A better Amazon road network for people and the environment

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The rapidly expanding network of roads into the Amazon is permanently altering the world's largest tropical forest. Most proposed road projects lack rigorous impact assessments or even basic economic justification. This study analyzes the expected environmental, social and economic impacts of 75 road projects, totaling 12 thousand kilometers of planned roads, in the region. We find that all projects, although in different magnitudes, will negatively impact the environment. Forty-five percent will also generate economic losses, even without accounting for social and environmental externalities. Canceling economically unjustified projects would avoid 1.1 million hectares of deforestation and US$ 7.6 billion in wasted funding for development projects. For projects that exceed a basic economic viability threshold, we identify the ones that are comparatively better not only in terms of economic return but also have lower social and environmental impacts. We find that a smaller set of carefully chosen projects could deliver 77% of the economic benefit at 10% of the environmental and social damage, showing that it is possible to have efficient tradeoff decisions informed by legitimately determined national priorities.

Amazon | roads network | deforestation | cost–benefit analysis

By any metric, the Amazon Basin is a global conservation priority. It hosts 10 to 15% of global terrestrial biodiversity (1) and is the largest source of freshwater in the world (2). The Amazon is also home to more than 30 million people (3), regulates local hydrological cycles and climate patterns (4–6), and stores 150 to 200 billion tons of carbon (1, 7). All of these benefits depend to a greater or lesser degree on conservation of the biome in a healthy, natural state.

Nonetheless, the Amazon Basin continues to experience rapid clearing and degradation (8). If the current trend in agricultural expansion continues, 40% of Amazonian forest will be eliminated by 2050 (9). Expansion of the road network, including both official and unofficial roads, into formerly inaccessible areas is a key driver of this change (10, 11). There is a consensus in the literature that the transportation network plays, and will continue to play, a direct and indirect role in future deforestation in the region (10, 12–14). Road-driven clearing is associated with biodiversity loss, displacement of indigenous communities, and increased greenhouse gas emissions and reduced carbon storage (11–15). Roads also increase land values in adjacent areas, which in turn drives speculation and deforestation in order to establish and maintain land tenure (16).

Despite negative environmental, social, and cultural effects, governments and development banks continue to prioritize expanding the Amazon road network as a means to increase employment opportunities and mobility, reduce transport costs, and support regional development (17). One current example is the Initiative for the Integration of Regional Infrastructure in South America's most recent development plan, which includes nine large road projects in the Amazon, to be completed by 2026, with a total proposed investment of US$ 9.4 billion (18). Little attempt is made to assess the cumulative impacts of these projects (19, 20). Many proposed roads do not have basic economic feasibility analyses, and fewer properly account for potential negative socioenvironmental impacts. The lack of information leaves decision-making in many cases to political priorities, with little means to identify and prioritize roads that are best for the economy and society or even know the degree to which such choices are a misuse of scarce public funds.

This paper addresses this information gap by developing an approach to comprehensively evaluate the benefits and costs of multiple (official) road projects. We contribute to the existing literature on roads' impact in the Amazon and, hopefully, to the decision-making process in three ways. First, we account for the possibility that projects have a negative economic benefit. Second, we include the costs of road building alongside the economic, environmental, and social outcomes for a more inclusive appraisal. Third, we use a multicriteria approach that integrates a diverse set of issues into a single index so the roads can be compared. The approach is applied to 75 planned projects in the Amazon Basin (*SI Appendix*, Fig. S1). Specifically, we evaluated all road projects considered national priorities, for which enough basic information was available to permit detailed analysis. The resulting subset contains some of the biggest and most controversial projects in the Amazon.

