Engert, Jayden E., Souza, Carlos M., Kleinschroth, Fritz, Bignoli, Diego Juffe, Costa, Stefany C.P., Botelho, Jonas, Ishida, F. Yoko, Nursamsi, Ilyas and Laurance, William F. (2025) *Explosive growth of secondary roads is linked to widespread tropical deforestation.* Current Biology, 35 (7). pp. 1641-1648. ISSN 0960-9822.

Explosive growth of secondary roads is linked to widespread tropical deforestation

Jayden E. Engert[1]*, Carlos M. Souza[2], Fritz Kleinschroth[3], Diego Juffe Bignoli[4], Stefany P. Costa[3], Jonas Botelho Jr.[3], F. Yoko Ishida[1], Ilyas Nursamsi[5] & William F. Laurance[1]*

[1]Centre for Tropical Environmental and Sustainability Science, and College of Science and Engineering, James Cook University, Cairns, 4878, Australia

[2]IMAZON-Amazon Institute of People and the Environment, Belém, 66055-200, Brazil

[3]Institute for Environmental Planning, Leibniz University, Hannover, 30167, Germany

[4]Durrell Institute of Conservation and Ecology, School of Anthropology and Conservation, University of Kent, Canterbury, CT2 7NR, UK

[5]School of the Environment, University of Queensland, St Lucia, 4072, Australia

*Corresponding authors: engert_ecospatial@outlook.com (Lead Contact) and bill.laurance@jcu.edu.au

X handle (Jayden E. Engert) – @jaydengert

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, 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 kilometre 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

36   greater, respectively, than that directly linked with first-cut roads. Our findings provide key

37   insights into the potential scale and extent of forest loss and degradation that will emerge with

38   proposed roads and development corridors in tropical forests.

39   *Keywords: conservation, development corridor, frontier, highway, impact assessment, land*

40   *colonisation*

41

42   **Results**

43   *Secondary roads*

44   So-called first-cut roads provide an important conduit for initial human incursions into natural

45   habitats[21,22]. In this way they can promote substantial planned or unplanned secondary road

46   expansion and land colonisation, particularly when exports of timber, minerals, and agricultural

47   commodities are a motivating factor[23-26] (Figure 1). Therefore, while first-cut roads may not

48   directly cause secondary road expansion (are not ultimate drivers), they are required for

49   secondary road expansion to occur (necessary condition) and influence the locations in which it

50   can occur (proximate driver) [24,27]. An urgent priority is hence understanding whether and how

51   secondary roads increase the environmental impacts of first-cut roads.

52   Here we identify first-cut roads in the Brazilian Amazon, Congo Basin, and New Guinea, and

53   then use network analyses[28] to identify and determine the lengths of their associated secondary

54   roads (Figure S1). We identified 92 examples of first-cut roads across the continental regions

55   using satellite imagery and existing publications (Figure 1). We then used a modified version of

56   the location-allocation method described in Cooper[28] to identify secondary roads stemming

57   from first cut roads, by separating out roads that originated from existing human settlements or

58   from other major roads (Methods and Supplementary Materials).

59   Location-allocation analysis is used to identify the nearest source point – in our study, source

60   points for roads and human impacts – while accounting for variable travel speeds or travel costs

61   over different surface types. By using network analyses to identify source points for roads and

62   human impacts, we are able to provide a more refined assessment of the length of secondary

63   road and area of related forest loss and degradation than using previous methods such as

64   distance-decay (i.e. Tulloch et al.[29]) or buffer-distance models (i.e. Spencer et al.[30]).

65   We found a substantial amount of secondary road stemming from first-cut roads, with

66   considerable variation within and among the three continental regions (Figure 2). The Congo

67 Basin had the lowest average length of secondary road, with a mean of 4.8 km of secondary

68 road per 1 km of first-cut road (90%CI = 0.1 km – 16.9 km). New Guinea had a higher mean

69 length of 9.8 km (90%CI = 3.7 km – 19.6 km); while the Brazilian Amazon had a substantially

70 higher mean length of 49.1 km of secondary road for every 1 km of first-cut road (90%CI = 1.0

71 km – 139.3 km) (Table S5).

72

73 *Secondary road impacts*

74 After identifying secondary roads stemming from first-cut roads, we were able to quantify their

75 associated forest loss and degradation (see Methods). For each of the three continental regions,

76 we disentangled impacts arising from first-cut roads and from secondary roads, to evaluate their

77 spatial footprints and overall environmental consequences. We separated these associated

78 impacts into those in the construction footprint of the first-cut road (direct impacts), those

79 associated with the first-cut road itself rather than secondary roads (indirect impacts, either <1

80 km from the first-cut road or closer to the first-cut road than to a secondary road), and those

81 associated with secondary roads (secondary impacts, >1 km from the first-cut road and closer to

82 a secondary road than a first-cut road) (Figure S1).

83 For all first-cut roads, the direct impacts were the smallest impact class (Figure 3). Indirect

84 impacts were roughly an order of magnitude larger than the direct impacts in all three

85 continental regions. Indirect impacts typically totaled 40-80 ha in area for every 1 km of first-

86 cut road (means of 73.6 ha for the Congo, 59.4 ha for Amazonia, and 43.2 ha for New Guinea).

87 The mean secondary impacts were even larger in extent, averaging 100.0 ha per 1 km of first-

88 cut road for the Congo Basin, 222.0 ha for New Guinea, and 1,857.0 ha for the Brazilian

89 Amazon (Table S6).

90 While secondary impacts were smallest in the Congo Basin, considering these when

91 quantifying total first-cut road impacts resulted in a mean increase of 126.1%. The mean

92 increase in impacts when considering secondary impacts was 399% for New Guinea and

93 2,826.5% for the Brazilian Amazon. Compared to the direct impacts alone, the total impacts of

94 first-cut roads were on average 31.5 times higher in the Congo Basin, 22.2 times higher in New

95 Guinea, and 305.2 times higher in the Brazilian Amazon. For the Brazilian Amazon and New

96 Guinea, the total impacts of first-cut roads were correlated with the length of secondary road.

97 This was not the case for the Congo Basin, however, where secondary road expansion is often

98   driven by selective logging, which degrades forest but does not typically lead to widespread

99   forest loss[31] (Figure S5).

100   When assessing the increase in human impacts through time, first-cut roads in the Brazilian

101   Amazon and New Guinea show similar linear trajectories of increase (Figure S6). Such roads in

102   the Congo Basin, however, have increased more slowly and intermittently, while accelerating

103   in recent years. Such differences in trajectories might reflect regional differences in resource-

104   extraction intensity. Brazil and Indonesia, for instance, are major exporters of agricultural

105   products, unlike most Congo Basin nations[32] (Figure S7).

106

107   *Extent of human impacts*

108   By classifying secondary roads and their associated impacts, we were able to determine the

109   geographical area affected by first-cut roads and the distance over which their impacts occurred

110   (see Methods). Modelled impact extents of first-cut roads were substantially larger when

111   considering their secondary roads and impacts than when considering only direct and indirect

112   impacts (Figure 4). Human impacts were detectable at distances of up to 35.9, 17.7, and 68.0

113   km from first-cut roads in the Congo Basin, New Guinea, and Brazilian Amazon, respectively

114   (95% of all impacts occurred within these distances). If secondary roads are ignored, however,

115   the impacts of first-cut roads extend just 3.9 km, 3.8 km, or 1.0 km from first-cut roads in the

116   Congo Basin, New Guinea, and Brazilian Amazon, respectively.

117   New Guinea had the smallest impact extent from roads, which is likely due to their

118   concentration in industrial plantations and logging concessions near first-cut roads (i.e. Figure

119   1J). Conversely, in the Brazilian Amazon many secondary roads were largely constructed

120   perpendicular to first-cut roads (i.e. Figure 1D). This creates a 'fishbone' pattern of forest loss

121   extending out from first-cut roads as a consequence of former government-sponsored forest-

122   colonization projects[33], which sharply increases the spatial scale of environmental damage in

123   the Brazilian Amazon.

124

125   **Discussion**

126   Roads that penetrate into frontier regions—so-called 'first-cut roads'—can trigger a surge of

127   secondary roads that can greatly amplify their environmental impacts. Such secondary roads are

128   rapidly proliferating across much of the tropics, being on average 29 times greater in length

129 than the first-cut roads from which they arose. Of even greater concern is that secondary roads

130 are dramatically increasing the scale of forest disruption, provoking more than 150 times as

131 much deforestation than did first-cut roads across our vast pantropical study area. We found, on

132 average, that each kilometer of first-cut roads facilitated a total of 1,923 ha (90% CI = 192 –

133 5,149 ha) of human impacts in the Brazilian Amazon, 272 ha (76 – 742 ha) in New Guinea, and

134 186 ha (32 – 509 ha) in the Congo Basin.

135

136 *Differences among regions*

137 Secondary roads and their associated impacts varied greatly among regions, being highest in the

138 Brazilian Amazon and lowest in the Congo Basin region. Such differences may reflect local

139 environmental, political, or socioeconomic factors. New Guinea, for example, has steep

140 mountainous regions that limit road construction and land conversion[34,35], and first-cut roads in

141 these areas had lesser impacts than did those in the flat lowlands. Conversely, the vast, flat

142 basins of the Brazilian Amazon and Congo permit relatively easy and inexpensive road

143 building, except in extensive flood-prone areas[36] where navigable rivers are often used for

144 transportation (i.e. Reed & Miranda[37]).

145 Beyond their environmental differences, our three study regions also have many political,

146 historical, and socioeconomic dissimilarities. High rates of forest loss in Brazil, for instance,

147 have been driven by commodity agriculture and livestock production to supply international

148 and domestic markets[38-41] (Figure S7). Notably, many of Brazil's current first-cut roads were

149 built during the military-dictatorship period of the 1960s and 1970s for the explicit purpose of

150 promoting land colonization and commodity agriculture[23].

151 Conversely, deforestation from large-scale agriculture is rare in the Congo Basin, which

152 currently produces only modest agricultural exports[32,38]. Much of the forested land in the Congo

153 is being used for industrial selective logging, which can generate dense networks of forest roads

154 and degrade forests but lead to little outright deforestation[31,42,43] (Figure S5). However, the

155 period over which reliable data is available also constrains these analyses. Certain areas in

156 Central Africa were key production regions for oil palm and rubber during the former colonial

157 period but these areas are by now largely human-dominated and can no longer be assessed as

158 'frontier' regions due to limited satellite-imagery timeframes[44,45].

159 In New Guinea, road impacts were highly variable but generally lower than those in the

160 Brazilian Amazon, as a consequence of the island's low historic levels of development.

161 However, first-cut roads in New Guinea are currently promoting large areas of commodity

162 agriculture (Figure S7). Beyond this, new megaprojects – such as massive palm-oil and food-

163 estate projects in Indonesian Papua intended to supply domestic and export markets – are

164 expected to increase road building and deforestation in the near future[34,35].

