways. We also removed all impacts for which the minimum travel time to any mapped source was greater than 420 minutes (>90% of impacts occurred within 420 minutes from a source point; Figure S4), as we assumed these were likely associated with some other unmapped source.

After identifying first-cut-road associated human impacts, we classified impacts as direct (in the road construction footprint), indirect (associated with the first-cut road itself), or secondary (associated with secondary road). To classify human impacts, we calculated both the Euclidean Distance to the first-cut road, as well as the travel time to the first-cut road and to secondary road. Direct impacts were those that occurred within 100 m of the first-cut road. Indirect impacts were all impacts within 1 km of the first-cut road regardless of proximity to secondary road, or that had a lower travel time to first-cut road than to secondary road; and secondary impacts were those with lower travel time to secondary road than to the first-cut road.

Using these impact classes, we calculated impact extents as the distance from the first-cut road in which 95% of impacts occur. We calculated impact extents separately when considering only the direct and indirect impacts, and when considering all impacts (direct, indirect, and secondary). We also overlaid the identified impacts with a map of deforestation drivers[38] to identify the dominant drivers in each region.

We opted not to assess the governance or legality of secondary roads or their impacts for two key reasons: (1) the governance or legality of roads is often difficult or even impossible to determine as (a) roads may be constructed illegally or informally but subsequently included in official government data or retroactively legalised, (b) some roads may be legal but not included in official data if they are not considered ‘roads’ for government purposes (i.e. small logging tracks), (c) roads may be constructed by legal landholders but informally and hence not recognised within official data, and (d) official road data may be poor and simply not contain all legal and official roads; and subsequently (2) legality or governance of secondary roads is not within the scope of this paper as we simply aim to quantify the amount of secondary road and their associated impacts.