Significance

In the next 5 y, more than 10 thousand kilometers of roads will be built or improved in the Amazon. Well-designed projects can increase employment opportunities, reduce transport costs, and support regional development. However, roads will also drive deforestation, threatening biodiversity and ecosystem services, jeopardizing the welfare of indigenous people, and moving the biome toward irreversible shifts in vegetation. Data to support good decisions are remarkably scarce. Typical feasibility studies, where they exist, inadequately address environmental and social impacts and do not facilitate comparison across projects. This study contributes to informed decision-making by quantifying the environmental, social and economic effects of 75 planned projects. It demonstrates that fewer projects in carefully chosen locations would dramatically improve outcomes of all types.

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We combine spatial analysis with traditional cost–benefit analysis to identify the subsets of these proposed projects that represent economic and socioenvironmental lose–lose situations, as well as those that generate the highest economic return with the least negative social and environmental impacts. The study was conducted in the five main Amazon Basin countries: Brazil, Bolivia, Colombia, Ecuador, and Peru. Over the next 5 y, these countries plan to construct or improve more than 12,000 km of roads in the region, with a total investment of approximately US$ 27 billion.

Results

Environmental, Social, and Economic Impacts. If all 75 proposed projects are implemented, they will cause deforestation of at least 2.4 million ha over the next 20 y, an area roughly equivalent to the land size of Belize. The spatial extent of predicted deforestation varies between road projects by three orders of magnitude, with a median of 19,392 ha and an average of 33,000 ha (*SI Appendix*, Fig. S2). The planned projects in Brazil have the highest predicted deforestation (Fig. 1). The set of proposed projects to improve Brazil's 2,234 km trans-Amazonian highway (BR-230) would cause forest cover loss of 561,000 ha or 23% of the total predicted for the region by 2030. Outside Brazil, the worst two projects in terms of deforestation are Colombia's Troncal Piedemonte (Los Pozos–La Macarena–La Leona) and Peru's Pucallpa–Contamana. These projects would cause a loss of 116,000 and 66,000 ha, respectively (*SI Appendix*, Table S1). Based on our deforestation model, we are unable to distinguish the different impacts on deforestation from improvement and new road projects. We find that both project types would result in ~100 ha of deforestation per kilometer. Further study is recommended to better investigate this point.

We also note that the construction and improvement of primary roads, such as the ones evaluated in this paper, might potentially lead to the construction of secondary, tertiary, and even illegal roads in the region, promoting additional impacts not accounted for here. Additionally, we note that there is a potential disconnection between investments in primary and nonprimary roads that has important implications for the development of the local economy and well-being of the local population. The direction of this disconnection, however, could be positive or negative depending on the rural communities, location, and the main economic activities developed in areas close to primary roads. At the same time that this is an important area for further study, it highlights the importance of strategic