165

166 *Proliferating first-cut roads*

167 Globally, new investments in roads and extractive industries are creating an unprecedented

168 wave of first-cut roads in forested regions, especially in lower-income nations where

169 development pressures are often intense[21,46]. Vast expanses of new roads are expected by mid-

170 century from major infrastructure schemes such as China's Belt and Road Initiative[47] the

171 Programme for Infrastructure Development in Africa[48], the Initiative for Integration of

172 Regional Infrastructure in South America[49], and national programs in Indonesia[35,50],

173 Malaysia[51], and Papua New Guinea[34], among others. Many proposed road projects will

174 penetrate areas with exceptional environmental and societal values, such as protected areas, key

175 biodiversity areas[52,53], and indigenous territories[54] and may enable extensive networks of

176 secondary roads and associated forest loss and degradation.

177 The Congo Basin and New Guinea are expected to see rapid increases in industrial oil palm and

178 pulp-wood plantations and logging concessions[55-57]. In the Congo, such concessions will likely

179 be spurred by large-scale development corridors[48,52] that are likely to enable further secondary-

180 road expansion and forest loss. Similarly, New Guinea has a number of proposed development

181 corridors, highways, and extractive-industry mega-projects that are likely to dramatically

182 expand secondary roads and forest disruption[34,35]. Large infrastructure projects in these and

183 other tropical regions[49,50,58] are expected to imperil hundreds of conservation areas, intact-forest

184 tracts, and indigenous territories while leading to globally significant carbon

185 emissions[49,51,52,54,59].

186

187 *Impact assessment and policy implications*

188 Environmental impact assessment (EIA) procedures for road projects often focus on their direct

189 effects[17,22,60-62] while ignoring their extensive secondary impacts, which can be massive in

190   scope. For example, an EIA for a mining road in Sumatra, Indonesia suggested that 424 ha of

191   forest would be lost during road construction — a far smaller total than the 3,000-6,000 ha of

192   forest loss expected by scientists and activists[20]. While it is currently possible to estimate the

193   indirect environmental impacts of first-cut roads (i.e. Engert, Ishida & Laurance[20]), as yet there

194   are no spatially resolved methods for modelling their often-substantial secondary impacts[29,52].

195   Infrastructure projects such as new roads can improve socioeconomic opportunities for rural

196   and indigenous communities[63,64] but may also increase the vulnerability of such communities to

197   land invasions, violence, and resource theft[65-67]. Refined estimates of the impacts of first-cut

198   roads presented here could be used to inform future impact assessment procedures and identify

199   projects with substantial environmental and socioeconomic risks that should be

200   avoided[49,62,68,69].

201   In this study, we used a novel mapping strategy to assess the source of ~3.85 million km of

202   roads across the world's major tropical forest regions. This approach yielded a massive dataset;

203   had we relied on human observers to manually classify these same roads, we would have

204   needed an estimate of ~18,000 person-hours[8], a challenging figure. Clearly, road networks are

205   temporally dynamic and can vary markedly in their lifespan and ecological impacts[31,43,70].

206   Further studies of frontier-road dynamics are a top priority given the daunting scale and pace of

207   their environmental and societal impacts.

208

209   **Resource availability**

210   *Lead contact*

211   Further information and requests for resources should be directed to and will be fulfilled by the

212   lead contact, Jayden E. Engert (engert_ecospatial@outlook.com).

213

214   *Materials availability*

215   This study did not generate new unique reagents.

216

217 *Data and Code Availability*

218 • New Guinea road data have been deposited at Zenodo and are publicly available as of the
219 date of publication at https://doi.org/10.5281/zenodo.14762338.

220 • Congo basin road data have been deposited at ETH Research Collection and are publicly
221 available as of the date of publication at https://www.research-
222 collection.ethz.ch/handle/20.500.11850/342221.

223 • The Brazilian Amazon roads data reported in this study cannot be deposited in a public
224 repository because it is copyrighted under the PrevisIA platform (https://previsia.org.br).
225 To access the data, contact Dr. Carlos Souza Jr. at souzajr@imazon.org.br.

226 • Travel cost layers have been deposited at Zenodo and are publicly available as of the date
227 of publication at https://doi.org/10.5281/zenodo.14762338.

228 • This paper does not report original code.

229 • Any additional information required to reanalyze the data reported in this paper is
230 available from the lead contact upon request.

231

238

239 **Author contributions:** *Conceptualization*: JEE, WFL. *Resources*: JEE, CS, FK, YI, SPC, JB,
240 IN. *Methodology*: JEE. *Analysis*: JEE. *Writing – original draft*: JEE, WFL. *Writing – editing*
241 *and revising*: JEE, WFL, CS, FK, DJB.

242

243 **Declaration of Interests:**

244 The authors declare no competing interests.

245

246   **Supplemental information:**

247   Document S1. Figures S1 – S7 and Tables S1 – S6.

248
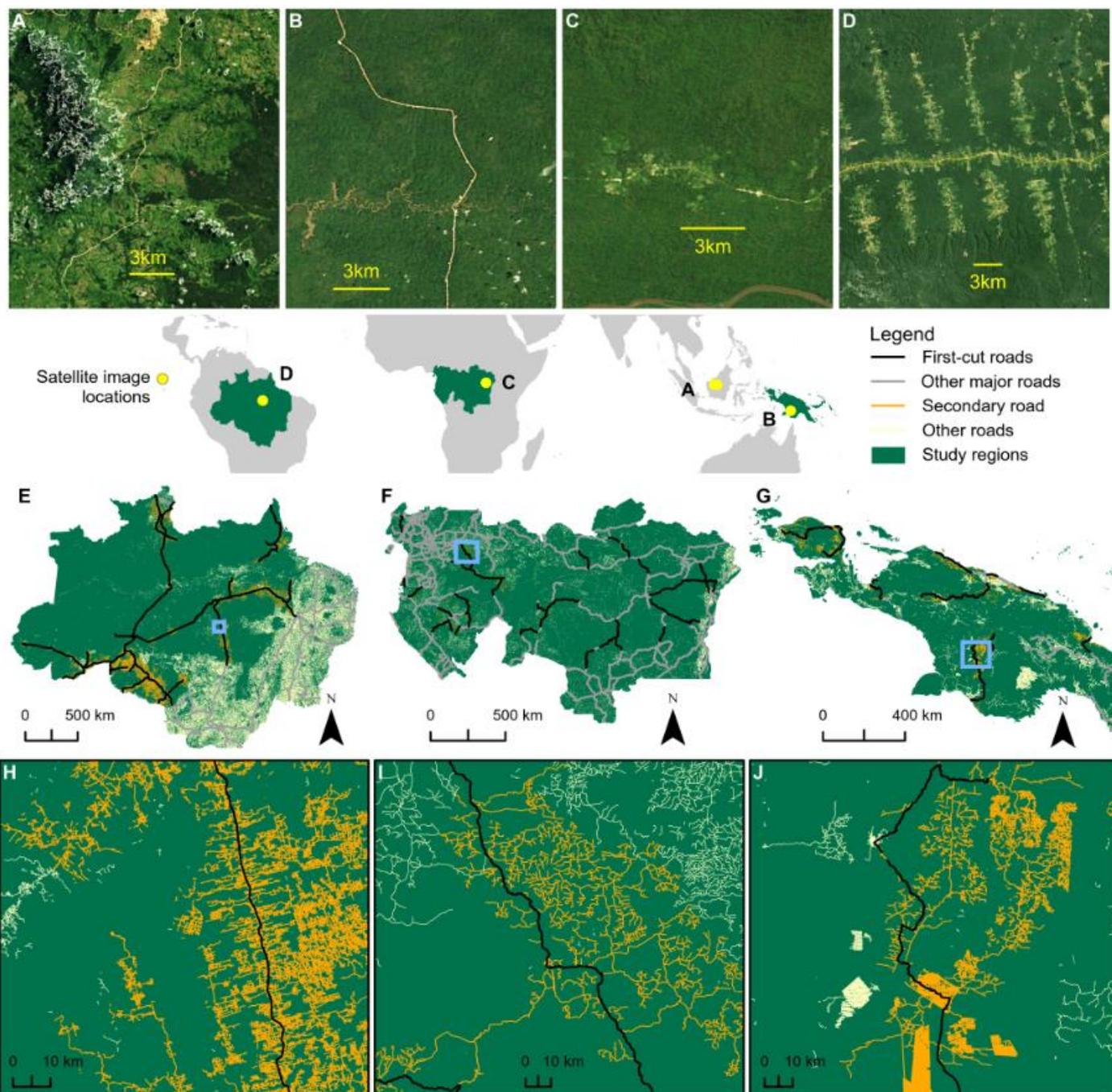
Figure 1. First-cut roads across the three continental regions assessed in this study, the Brazilian Amazon, Congo Basin, and New Guinea.

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 centred around the road, and (D) a first-cut road with some land colonisation 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 due to pixel size. See also Figure S1.

259
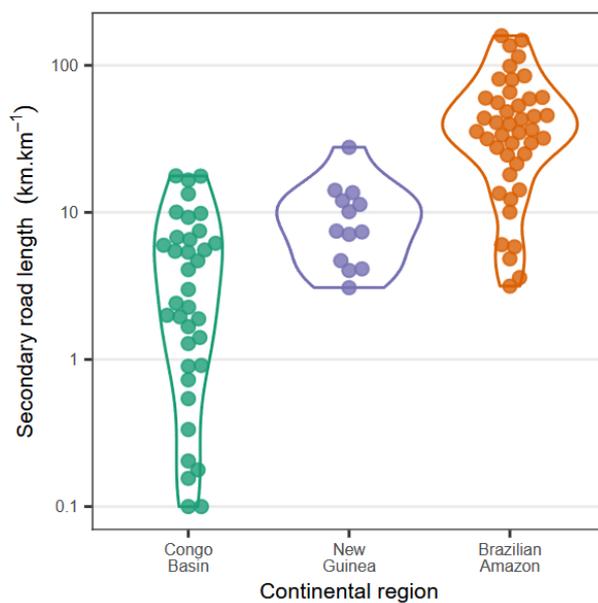
Figure 2. Length of secondary road constructed from each first-cut road in three of the world's major tropical forest frontiers.

(A) 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.
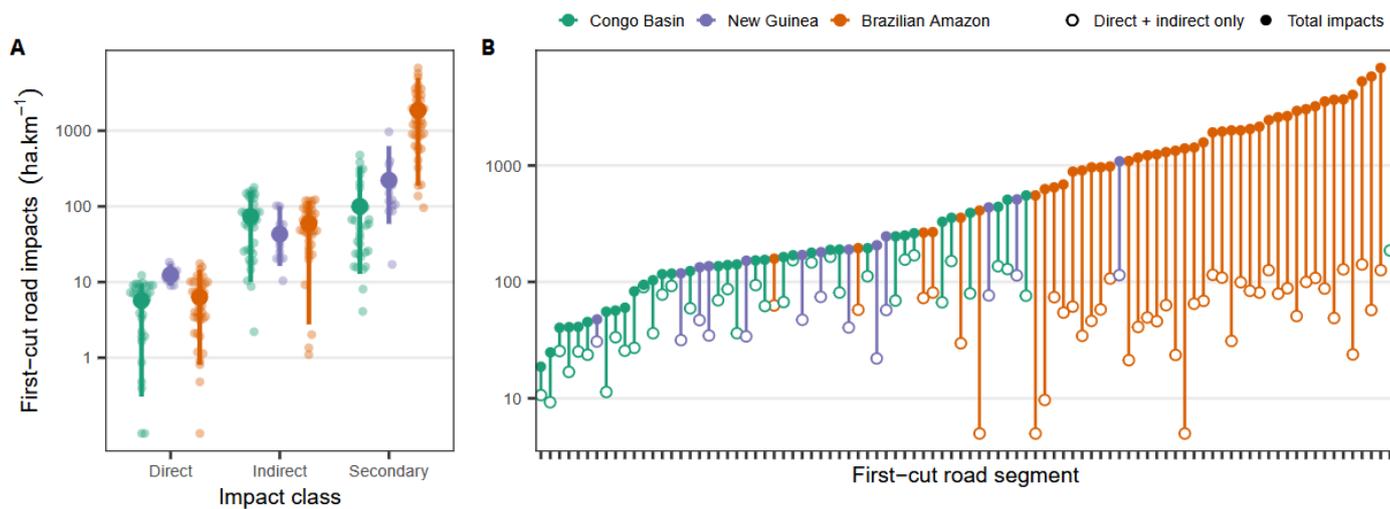
Figure 3. Human impacts facilitated by first-cut roads.

(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), dots represent mean values and lines indicate the 5-95% interquartile range. See also Table S6, Figure S5, Figure S7.
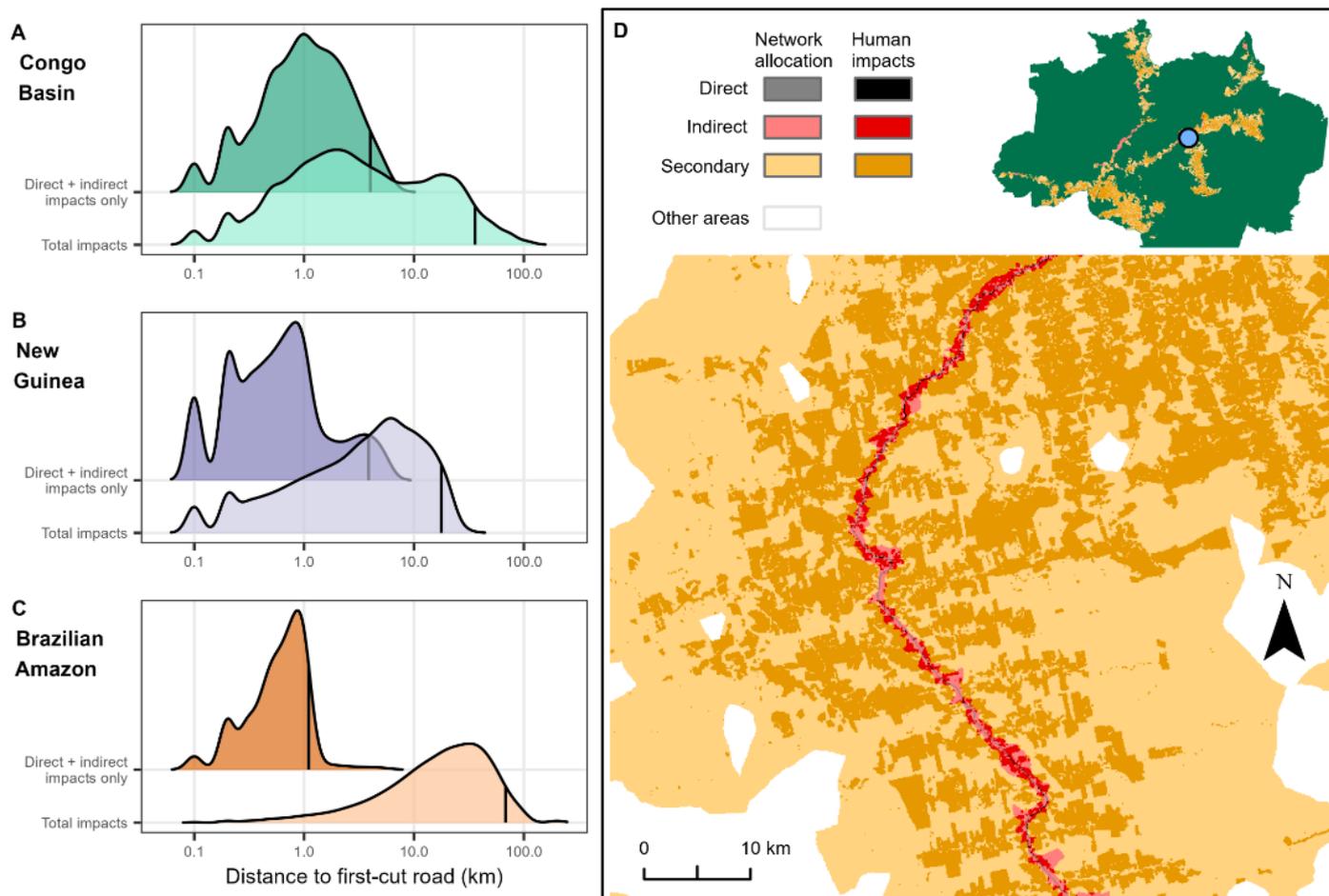
Figure 4. Relative density of human impacts by distance from first-cut roads for each continental region.
(A – C) show relative density distributions of human impacts as a function of distance to first-cut roads in the three
study regions: (A) Congo Basin, (B) New Guinea, (C) Brazilian Amazon. (D) Map 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.

280 **STAR★Methods**

281

282 **Experimental model and subject details**

283 We identified examples of 'first-cut' roads across the worlds major tropical forest 'frontiers':

284 the Amazon and Congo Basins and the island of New Guinea. A road was considered a 'first-

285 cut' road if it met the following criteria:

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

290 We identified 92 'first-cut' roads across our study region: 13 in New Guinea, 33 in the Congo

291 Basin, and 46 in the Brazilian Amazon. For each first-cut road, we identified secondary road

292 which had been constructed from the first-cut road as a source and calculated the length of said

293 secondary road. We then delineated and classified human impacts (forest loss and degradation)

294 associated with the first-cut road itself and the connected secondary road.

295 All data used are detailed in the key resources table.

296

297 **Method details**

298 Our study methodology consists of four key steps: (1) identifying first-cut roads; (2) developing

299 network analyses; (3) identifying and measuring secondary road length; and (4) classifying and

300 quantifying human impacts (Figure S1).

301 Our study area covers the island of New Guinea, Congo Basin, and Brazilian Amazon (Figure

302 1). The study area was selected based on complete coverage of recent, high-quality road data.

303 For the spatial unit of analysis, travel time and network analyses were conducted at 1 ha

304 resolution, and human impacts were also quantified at this spatial resolution. The analyses did

305 not include an explicit temporal component, though human impact data was based on landcover

306 changes identifiable in satellite imagery that started in circa 1985, and first-cut roads were

307 included that were constructed within the last ~100 years.

308

309 *Identifying first-cut roads*

310 To identify first-cut roads and classify and quantify their secondary road and impacts on forest

311 loss and degradation we selected study regions that complied with three key criteria: (1) have

312 high-quality, updated road maps available, (2) have experienced large-scale anthropogenic

313 landscape conversion predominantly within recent decades, and (3) have experienced rapid land

314 colonization and conversion within this period or are expected to in the future. Based on these

315 criteria, we identified the Brazilian Amazon, Congo Basin, and island of New Guinea as

316 important study regions.

317 We defined "first-cut roads" as major roads (trunk roads, motorways, highways, or primary

318 roads) that were constructed in landscapes that had not yet experienced significant human

319 invasion and modification. Therefore, major roads that were constructed in landscapes that had

320 already experienced notable human modification, for example conversion for perennial

321 agriculture, were not considered first-cut roads. For New Guinea and the Congo Basin, major

322 roads were identified using the aforementioned road classes in the Open Street Map database.

323 Open Street Map data is compiled from a variety of sources including official government data,

324 data provided by non-governmental organisations, and an open-source global mapping

325 community[71]. While Open Street Map data has been shown to be incomplete in some regions

326 (i.e. Engert et al.[8]), it typically achieves a high degree of spatial precision[72,73] and often more

327 complete in the major road classes from which we drew 'first-cut' roads (i.e. Zhou & Lin[74]).

328 For the Brazilian Amazon we considered national highways with BR classification to be major

329 roads, which included some "secondary" roads in frontier regions (i.e. BR-230). We determined

330 which major roads could be considered 'first-cut roads' using satellite imagery accessed

331 through Google Earth (Figure 1) and published information (i.e. Fearnside[10]), and hence

332 focused on roads constructed in the last 100 years. These major roads were then separated into

333 discrete "first-cut road" units by splitting at intersections and existing human settlements. To

334 exclude small line segments and small link roads, first-cut roads were excluded from analyses if

335 they were less than 40km long. Our dataset included 13 first-cut roads in New Guinea, 33 in the

336 Congo Basin, and 46 in the Brazilian Amazon.

337

338 *Network analyses*

339 We used network analyses, specifically a form of location allocation analysis[28], to identify both

340 secondary roads and related deforestation and forest degradation. Location allocation analysis is

341 a modified version of Euclidean allocation that includes a friction surface to identify the nearest

342 source point while accounting for variable travel speeds or travel costs over different surface

343 types. In our assessment, we created a travel cost layer for use as the friction surface, and

344 considered settlements and major roads to be source points for minor roads, and settlements, all

345 roads, and rivers to be source points for human impacts. As road expansion and forest loss and

346 degradation are primarily dependent on human populations and enabled by roads, our network

347 analyses required accurate information on road networks and human settlements.

348 Firstly, we developed high-accuracy road and settlement maps using the best available data for

349 each region. For roads in New Guinea we used the "ghost roads" dataset described in Engert et

350 al.[8]; for the Brazilian Amazon we used the AI-detected road dataset described in Botelho Jr. et

351 al.[75]; and for the Congo Basin we used the road dataset described in Kleinschroth et al.[31]. As

352 both Engert et al.[8] and Kleinschroth et al.[31] relied on inconsistent freely-available satellite

353 imagery, they were also supplemented with the most recent Open Street Map data by selecting

354 and appending any OSM roads not included in the aforementioned datasets. All roads that were

355 not classed as major roads as above (BR- designated roads in the Brazilian Amazon; trunk,

356 motorway, highway, or primary road classes in New Guinea and the Congo Basin) were

357 considered 'minor' roads from which we identified secondary roads. Our human settlement

358 layer was created using both Landscan population density maps[76] and Open Street Map

359 building locations[77] to account for any gaps in either of these datasets (Supplementary

360 Methods). As with the road data, Open Street Map building data is incomplete in many regions,

361 but often includes buildings not present in official government data (i.e. Brovelli & Zamboni[73])

362 or remotely-sensed population density maps (from visual inspection).