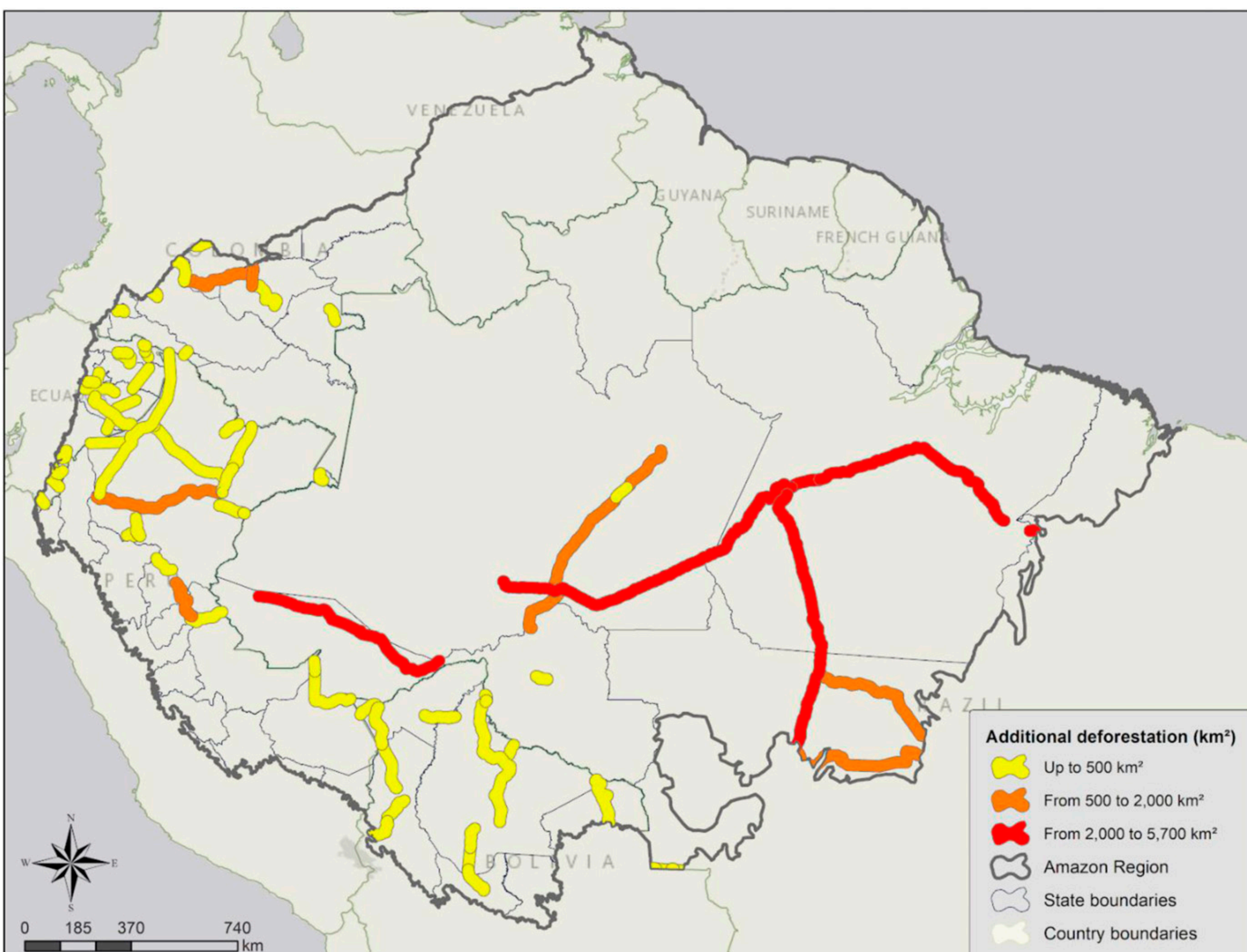

Fig. 1. Predicted deforestation in the 20-km buffer around selected road projects (20 y). Using historical data on tree cover loss and a spatial simulator software (DinamicaEGO), we estimated the deforestation that would be caused by each road project as the difference between predicted deforestation with and without implementation of the road. The countries are in beige and their boundaries are in gray/olive.

planning and the use of more comprehensive approaches such as the one proposed in this study.

When accounting for the ecological importance of the area that would be cleared around each road as measured by impact on species diversity, ecosystems, surface water, carbon storage, and national protected areas, we find that along with completing and paving the trans-Amazonian highway, paving Brazil's BR-163 highway would cause the worst environmental damage. In terms of carbon loss, for example, paving 496 km of BR-163 would cause emissions of 400 million tons of carbon by 2030. *SI Appendix*, Table S6, ranks the road projects based on normalized scores disaggregated by five environmental risk variables (biodiversity, ecoregion, water, carbon, and protected area).

From a social perspective, we find that if implemented as planned, at least 17% of the proposed roads would result in legal infractions related to environmental statutes, consultative processes, or indigenous rights. With regard to indigenous rights in particular, 3 of the 75 road projects analyzed would directly cross the territory of indigenous people in voluntary isolation. These are Capitán Augusto Rivadeneira–Reperado in Ecuador and Mitú–Monforth and Puerto Leguizamo–La Tagua in Colombia. Additionally, social conflicts and clashes over environmental and cultural issues have already occurred in 5% of the road projects. On the other hand, nearly half of the roads analyzed would improve access to schools and health centers by reducing travel time. *SI Appendix*, Table S7, ranks the road projects regarding their social risk.

With regard to the economic benefit that might counterbalance negative impacts, because most proposed roads are planned in remote areas in the Amazon Basin, expected traffic volume is typically low. Our traffic modeling in terms of annual average daily traffic (AADT) suggests that the volume would vary from a low of 156 vehicles per day (along the Iquitos–Saramiriza road, in Peru) to a high of 970 vehicles per day (San Pedro de los Cofanes–Alipamba, in Ecuador). As a point of reference, the AADT along the BR-116 highway in São Paulo, Brazil, is 36,441 (21), more than 37 times the highest value estimated for the Amazon roads considered here (*SI Appendix*, Fig. S3).

Investment costs vary considerably among the planned roads. If we exclude the projects that include the construction of bridges—in which cases, investments exceed US$ 10 million per kilometer—the average and the median investments are US$ 2,150,000 per kilometer and US$ 1,840,000 per kilometer, respectively (*SI Appendix*, Table S2).

By using traffic estimation, investment costs and other road-specific variables, we find that the net present value (NPV) ranges greatly, from a low of US$ −1.1 billion to a high of US$ 3.5 billion. Surprisingly, given the standard economic justification for roads, our calculations show that 45% of the proposed projects would cost more to build and maintain than they would generate in economic benefit as typically measured for transport projects (*SI Appendix*, Table S3). The fraction of economically unjustified roads is even higher in some countries, in particular Bolivia, where 85% of the planned roads are not economically viable. In this case, the two exceptions are Apolo–Tumupasa and Santo Domingo–San Antonio. Additionally, the fraction of projects with negative economic return is higher among the improvement projects (50%) when compared to new road projects (38%). If all NPV < 0 projects in our portfolio, including improvement and new road projects, were implemented, economic losses would total US$ 7.6 billion. Among the roads with positive economic returns, NPVs range by three orders of magnitude, with a median of US$ 145 million (Fig. 2).

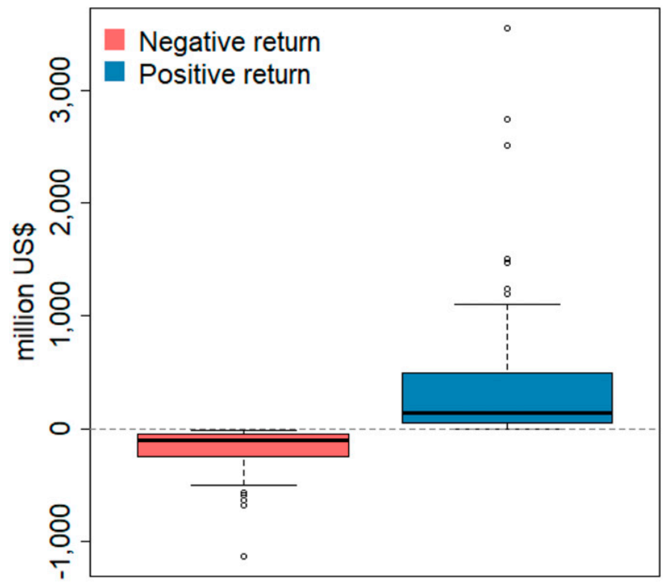

Fig. 2. Distribution of economic returns (NPV over 20 y, 7% discount rate). For each proposed road, we calculated the expected economic return using the widely used Roads Economic Decision model. On the cost side, we considered initial investments and maintenance. On the benefit side, we considered reductions in vehicle operating costs and travel time. The small clear circles are outliers.