363 We then used the high-accuracy road maps to identify discrete, inter-connected road networks.

364 To do this, we created road presence raster layers at 1 -km resolution and identified discrete

365 networks of connected roads using the Region Group tool with 8-cell neighbourhood in

366 Arcmap 10.8. We chose the 1 -km resolution to account for small gaps in road shapefiles that

367 may occur due to slight inaccuracies in mapping or road detection. The discrete networks were

368 then converted from raster to polygons, and we identified those that were within 2 -km of a

369 first-cut road and considered these to be connected to the first-cut road. This 2 -km distance

370 was selected to account for small gaps in road shapefiles that may be due to mapping

371 inaccuracies or gaps introduced in the data cleaning steps. Secondary roads could henceforth

372 only be identified from those road networks connected to a first-cut road.

373 As first-cut-road-associated land-colonisation may result in the development of new human

374 settlements, we then classified human settlements as either dependent on first-cut roads, or

375 independent of first-cut roads. Independent settlements are those that were present before the

376 first-cut road was constructed (Supplementary Information) or are not connected to the first-cut

377 road by minor road networks, while dependent settlements are those connected to the first-cut

378 road and established after its construction (Supplementary Information). While existing

379 settlements may increase in size and population due to the increased access provided by a first-

380 cut road[78], we opted to ignore this effect in order to provide a more conservative estimate of the

381 impacts first-cut roads.

382 These initial data preparation steps allowed us to develop a robust network analysis workflow

383 to identify secondary roads and impacts. For the network analyses, we considered human

384 settlements and major roads to be source points for minor roads; and settlements, roads, and

385 rivers to be source points for forest loss and degradation. To account for differences in travel

386 cost over different surface types, we created a travel time map to use as a friction surface

387 (Supplementary Material, Table S3, S4, S5). The travel time map was created using a modified

388 version of the methods outlined in Weiss et al.[79] and Engert et al.[20] that estimates travel time

389 based on pre-clearing vegetation cover, topography, waterways, and roads. Travel times from

390 source locations were created using the Cost Distance tool in Arcmap 10.8.

391

392 *Travel time*

393 To estimate travel time for the study regions (New Guinea, Brazilian Amazon, Congo Basin) we used a

394 method developed from an adaption of Weiss et al.[79] and Engert et al. [20]. Our adapted travel time map

395 used information on vegetation type, slope, road locations, and waterways (Table S1; Table S2).

396 Contrary to Weiss et al.[79], we did not use information on current land-cover type or anthropogenic land-

397 cover types, rather we attempted to estimate travel times prior to conversion to anthropogenic land-uses.

398 To accomplish this, we created a map of pre-human-modification vegetation types (Table S3) using a

399 variety of published spatial datasets. Travel times for roads were taken from the reported maximum

400 travel speed in OpenStreetMap when available, and estimated based on road class when maximum

401 speed was not available. All travel speeds and travel times were converted to minutes per meter travel

402 time before creating the maps.

403 In order to develop network allocation models to identify the sources of both minor roads and human

404 impacts (deforestation and degradation), we developed three separate travel time maps. The first map,

405 used to identify the source of minor roads, was created while excluding major roads in order to identify

406 the travel time to minor roads if the major roads were not present (major roads used as a source, rather

407 than a component of the map). The second and third maps, used to identify the source of human

408 impacts, included all road types (major and minor). The second map was created to identify sources of

409 human impacts associated with land-based travel (roads and settlements as sources) and hence

410 considered waterways to be a barrier to movement. Finally, the third map was created to identify sources

411 of human impacts associated with water-based travel and hence considered waterways to be conduits of

412 movement.

413

414 *Classifying human settlements*

415 We created maps of human settlements by combining Landscan population density maps [80] with Open

416 Street Map building locations [77]. Settled cells were identified from Landscan maps by rescaling the map

417 to 1 ha resolution and reclassifying the population density map as either settled (1) or not settled (0)

418 using a cut-off of 4 people per hectare. We then identified settlements (defined as groups of settled cells)

419 by calculating the proportion of cells within a 1km neighbourhood that were settled and classifying all

420 areas with >20% of the neighbourhood settled as a 'settlement'. Similarly, we converted Open Street

421 Map building locations to a building presence layer at 1 ha resolution, and classified all areas with more

422 than 20% of cells containing buildings within a 1 km neighbourhood as being settlements.

423 To identify settlements dependent on first-cut roads, we first used the network analyses to identify

424 settlements that were both (1) linked to first-cut roads through the road network, and (2) more accessible

425 by first-cut roads than other major roads. We then used satellite imagery (including high-resolution

426 imagery and timeseries Landsat imagery) accessed through Google Earth, information available from

427 published sources and grey literature (e.g. Wikipedia), and expert assessment from paper authors, to

428 identify which of these settlements appeared after the construction of the nearest first-cut road and

429 which appeared before (Figure S2). High resolution and Landsat imagery was used to confirm

430 settlement locations and Landsat timeseries imagery was used alongside published and grey literature to

431 identify time of emergence. Settlements that were connected to the first-cut road, more accessible via

432 first-cut road than other major roads, and that appeared after first-cut road construction were considered

433 dependent on the first-cut road, all other settlements were considered independent (Figure S3).

434

435 *Identifying secondary roads*

436 We used the above outlined network analyses to identify secondary roads stemming from first-

437 cut roads. We considered secondary roads to be those minor roads that were (1) part of a

438 network directly connected to the first-cut road, (2) had a lower travel time (by 20 mins or

439 more) from first-cut roads than from independent settlements, and (3) had a lower travel time

440 from first-cut roads than from other major roads. We therefore created travel time maps using

441 as starting points (1) first-cut roads, (2) other major roads, and (3) independent settlements, and

442 calculated the minimum travel time for each minor road across each of the three travel time

443 maps using the Zonal Statistics tool in Arcmap 10.8. This allowed us to identify minor roads for

444 which the travel time was lower from first-cut roads than from other major roads or

445 independent settlements. We conducted visual inspections across the road networks to ensure

446 these classifications were reasonable. After identifying secondary roads, we determined their

447 first-cut road source using the Cost Allocation tool in Arcmap 10.8, and summed the total

448 length of secondary-road for each first-cut road.

449

450 *Classifying human impacts*

451 We used a similar process to classify impacts as was used to classify secondary road. To

452 identify 'human impacts', we first classified Vancutsem et al.[81] land-cover change data as

453 'human impacted' or not at the original raster resolution (Table S4), then aggregated to 1 ha

454 resolution by calculating the proportion of each cell that had experienced human impacts. The

455 Vancutsem et al.[81] dataset captures a wide range of impacts including complete deforestation,

456 logging, and fires, and we developed a classification scheme that aimed to separate human

457 impacts from natural disturbances, such as river inundation. The Vancutsem et al.[81] dataset,

458 which assesses Landsat imagery for the period 1982-2021, also includes various classes of

459 'forest regrowth' which they classify as a form of forest degradation and which we used to

460 identify forest loss or degradation that either subsequently regrew or occurred before this

461 period. As many of the major roads constructed in the Brazilian Amazon and Congo Basins

462 were constructed prior to 1982, the inclusion of this class was important for accurately

463 quantifying the scale of impacts. A limitation of the Vancutsem et al.[81] dataset is a lower ability

464 to detect selective logging, which is a major driver of road network expansion in the Congo

465 Basin[31]. Additionally, accuracy in detecting non-forest land cover types was higher for Africa

466 than Latin America or Asia[81], hence human incursions may be slightly underestimated for this

467 region.

468 The new 1-ha cells were considered to be impacted if the proportion of the area with some

469 'human impact' was >10%. This 10% threshold was set in order to further exclude cells that

470 were more likely to be impacted through some stochastic natural process than through human

471 action. The use of this threshold and the ~19% omission error rate of the Vancutsem et al.[81]

472 transition data suggests that our estimates of forest loss and degradation are likely to be an

473 underestimate. While the environmental effects of 'human impacts' differ between impact types

474 (i.e. short-term degradation versus persistent deforestation[82]), we considered impacts to be

475 equal as the main aim was to assess the extent and scale of area affected. We also recorded the

476 year in which the majority of impacts occurred for each 1 ha cell (the year that had the greatest

477 percentage of impacts within each cell) to assess changes through time.

478 To disentangle first-cut-road-associated impacts from other human impacts we identified

479 impacted cells that had a lower travel time to first-cut roads and their secondary roads than (1)

480 independent settlements and their connected roads, (2) other major roads and their associated

481 roads, (3) all other roads (networks not connected to settlements or major roads), and (4) rivers

482 and other navigable waterways. We also removed all impacts for which the minimum travel

483 time to any mapped source was greater than 420 minutes (>90% of impacts occurred within

484 420 minutes from a source point; Figure S4), as we assumed these were likely associated with

485 some other unmapped source.

486 After identifying first-cut-road associated human impacts, we classified impacts as direct (in

487 the road construction footprint), indirect (associated with the first-cut road itself), or secondary

488 (associated with secondary road). To classify human impacts, we calculated both the Euclidean

489 Distance to the first-cut road, as well as the travel time to the first-cut road and to secondary

490 road. Direct impacts were those that occurred within 100 m of the first-cut road. Indirect

491 impacts were all impacts within 1 km of the first-cut road regardless of proximity to secondary

492 road, or that had a lower travel time to first-cut road than to secondary road; and secondary

493 impacts were those with lower travel time to secondary road than to the first-cut road.

494 Using these impact classes, we calculated impact extents as the distance from the first-cut road

495 in which 95% of impacts occur. We calculated impact extents separately when considering only

496 the direct and indirect impacts, and when considering all impacts (direct, indirect, and

497 secondary). We also overlaid the identified impacts with a map of deforestation drivers[38] to

498 identify the dominant drivers in each region.

499 We opted not to assess the governance or legality of secondary roads or their impacts for two

500 key reasons: (1) the governance or legality of roads is often difficult or even impossible to

501 determine as (a) roads may be constructed illegally or informally but subsequently included in

502 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.

References

1. Goosem, M. (2007). Fragmentation impacts caused by roads through rainforests. *Current Science*, 1587-1595.

2. Laurance, W.F., Camargo, J.L., Fearnside, P.M., Lovejoy, T.E., Williamson, G.B., Mesquita, R.C., Meyer, C.F.J., Bobroweic, P.E.D., and Laurance, S. G. (2018). An A mazonian rainforest and its fragments as a laboratory of global change. *Biological reviews*, 93(1), 223-247.

3. Nepstad, D., Carvalho, G., Barros, A.C., Alencar, A., Capobianco, J.P., Bishop, J., Moutinho, P., Lefebvre, P., Silva Jr, U.L., and Prins, E. (2001). Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management*, 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. *PNAS*, 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. Conservation Letters, 7(3), 302-311.

6. Busch, J., and Ferretti-Gallon, K. (2017). What drives deforestation and what stops it? A meta-analysis. *Review of Environmental Economics and Policy*, 11, 3-23.

7. Sales, M., De Bruin, S., Herold, M., Kyriakidis, P., and Souza Jr, C. (2017). A spatiotemporal geostatistical hurdle model approach for short-term deforestation prediction. *Spatial statistics*, 21, 304-318.

8. Engert, J.E. & Campbell, M.J., Cinner, J.E., Ishida, F.Y., Sloan, S., Supriatna, J., Alamgir, A., Cislowski, J. and William F. Laurance. (2024). Ghost roads and the destruction of Asia-Pacific tropical forests. *Nature*, 629, 370–375

9. Fearnside, P.M., 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. *Environmental Management* 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. *Environmental Management* 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., and Schmink, M. (2008). Road building, land use and climate

change: prospects for environmental governance in the Amazon. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363, 1889-1895.

12. Laurance, W. F., Goosem, M., and Laurance, S. G. (2009). Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution*, 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. *Current Biology*, 25, R259-R262.

14. Barber, C. P., Cochrane, M. A., Souza Jr, C. M., and Laurance, W. F. (2014). Roads, deforestation, and the mitigating effect of protected areas in the Amazon. *Biological conservation*, *177*, 203-209.

15. Fearnside, P. M. (2015). Highway construction as a force in the destruction of the Amazon forest. Handbook of road ecology, 414-424.

16. Fearnside P.M. (1987) Deforestation and international economic development projects in Brazilian Amazonia. *Conservation Biology* 1:214–221.

17. Johnson, C. J., Venter, O., Ray, J. C., and Watson, J. E. (2020). Growth-inducing infrastructure represents transformative yet ignored keystone environmental decisions. *Conservation Letters*, 13, e12696.

18. Holden, C. (1987). World Bank launches new environment policy. *Science*, 236, 769-770.

19. Laurance, W. F., Cochrane, M. A., Bergen, S., Fearnside, P. M., Delamônica, P., Barber, C., D'Angelo, S., and Fernandes, T. (2001). 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. *Conservation Science and Practice*, 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., Van Der Ree, R., and Arrea, I.B. (2014). A global strategy for road building. *Nature*, 513, 229-232.

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), Oak Ridge, TN (United States).

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(2), 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 (pp. 369-386). Brill.

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/

583   28. Cooper, L. (1963). Location-allocation problems. *Operations research*, 11, 331-343.

584   29. Tulloch, A. I., Gordon, A., Runge, C. A., and Rhodes, J. R. (2019). Integrating spatially
585   realistic infrastructure impacts into conservation planning to inform strategic environmental
586   assessment. *Conservation Letters*, 12, e12648.

587   30. Spencer, K.L., Deere, N.J., Aini, M., Avriandy, R., Campbell-Smith, G., Cheyne, S.M.,
588   Gaveau, D.L., Humle, T., Hutabarat, J., Loken, B., Macdonald, D.W., and Struebig, M. J.
589   (2023). Implications of large-scale infrastructure development for biodiversity in
590   Indonesian Borneo. *Science of the Total Environment*, 866, 161075.

591   31. Kleinschroth, F., Laporte, N., Laurance, W.F., Goetz, S.J., and Ghazoul, J. (2019). Road
592   expansion and persistence in forests of the Congo Basin. *Nature Sustainability*, 2, 628-634.

593   32. Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos
594   Lima, M.G., Baumann, M., Curtis, P.G., De Sy, V., Garrett, R., and West, C. (2022).
595   Disentangling the numbers behind agriculture-driven tropical deforestation. *Science*, 377,
596   eabm9267.

597   33. Alves, M. T., Piontekowski, V., Buscardo, E., Pedlowski, M., Sano, E., and Matricardi, E.
598   2021. Effects of settlement designs on deforestation and fragmentation in the Brazilian
599   Amazon. *Land Use Policy* 109, 105710.

600   34. Alamgir, M., Sloan, S., Campbell, M.J., Engert, J., Kiele, R., Porolak, G., Mutton, T.,
601   Brenier, A., Ibisch, P.L. and Laurance, W. F. (2019b). Infrastructure expansion challenges
602   sustainable development in Papua New Guinea. *PLoS One*, 14, e0219408.

603   35. Sloan, S., Campbell, M.J., Alamgir, M., Engert, J., Ishida, F.Y., Senn, N., Huther, J. and
604   Laurance, W.F. (2019a). Hidden challenges for conservation and development along the
605   Trans-Papuan economic corridor. *Environmental science & policy*, 92, 98-106.

606   36. Douven, W., and Buurman, J. (2013). Planning practice in support of economically and
607   environmentally sustainable roads in floodplains: the case of the Mekong delta floodplains.
608   *Journal of environmental management*, 128, 161-168.

609   37. Reed, E. and Miranda, M. (2007). Assessment of the mining sector and infrastructure
610   development in the Congo Basin region. *Washington DC, USA: World Wildlife Fund,*
611   *Macroeconomics for Sustainable Development Program Office, 27.*

612   38. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., and Hansen, M. C. (2018).
613   Classifying drivers of global forest loss. *Science*, 361, 1108-1111.

614   39. Pendrill, F., Persson, U.M., Godar, J., and Kastner, T. (2019a). Deforestation displaced:
615   trade in forest-risk commodities and the prospects for a global forest transition.
616   *Environmental Research Letter*s, 14, 055003.

617   40. Pendrill, F., Persson, U.M., Godar, J., Kastner, T., Moran, D., Schmidt, S., and Wood, R.
618   (2019b). Agricultural and forestry trade drives large share of tropical deforestation
619   emissions. *Global Environmental Change*, 56, 1-10.

620   41. Hoang, N.T. and Kanemoto, K. (2021). Mapping the deforestation footprint of nations
621   reveals growing threat to tropical forests. *Nat Ecol Evol* 5, 845–853.

622   42. Laporte, N. T., Stabach, J. A., Grosch, R., Lin, T. S., and Goetz, S. J. (2007). Expansion of
623   industrial logging in Central Africa. *Science*, 316, 1451-1451.

624   43. Kleinschroth, F., Healey, J. R., Sist, P., Mortier, F., and Gourlet-Fleury, S. (2016). How
625   persistent are the impacts of logging roads on Central African forest vegetation?. *Journal of*
626   *Applied Ecology*, 53, 1127-1137.

627   44. Marchal, J. (2017). Lord Leverhulme's ghosts: colonial exploitation in the Congo. Verso
628   Books.

629   45. Wong, G. Y., Holm, M., Pietarinen, N., Ville, A., and Brockhaus, M. (2022). The making
630   of resource frontier spaces in the Congo Basin and Southeast Asia: A critical analysis of
631   narratives, actors and drivers in the scientific literature. *World development perspectives*,
632   27, 100451.

633   46. Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N.,
634   Rozenberg, J., Watkins, G. and Hall, J.W. (2019). Infrastructure for sustainable
635   development. *Nature Sustainability*, 2, 324-331.

636   47. Ascensão, F., Fahrig, L., Clevenger, A.P., Corlett, R.T., Jaeger, J.A., Laurance, W.F. and
637   Pereira, H.M. (2018). Environmental challenges for the Belt and Road Initiative. *Nat*
638   *Sustain* 1, 206–209.

639   48. Thorn, J. P., Bignoli, D. J., Mwangi, B., amd Marchant, R. A. (2022). The African
640   Development Corridors Database: a new tool to assess the impacts of infrastructure
641   investments. *Scientific data*, 9, 679.

642   49. Vilela, T., Malky Harb, A., Bruner, A., Laísa da Silva Arruda, V., Ribeiro, V., Auxiliadora
643   Costa Alencar, A., Julissa Escobedo Grandez, A., Rojas, A., Laina, A. and Botero, R.
644   (2020). A better Amazon road network for people and the environment. *PNAS*, 117, 7095-
645   7102.

646   50. Alamgir, M., Campbell, M. J., Sloan, S., Suhardiman, A., Supriatna, J., and Laurance, W. F.
647   (2019a). High-risk infrastructure projects pose imminent threats to forests in Indonesian
648   Borneo. *Scientific Reports*, 9, 140.

649   51. Sloan, S., Campbell, M. J., Alamgir, M., Lechner, A. M., Engert, J., and Laurance, W. F.
650   (2019b). Trans-national conservation and infrastructure development in the Heart of
651   Borneo. *PloS one*, 14, e0221947.

652   52. Laurance, W. F., Sloan, S., Weng, L., and Sayer, J. A. (2015). Estimating the environmental
653   costs of Africa's massive "development corridors." *Current Biology,* 25, 3202–3208.

654   53. Sloan, S., Bertzky, B., and Laurance, W.F. (2017). African development corridors intersect
655   key protected areas. *African Journal of Ecology*, 55, 731-737.

656   54. Estrada, A., Garber, P.A., Gouveia, S., Fernández-Llamazares, Á., Ascensão, F., Fuentes,
657   A., Garnett, S.T., Shaffer, C., Bicca-Marques, J., Fa, J.E., Hockings, K., and Volampeno, S.
658   (2022). Global importance of Indigenous Peoples, their lands, and knowledge systems for
659   saving the world's primates from extinction. *Science advances*, 8, eabn2927.

660   55. Pallares, G. and Ngeunga, M. (2021). DRC: A Polluting Palm Oil Business is Shaming
661   European Development Banks. InfoCongo. Accessed at https://infocongo.org/en/drc-a-
662   polluting-palm-oil-business-is-shaming-european-development-banks/

663   56. Blaise, A. (2023). Asian demand for timber to intensify pressure on Central Africa's forests.
664   Forest News. Accessed at https://forestsnews.cifor.org/80672/asian-demand-for-timber-to-
665   intensify-pressure-on-central-africas-forests?fnl=

666   57. Bokanga, M. (2024). Congo: The Next Frontier for the Palm Oil Industry. In *Elaeis*
667   *guineensis - New Insights*. IntechOpen.

668   58. Kaszta, Ż., Cushman, S.A., Htun, S., Naing, H., Burnham, D., and Macdonald, D.W.
669   (2020). Simulating the impact of Belt and Road initiative and other major developments in
670   Myanmar on an ambassador felid, the clouded leopard, *Neofelis nebulosa*. *Landscape*
671   *Ecology*, 35, 727-746.

672   59. Houghton, R.A., House, J.I., Pongratz, J., Van Der Werf, G.R., Defries, R.S., Hansen, M.C.,
673   Le Quéré, C. and Ramankutty, N. (2012). Carbon emissions from land use and land-cover
674   change. *Biogeosciences*, 9, 5125-5142.

675   60. Karlson, M., Mörtberg, U., and Balfors, B. (2014). Road ecology in environmental impact
676   assessment. Environmental impact assessment review, 48, 10-19.