Tradeoffs. Since the 1980s, governments, and development agencies have increasingly taken the view that economic growth and environmental conservation are not mutually exclusive (22). However, despite global awareness and multilateral efforts to implement a sustainability agenda (23), developing countries have continued to experience increasing demand for goods and services, degradation of nature and ecosystem services, and deterioration of environmental quality (24). In the Amazon region, the extent to which there is a dichotomy between development objectives and environmental conservation has been central to the political and developmental discourse (25).

In this context, a useful framework for decision making with regard to roads is to consider the tradeoff between economic benefit and environmental and social risks. In this section, we present several perspectives on this issue. We do not analyze projects with NPV < 0, because in these cases there is both economic loss and socioenvironmental damage, such that there is no reasonable tradeoff to be considered. We wish to emphasize, however, that the NPV < 0 projects remain political priorities. *SI Appendix*, Tables S3, S6, and S7, provide the full results for each of the three indicators for all road projects in our sample; this information may be relevant to decision making beyond what can be revealed by considering tradeoffs.

For the NPV > 0 projects, tradeoffs range considerably (Fig. 3). The extent of dispersion suggests ample scope to pick projects that are both better in absolute terms (movement up and to the right in Fig. 3). It is also clear that selecting projects will in many cases involve tradeoffs of a classic type: sacrificing the environment and social issues to increase economic return (movement down and to the right) or accepting reduced economic returns to improve socioenvironmental outcomes (movement up and to the left).

Rank ordering the projects with NPV > 0 from the highest to the lowest ratio of economic benefit to socioenvironmental impact, we observe a concave line in which 77% of economic value is achieved at only 10% of the damage (Fig. 4). These projects, corresponding to 12% of the roads analyzed, represent the greatest opportunity for economic gain relative to the damage they cause. All of the economic benefit is realized by a subset of roads (n = 41) causing 54% of the total projected damage, with the remaining roads both causing damage and economic loss.

Many of the most efficient projects are outliers in terms of their positive economic effects such that the most efficient 12% of roads identified still cause 33% of all projected deforestation

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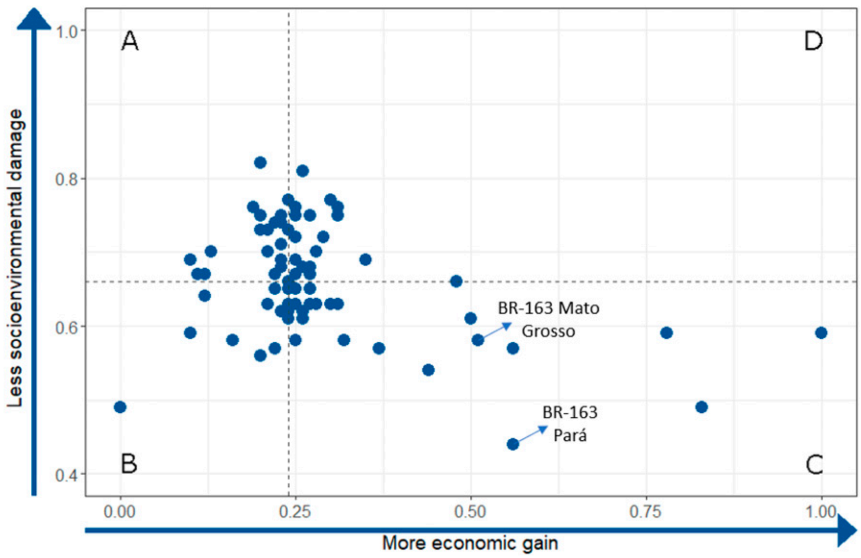

Fig. 3. Tradeoff between economic benefits and socioenvironmental impacts. Each dot represents a road project. Projects to the left of the dashed vertical line have a negative economic return (NPV < 0). Projects below the dashed horizontal line have worse than the average socioenvironmental impact. Projects in quadrant D have a positive economic benefit and less than average socioenvironmental damage.