677   61. Jaeger, J.A.G. (2015). Improving Environmental Impact Assessment and Road Planning at
678   the Landscape Scale. In Handbook of Road Ecology (eds R. van der Ree, D.J. Smith and C.
679   Grilo).

680   62. Juffe-Bignoli, D., Burgess, N. D., Hobbs, J., Smith, R. J., Tam, C., Thorn, J. P., and Bull, J.
681   W. (2021). Mitigating the impacts of development corridors on biodiversity: a global
682   review. *Frontiers in Ecology and Evolution*, 9, 683949.

683   63. Hettige, H. (2006). When do rural roads benefit the poor and how? An in-depth analysis
684   based on case studies. Asian Development Bank.

685   64. Clements, R. G., Aziz, S., Bulan, R., Bentruppenbaumer, J., Goosem, M., Giam, X.,
686   Laurance, S., and Laurance, W. F. (2018). Not everyone wants roads: Assessing indigenous
687   people's support for roads in a globally important tiger conservation landscape. *Human*
688   *Ecology* 46: DOI:10.1007/s10745-018-0029-4.

689   65. Davis, M. (2002). Late Victorian holocausts: El Niño famines and the making of the third
690   world. Verso Books.

691   66. Hecht, S.B and Cockburn, A. (2010). The fate of the forest: developers, destroyers, and
692   defenders of the Amazon. University of Chicago Press, USA.

693   67. Laltaika, E.I. and Askew, K.M. (2021). Modes of dispossession of indigenous lands and
694   territories in Africa. *Lands of the Future: Anthropological Perspectives on Pastoralism,*
695   *Land Deals and Tropes of Modernity in Eastern Africa*. New York: Berghahn Books, 99-
696   122.

697   68. Laurance, W. F. (2018a). Conservation and the global infrastructure tsunami: Disclose,
698   debate, delay! *Trends in Ecology and Evolution*, 33, 568–571.

699   69. Laurance, W. F. (2018b). If you can't build well, then build nothing at all. *Nature*, 563, 295.

700   70. Ahmed, S. E., Souza, C. M., Riberio, J., and Ewers, R. M. (2013). Temporal patterns of
701   road network development in the Brazilian Amazon. *Regional Environmental Change*, 13,
702   927-937.

703   71. Haklay, M., and Weber, P. (2008). Openstreetmap: User-generated street maps. IEEE
704   Pervasive computing, 7(4), 12-18.

705   72. El-Ashmawy, K. L. (2016). Testing the positional accuracy of OpenStreetMap data for
706   mapping applications. Geodesy and cartography, 42(1), 25-30.

707 73. Brovelli, M. A., and Zamboni, G. (2018). A new method for the assessment of spatial
708   accuracy and completeness of OpenStreetMap building footprints. ISPRS International
709   Journal of Geo-Information, 7(8), 289.

710 74. Zhou, Q., and Lin, H. (2019). Investigating the completeness and omission roads of
711   OpenStreetMap data in Hubei, China by comparing with Street Map and Street View. arXiv
712   preprint arXiv:1909.04323.

713 75. Botelho Jr, J., Costa, S.C., Ribeiro, J.G., and Souza Jr, C.M. (2022). Mapping roads in the
714   Brazilian Amazon with artificial intelligence and Sentinel-2. *Remote Sensing*, 14, 3625.

715 76. Rose, A., McKee, J., Sims, K., Bright, E., Reith, A., and Urban, M. (2021). LandScan
716   Global 2020 [Data set]. Oak Ridge National Laboratory. https://doi.org/10.48690/1523378

717 77. OpenStreetMap contributors. (2022). Retrieved from GeoFabrik
718   https://download.geofabrik.de/.

719 78. Voss, P. R., and Chi, G. (2006). Highways and population change. *Rural sociology*, 71, 33-
720   58.

721 79. Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M.,
722   Poyart, E., Belchior, S., Fullman, N. and Mappin, B. (2018). A global map of travel time to
723   cities to assess inequalities in accessibility in 2015. *Nature* 553, 333–336.
724   https://doi.org/10.1038/nature25181

725 80. Rose, A., McKee, J., Sims, K., Bright, E., Reith, A., and Urban, M. (2021). LandScan
726   Global 2020 [Data set]. Oak Ridge National Laboratory. https://doi.org/10.48690/1523378

727 81. Vancutsem, C., Achard, F., Pekel, J.F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego,
728   J., Aragao, L.E. and Nasi, R. (2021). Long-term (1990–2019) monitoring of forest cover
729   changes in the humid tropics. Science Advances, 7, eabe1603. DOI:10.1126/sciadv.abe1603

730 82. Nunes, C.A., Berenguer, E., França, F., Ferreira, J., Lees, A.C., Louzada, J., Sayer, E.J.,
731   Solar, R., Smith, C.C., Aragão, L.E. and Braga, D.D.L. (2022). Linking land-use and land-
732   cover transitions to their ecological impact in the Amazon. *PNAS*, 119, e2202310119.

733 83. Allen, G.H. & Pavelsky, T.M. (2018). Global extent of rivers and streams. Science 361,
734   585–588.

735 84. Jarvis, A. (2008). Hole-filed seamless SRTM data. http://srtm.csi.cgiar.org.

736 85. Gumbricht, T., Román-Cuesta, R.M., Verchot, L.V., Herold, M., Wittmann, F.,
737   Householder, E., Herold, N. & Murdiyarso, D. (2017). Tropical and subtropical wetlands
738   distribution version 2.

739 86. ESA. (2017). Land Cover CCI Product User Guide Version 2. Tech. Rep. Available at:
740   maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

741 87. Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.,
742   Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C. & Loucks, C.J.
743   (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global
744   map of terrestrial ecoregions provides an innovative tool for conserving biodiversity.
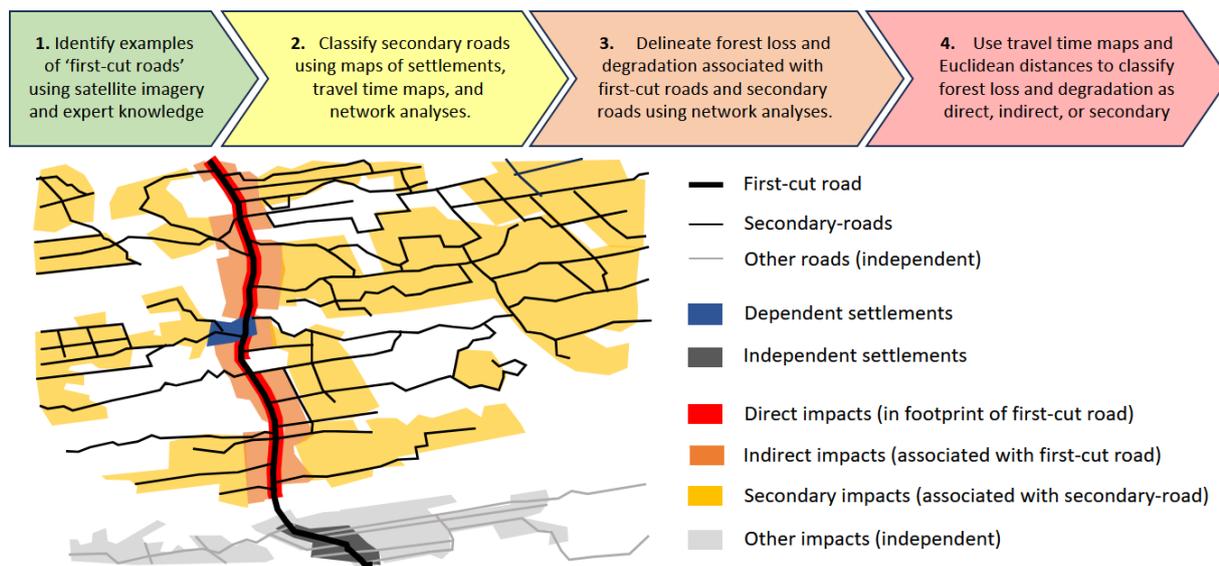745   BioScience, 51(11), pp.933-938.

746

747 **Key resources table**

| REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Major road locations	This paper, Methods	https://www.openstreetmap.org/
New Guinea roads	Engert et al.[8]	See Table S1.
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 Jr. et al.[75]	https://previsia.org.br/
Supplemental roads	Open Street Map[77]	https://www.openstreetmap.org/
Waterways	Allen & Pavelsky[83]	https://zenodo.org/records/1297434#.YfGIXf7MLcu
Topographic slope	Jarvis[84]	http://srtm.csi.cgiar.org
Wetlands	Gumbricht et al.[85]	https://data.cifor.org/dataset.xhtml?persistentId=doi:10.17528/CIFOR/DATA.00058
Remotely-sensed vegetation type	ESA[86]	https://www.esa-landcover-cci.org/
WWF Ecoregion	Olson et al.[87]	https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world
Open Street Map buildings	Open Street Map[77]	https://www.openstreetmap.org/
Human population density	Landscan[80]	https://landscan.ornl.gov/
Human impacts	Vancutsem et al.[81], 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
Other		

748

749 **Supplement**

750

751

752 **Figure S1. Conceptual figure demonstrating the classification of secondary roads and impacts,**

753 **related to Figure 1 and STAR Methods.** Direct impacts occur within the road footprint (clearing for

754 road construction), indirect impacts are those within 1 km of the first-cut road (regardless of proximity

755 to secondary roads) or closer to the first-cut road than secondary roads. Secondary impacts are all other

756 impacts associated with secondary roads. By assuming that all impacts within 1 km of the first-cut road

757 would happen without secondary road development, we are being conservative in our estimate of the

758 secondary impacts.

759
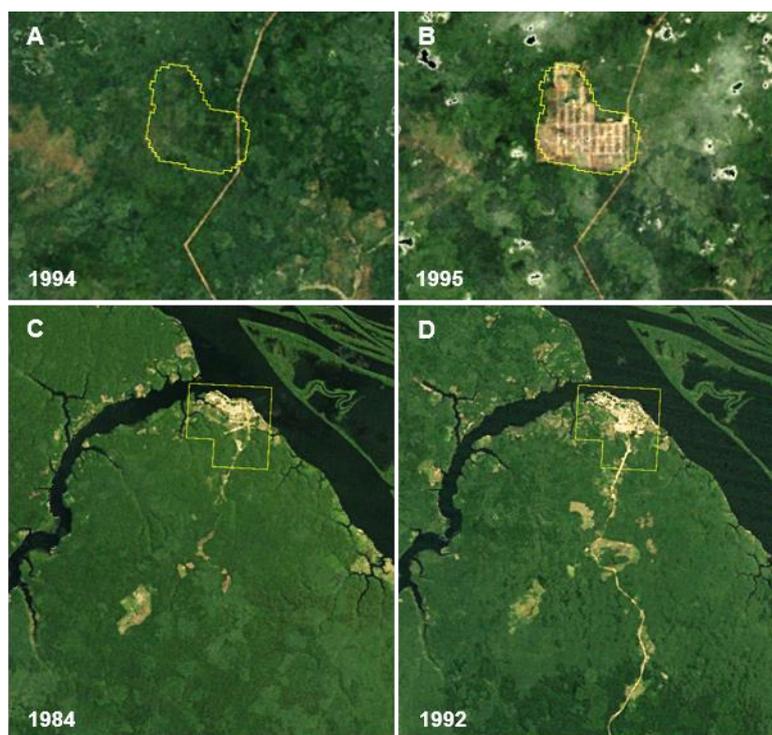
Figure S2. Example of dependent and independent settlements identified using satellite imagery accessed through Google Earth, related to STAR Methods. (A – B) a dependent settlement in New Guinea that emerged following construction of a first-cut road. (C – D) an independent settlement in the Brazilian Amazon that was present before a first-cut road was constructed.
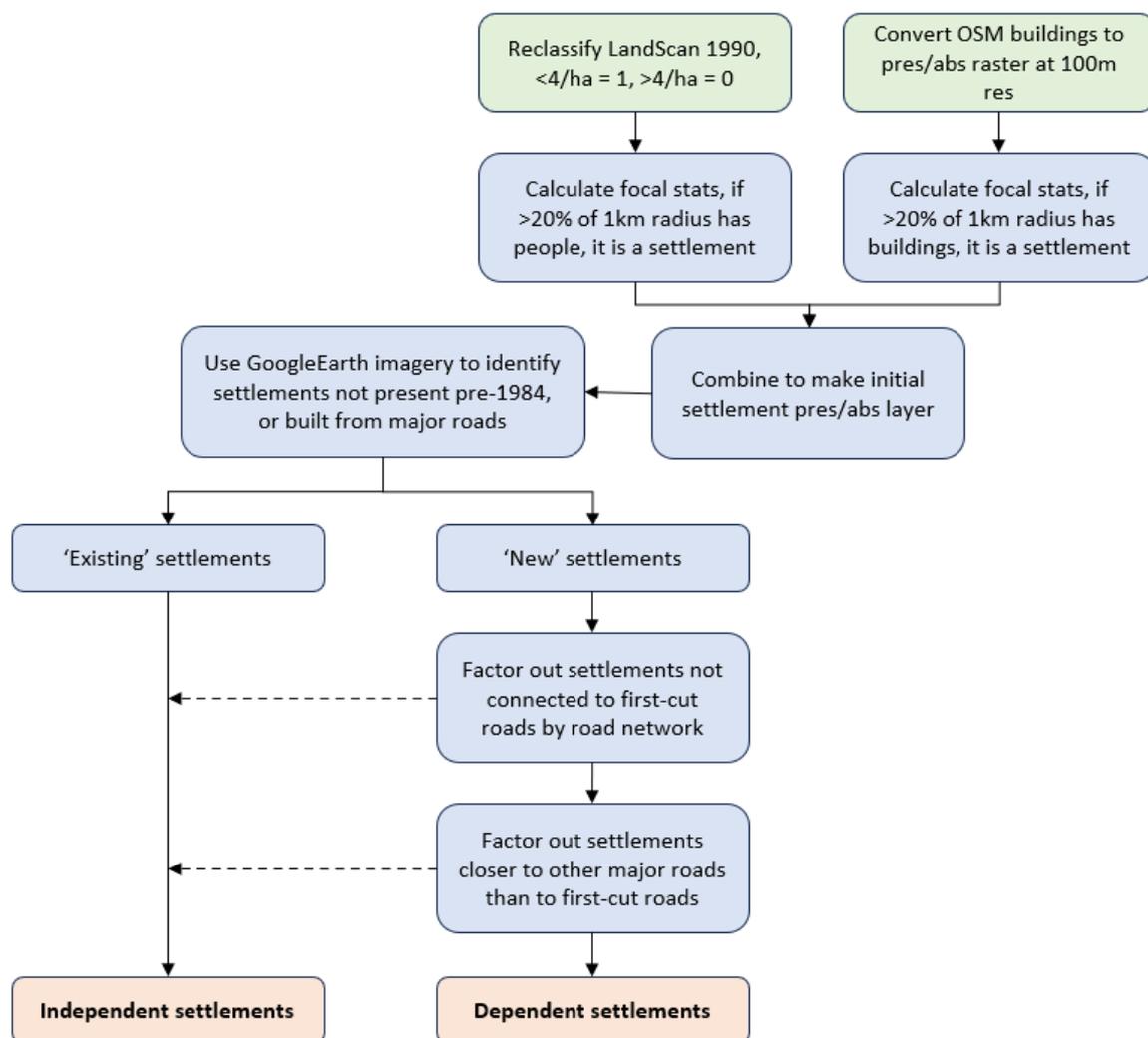
Figure S3. Method flowchart for the generation and classification of human settlement data, related to STAR Methods. Green boxes indicate input data, blue boxes indicate intermediate layers, and orange boxes indicate final outputs.

771
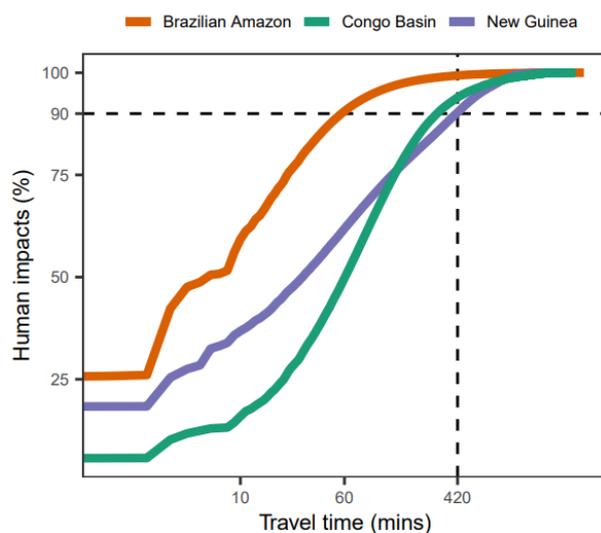
Figure S4. Cumulative distribution of human impacts by minimum travel time to any mapped source, related to STAR Methods. Based on distribution of impacts, we used 420 minutes (7 hours) as a cut-off point at which we considered human impacts to no-longer be dependent on a secondary road or first-cut road.

776
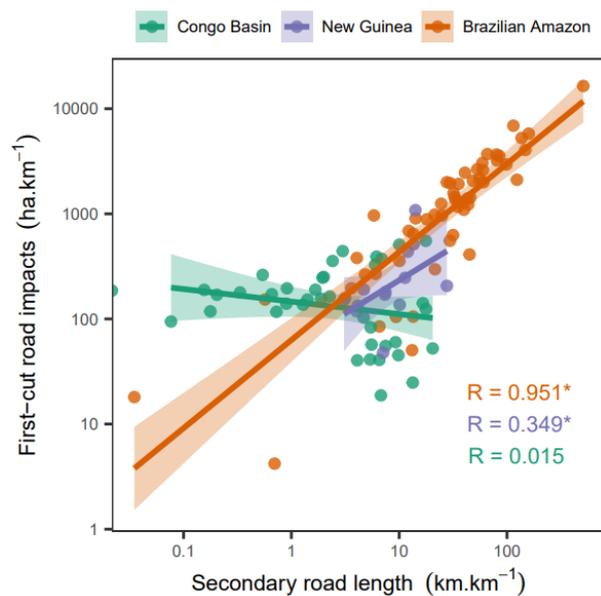
Figure S5. Relationship between secondary road length and total human impacts of first-cut roads in the three continental regions, related to Figure 3. R values indicate Pearson correlation statistics for each region, with asterisks indicating significant results. In New Guinea and the Brazilian Amazon, total first-cut road impacts are correlated with the amount of secondary road, however, in the Congo Basin they are not.
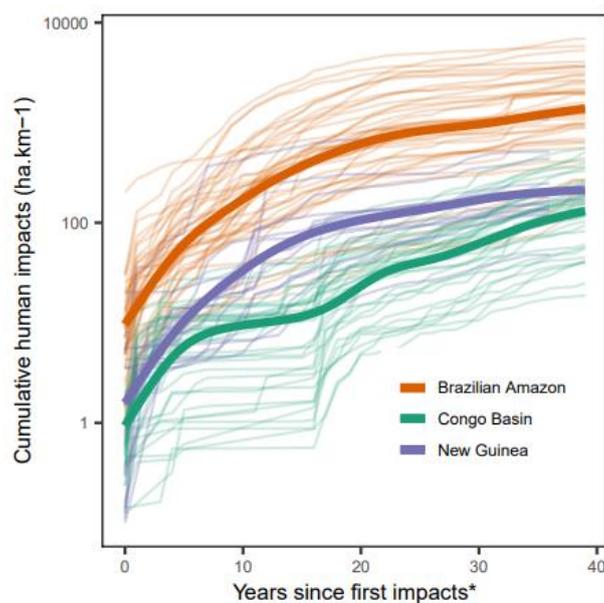
Figure S6. Accumulating impacts of the first-cut roads in this study, related to Figure 4. Shaded lines indicate individual first-cut roads, solid lines are the median values for each continental region. Years since first impact is the number of years since the earliest date of human impact for each individual first-cut road, or the number of years since 1983 for older roads, as the data from Vancutsem et al. [S1] starts in 1984. Many of the first-cut roads – particularly in the Brazilian Amazon and the Congo Basin – were constructed many years before this date. Therefore, the general form of the trajectory is more illuminating than the magnitude of the impacts.
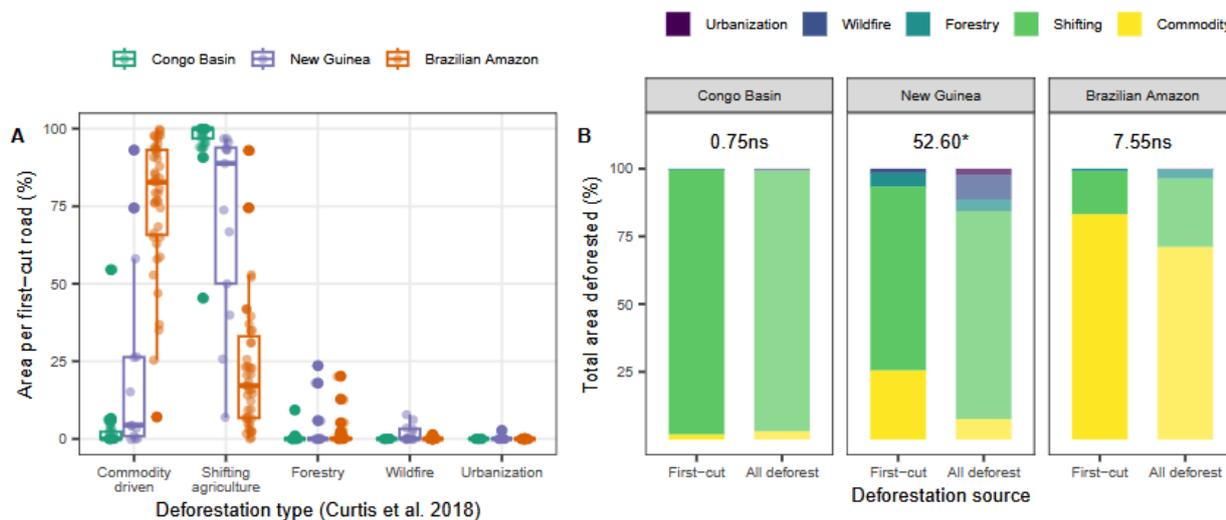
Figure S7. Deforestation types (as classified in Curtis et al.[S2]) by region, related to Figure 3. (a) comparison of relative deforested area by class for each region. (b) comparison of deforested area by class for first-cut road impact areas and the total deforested area in each region. Inset text in (b) indicates results of chi-square test of independence, ns = non-significant comparison, * = significant comparison. Deforestation classes are taken directly from Curtis et al.[S2] and are: commodity-driven deforestation (permanent conversion to non-forest landuse such as agriculture or mining), shifting agriculture (small to medium scale agriculture that is later abandoned to forest regrowth), forestry (large-scale forestry within managed forests and tree plantations with evidence of subsequent forest regrowth), wildfire (large-scale forest loss resulting from burning vegetation with no subsequent human conversion), and urbanization (conversion for the expansion or intensification of urban centers).