(803,000 ha) albeit in comparatively less environmentally important areas. One possible source of skepticism with regard to these roads is their comparatively lower reported investment costs. Considering the five most efficient projects, the average initial investment is US$ 1,344,000 per kilometer, 37% lower than the average for the full set of projects, excluding the ones that include bridge construction. To the extent that there is a risk that official costs may not be realized in actual implementation, the high apparent efficiency of this group of projects would be reduced.

Furthermore, other studies have shown that 9 out of 10 infrastructure megaprojects (those that cost more than US$ 1 billion) go over budget; for roads, 20% of projects incur cost overruns (26, 27). An alternative approach to identifying comparatively better projects is to select those that have NPV > 0 but also have lower socioenvironmental impacts (i.e., projects in quadrant D of Fig. 3). Investing in these 18 projects would generate US$ 4 billion in net economic benefit and less than 10% of the total projected deforestation (240,000 ha). This damage is still significant but is 70% less than the most economically efficient group. As a point of comparison, if the same amount was invested in the worst projects (those in quadrant B of Fig. 3), the result would be both a loss of US$2 billion and 561,000 ha of deforestation. In both cases, the number of beneficiaries that would improve their access to services would be similar.

Concluding Remarks

Historically, political factors and broad but typically unsubstantiated economic aspirations have driven the planning and decision processes for infrastructure. In this paper, we showed that it is possible to improve outcomes with a better-informed decision-making process. We find that taking environmental and social concerns seriously does not mean giving up on development. On the contrary, it is possible to generate large economic returns at a lower environmental and social cost, but this will mean

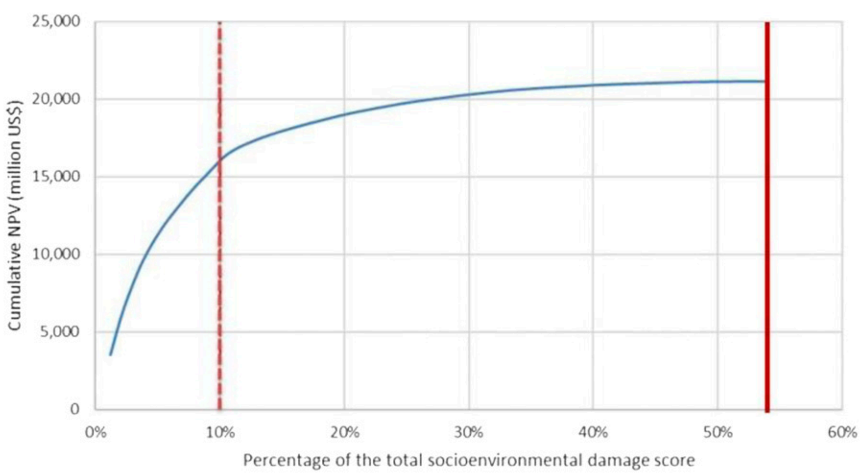

Fig. 4. Cumulative economic return and impact for NPV > 0 projects. Roads with positive returns (n = 41) are sorted from the highest to the lowest ratio of economic benefit per unit of socioenvironmental damage. Projects to the right of the solid red line (not shown) are both economically and socioenvironmentally bad and should not be implemented. The cumulative economic return is represented by the blue line. The dashed and solid red lines indicate 10% and 54% of the total socioenvironmental damage score, respectively.

construction of far fewer roads in carefully chosen locations where economic returns are clearly positive and negative impacts are comparatively low.

Based on these findings, we suggest three priority actions by governments, development banks, and civil society. First, do not carry out road projects with NPV < 0. There is no rational basis for spending scarce public resources to generate both economic loss and socioenvironmental harm. We acknowledge that projects may remain national or regional priorities. However, in the face of apparent lose–lose investments, the onus should be on road proponents to publicly justify their projects' legitimacy. Where these road projects are not well justified or else canceled, civil society may reasonably question the legitimacy of the interests served by their construction.

Second, for projects with NPV > 0, carefully consider tradeoffs between economic benefit and environmental and social risks. The level of negative impact that is acceptable in exchange for economic benefit should be defined not only by government authorities but also by stakeholders (28).

Finally, invest in rigorous analyses to drive road network decision-making. Priorities for forward-looking research include better understanding the differential impacts of investments in new roads as compared to road improvement projects; designing optimal routes to meet policy goals; and the relationship between investment in primary, secondary, and tertiary roads and how these drive impact on well-being as well as socioenvironmental damage. More immediately, the potential for both socioenvironmental disaster and economic loss easily justifies the time and cost of generating good information for current road priorities. Our findings suggest that good planning would result in far fewer roads, following routes carefully chosen to deliver economic return while avoiding socially and environmentally sensitive areas.

Materials and Methods

Data. We assembled a country, regional, and road-specific dataset that combines information about deforestation, land use, road network (including road length and surface type—paved, gravel, or earth), and other possible determinants of deforestation, potential environmental variables (e.g., ecoregion and biomass), financial and maintenance costs of proposed road projects, number of schools and hospitals within 20 km of each proposed road, and other social and cultural variables. In total, the analysis considered 30 variables. For each, we used the most recent high-quality data source available (see *SI Appendix*, Table S4, for a description of all data used).

Road projects were identified for inclusion based on two steps. First, we reviewed official documentation and consulted with road agency staff to identify as many road projects as possible that were prioritized for implementation by national governments. Identified projects included both road improvements and new construction. Second, we eliminated from this group both projects outside the Amazon Basin as delimited by the Amazon Geo-Referenced Socio-Environmental Information Network (RAISG) and those for which basic information (e.g., road surface type or specific route) was insufficient to carry out further analysis. The selected projects cover 12,263 km (7,620 miles), with a total proposed investment of US$ 27 billion.

Method. We used a multicriteria approach that integrates a diverse set of issues, including standard road costs and benefits, into a single index. In this section, we present a detailed description of the assumptions and methods used to calculate the environmental, social, and economic indicators, as well as the efficiency measure.

Central Assumptions and Parameters. We used two general parameters for analysis throughout the paper: 1) an evaluation period of 20 y, including the construction period, and 2) a discount rate of 7%. The first was chosen based on a standard road project life cycle (29). The second corresponds to the long-term interest rate in Brazil, the country with the largest set of road projects in our sample. In Table 1, we describe additional assumptions and discuss any potential bias they might cause. Positive bias implies that the assumption

Table 1. Main assumptions used to construct each indicator

Assumption	Potential bias on the final efficiency indicator
Impacts calculated for a 20-km buffer around each proposed road.	Positive bias. In practice, road impacts can go beyond a buffer this size (30–32), such that underestimating negative impact would exaggerate projected efficiency. See *SI Appendix*, Table S14 (a), for additional data on road impacts.
For road projects in areas that do not currently have roads, predictive models derived from nearby areas with roads.	Unclear. The extent to which drivers have a consistently different impact in nearby areas is not known.
Equal weight assigned to each variable in the environmental and social indicators; then equal weight assigned to social and environmental indicators to create a cumulative score.	Unclear. The relative importance of each variable is not quantified in the literature and is reasonably understood as subjective.
Potential benefits from reducing traffic accidents not considered.	Negative bias. A potential benefit is excluded. However, due to a lack of data, this simplification is commonly made when evaluating road projects.
Standard maintenance costs used for the entire study period.	Unclear bias. While the roads in this study are relatively remote and potentially more expensive to maintain than those from which the standard was derived (e.g., constant need to trim nearby vegetation and high cost of worker and equipment displacement), at the same time, because the roads are in remote places, there is less traffic. Because of this, the time between maintenance operations might be longer.
Induced traffic not estimated.	Unclear. Induced traffic depends on hard-to-predict potential economic transformations (both positive and negative) in the region where the road would be built. Due to lack of data, this simplification is commonly made when evaluating road projects.
For all new road projects, current transit is estimated assuming an alternative road exists, following the route of the proposed road but in the worst condition possible.	Unclear. Negative bias if in reality there is more demand for transit, for instance, currently using alternative existing routes. Positive bias if in practice there is less demand.

may overestimate the value of the final efficiency indicator calculated as the ratio between the economic impact and the socioenvironmental damage (i.e., a positive bias means less socioenvironmental risk and/or more economic return), while negative bias implies the opposite. These assumptions are also included in the text.