Variable	Component	Travel time	Data source
Major roads	OSM roads with listed max speed	60km/h – 120km/h	OpenStreetMap [S3]
	OSM roads with fclass (Table S2)	60km/h – 100km/h	
Minor roads	OSM roads with listed max speed	5km/h – 110km/h	OpenStreetMap [S3]
	OSM roads with fclass (Table S2)	5km/h – 60km/h	
	Roads not in OSM	40km/h	Engert et al. [S4] Botelho Jr. et al. [S5] Kleinschroth et al. [S6]
Waterways	Waterways as barriers	240 mins/km	Allen & Pavelsky [S7]
	Waterways as conduits	2 mins/km	
Slope	Topographic slope	$v = v_0 e^{-ks}$	Jarvis et al. [S8]
Pre-cleared vegetation (Table S5)	Closed forest	60 mins/km	Gumbricht et al. [S9] ESA [S10] Olson et al. [S11]
	Open forest	48 mins/km	
	Flooded forest	120 mins/km	
	Grass/shrubland	36 mins/km	
	Flooded grass/shrubland	48 mins/km	
	Montane	36 mins/km	
	Wetlands	120 mins/km	

805 **Table S1. Travel time map component layers, related to STAR Methods.**

806

807

Fclass	Max speed estimate
Footway, steps, pedestrian	5 km/h
Path, cycleway, bridleway, living street	20 km/h
Residential	40 km/h
Service, unclassified, unknown, track	40 km/h
Tertiary, tertiary link	60 km/h
Secondary, secondary link	60 km/h
Primary, primary link	80 km/h
Trunk, trunk link	100 km/h
Motorway, motorway link	100 km/h

Table S2. Open Street Map (OSM) road speed by fclass, related to STAR Methods.
Maximum speeds were estimated based on the values for roads of the same fclass that did have reported maximum speeds.

Layer	Original class	New class	Data source
Wetlands	Open water	Waterways	Gumbricht et al. [S8]
	Mangroves	Wetlands	
	Swamps	Wetlands	
	Fens	Wetlands	
	Riverine and lacustrine	Flooded forest	
	Floodouts	Wetlands	
	Floodplains	Flooded grass/shrubland	
	General Marshes	Wetlands	
	Marshes in arid climates	Wetlands	
	Marshes wet meadows	Flooded grass/shrubland	
Remote-sensed land-cover	Tree cover, broadleaved, evergreen, closed to open (>15%)	Closed forest	ESA [S9]
	Tree cover, broadleaved, deciduous, closed to open (>15%)	Open forest	
	Tree cover, needleleaved, evergreen, closed to open (>15%)	Closed forest	
	Tree cover, needleleaved, deciduous, closed to open (>15%)	Open forest	
	Tree cover, mixed leaf type (broadleaved and needleleaved)	Closed forest	
	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Closed forest	
	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	Grass/shrubland	
	Shrubland	Grass/shrubland	
	Grassland	Grass/shrubland	
	Lichens and mosses	Grass/shrubland	
	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	Grass/shrubland	
	Tree cover, flooded, fresh or brackish water	Flooded forest	
	Tree cover, flooded, saline water	Flooded forest	
	Shrub or herbaceous cover, flooded, fresh/saline water	Flooded grass/shrubland	
	Water	Waterways	
WWF Ecoregion	Tropical and subtropical moist broadleaf forest	Closed forest	Olson et al. [S10]
	Tropical and subtropical dry broadleaf forest	Open forest	
	Tropical and subtropical coniferous forest	Open forest	
	Tropical and subtropical grasslands/shrublands	Grass/shrubland	
	Flooded grasslands and savannas	Flooded grass/shrubland	
	Montane grasslands and savannas	Montane	
	Mangroves	Wetlands	

817 **Table S3. Input layers for determining pre-existing vegetation types, related to STAR Methods.**

818

Original land-cover class	New impact class	Human impact presence (1)
NoData	NA	0
Undisturbed tropical moist forest	NA	0
Bamboo-dominated forest	NA	0
Undisturbed mangrove	NA	0
Degraded forest short-duration disturbance	Short degradation	1
Degraded forest long-duration disturbance	Long degradation	1
Degraded forest 2/3 short degradation periods	Short degradation	1
Old forest regrowth (disturbed before 2002)	Regrowth**	1
Young forest regrowth (disturbed in 2002-2011)	Regrowth**	1
Very young forest regrowth (disturbed in 2012-2018)	Regrowth**	1
Deforestation (any start date)	Deforestation	1
Degradation (any start date)	Short degradation	1
Degraded mangrove (started before 2012)	Long degradation	1
Mangrove regrowing	Regrowth**	1
Mangrove deforested	Deforestation	1
Mangrove recently disturbed (started in 2019-2021)	Short degradation	1
Permanent Water	NA	0
Seasonal Water	NA	0
Deforestation to permanent Water	NA	0
Deforestation to seasonal water	NA	0
Old plantation	Deforestation	1
Plantation regrowing	Deforestation	1
Conversion to tree plantation	Deforestation	1
Recent conversion to plantation	Deforestation	1
Other LC without afforestation	Deforestation	0
Young afforestation (between 3 and 9 years of regrowth)	Regrowth**	1
Old afforestation (between 10 and 20 years of regrowth)	Regrowth**	1
Water converted recently into forest regrowth	Regrowth**	1

819 **Table S4. Reclassification of Vancutsem et al.[S1] forest change data into human impact layers,**
820 **related to STAR Methods.**

821 *value of 1 indicates human impacts, value of 0 indicates areas free from human impacts

822 **regrowth was considered indicative of human impacts as it is often evidence of historical
823 deforestation

824

Region	Secondary road length by first-cut road length (km.km^{-1})					
	Mean	Median	5% Conf	25% Conf	75% Conf	95% Conf
Brazilian Amazon	49.13	32.25	1.03	12.94	56.54	139.30
Congo Basin	4.84	2.70	0.14	0.91	6.60	16.90
New Guinea	9.75	7.46	3.65	4.70	12.00	19.60
Global*	28.52	10.08	0.25	3.92	32.83	108.98

825 **Table S5. Summary of the length of secondary road per kilometre length of first-cut road for each**
826 **region separately, and all study regions together (Global), related to Figure 2.**

827 *for all first-cut roads included in this study

828

Region	Impact class	Impact area by first-cut road length (ha.km^{-1})					
		Mean	Median	5% Conf	25% Conf	75% Conf	95% Conf
Brazilian Amazon	Direct (Footprint)	6.30	5.06	0.81	3.27	9.48	14.60
	Indirect	59.40	53.90	2.75	38.60	82.80	118.00
	Secondary	1857.00	1364.00	188.00	849.00	2544.00	5016.00
Congo Basin	Direct (Footprint)	5.69	6.39	0.31	3.06	8.41	9.58
	Indirect	73.60	65.60	10.00	26.30	111.00	159.00
	Secondary	100.00	59.20	12.80	24.30	101.00	333.00
New Guinea	Direct (Footprint)	12.50	11.50	9.02	10.50	13.40	17.20
	Indirect	43.20	34.10	16.30	20.60	57.80	101.00
	Secondary	222.00	123.00	58.70	102.00	189.00	627.00
Global*	Direct (Footprint)	6.95	7.04	0.48	3.45	9.69	14.40
	Indirect	62.70	57.80	9.01	26.60	84.70	145.00
	Secondary	948.00	306.00	16.00	85.30	1278.00	3597.00

829 **Table S6. Summary of impacts by impact class for each region separately and all study regions**
830 **together (Global), related to Figure 3.**

831 *for all first-cut roads included in this study

832

Supplementary References

833

834 S1. Vancutsem, C., Achard, F., Pekel, J.F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J.,
835   Aragao, L.E. and Nasi, R. (2021). Long-term (1990–2019) monitoring of forest cover changes
836   in the humid tropics. Science Advances, 7, eabe1603. DOI:10.1126/sciadv.abe1603

837 S2. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., and Hansen, M. C. (2018). Classifying
838   drivers of global forest loss. *Science*, 361, 1108-1111.

839 S3. Engert, J.E. & Campbell, M.J., Cinner, J.E., Ishida, F.Y., Sloan, S., Supriatna, J., Alamgir, A.,
840   Cislowski, J. and William F. Laurance. (2024). Ghost roads and the destruction of Asia-Pacific
841   tropical forests. *Nature*, 629, 370–375

842 S4. Botelho Jr, J., Costa, S.C., Ribeiro, J.G., and Souza Jr, C.M. (2022). Mapping roads in the Brazilian
843   Amazon with artificial intelligence and Sentinel-2. *Remote Sensing*, 14, 3625.

844 S5. Kleinschroth, F., Laporte, N., Laurance, W.F., Goetz, S.J., and Ghazoul, J. (2019). Road expansion
845   and persistence in forests of the Congo Basin. *Nature Sustainability*, 2, 628-634.

846 S6. Allen, G.H. & Pavelsky, T.M. (2018). Global extent of rivers and streams. *Science* 361, 585–588.

847 S7. Jarvis, A. (2008). Hole-filed seamless SRTM data. http://srtm.csi.cgiar.org.

848 S8. Gumbricht, T., Román-Cuesta, R.M., Verchot, L.V., Herold, M., Wittmann, F., Householder, E.,
849   Herold, N. & Murdiyarso, D. (2017). Tropical and subtropical wetlands distribution version 2.

850 S9. ESA. (2017). Land Cover CCI Product User Guide Version 2. Tech. Rep. Available at:
851   maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

852 S10. Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V., Underwood,
853   E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C. & Loucks, C.J. (2001). Terrestrial
854   Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial
855   ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, 51(11), pp.933-
856   938.

857

858