Deforestation Prediction. To predict deforestation around each project, we used Dinamica EGO (33), which simulates future land cover change based on a probabilistic model of past deforestation, as explained by biophysical and socioeconomic variables (34). The approach has four main steps: 1) calculate transition matrices, 2) calculate a transition probability map, 3) set up and simulate the model with and without the road project, and 4) validate the simulation.

We calculated transition matrices based on observed deforestation (i.e., loss of native vegetation) from 2011 to 2015, considering three land cover classes: deforested, forested, and nonforest (35). It is possible that road-induced deforestation is overestimated in our study because the data source includes deforestation not caused by humans, as well as conversions from primary forests to, for example, plantations, which are considered forests by some countries. In the absence of better data, however, Hansen et al. (36, 37) have been accepted and used as a proxy for deforestation in the literature.

Because the importance of each potential driver of change varies by location, we calculated individual transition matrices for the specific area in which each potential project would occur. In some particularly remote places, however, there are no existing roads from which transition probabilities could be estimated. In these cases, we derived the transition probabilities from nearby regions that already have roads. This approach is justified by the influence of broader patterns on the local scale (38).

For step 2, Dinamica EGO uses the weight of evidence approach to calculate the influence of a set of spatial features on the probability of each pixel transitioning to another class. We use distance to/presence of/value of the following features: roads, dams, river transport routes, mining, protected areas, indigenous lands, military areas, cities, and elevation. Since the weight of evidence approach only applies to categorical data, all continuous variables such as elevation and distance were transformed into categorical variables. More specifically, the continuous variables were transformed into bins where the number of intervals and their buffer size were selected to best preserve the original data structure. Once the bins were calculated, the effect of each variable on the spatial probability of a transition (i.e., from native vegetation to deforestation) was also calculated. Based on these effects (or the weights of evidence), we were able to produce a transition probability map (39).

Additionally, to use the weights of evidence approach, all variables must be spatially independent. We estimated the correlation between the independent variables using Pearson's correlation test to measure the pairwise correlation. Where the correlation coefficient was more than 0.7, we excluded the one that made the performance of the model worse (40, 41).

We used site-specific conditional transition probabilities to simulate future changes in land cover considering two scenarios: first, with no change to the existing road network, and second, adding the proposed roads or changing road surface type from unpaved to paved, as appropriate. The difference in deforestation between scenarios is the additional deforestation that would be caused if a given road project was implemented. This relationship can be considered causal as long as 1) deforestation does not drive the decision to implement roads (i.e., no inverse causality) and 2) all channels through which roads drive deforestation are controlled for in the model (i.e., no omitted variable bias).

To validate model predictions, we simulated deforestation in 2016 and compare the results to observed values from the same year. Omission errors, in which the model fails to correctly predict deforestation, averaged 2.82%. The average commission rate, in which the model predicts deforestation that did not occur, is 0.56%. These results suggest that our deforestation model is reasonable but that predictions are underestimated for some road projects. Accuracy of predictions as tested using a decay window size method calculated automatically in Dinamica EGO was also satisfactory (*SI Appendix*, Table S5).

Environmental Impact. To estimate environmental damage, we overlaid projected additional deforestation caused by the proposed roads on map layers accounting for five elements of ecological importance: species diversity, ecosystem coverage, surface water, carbon storage, and national protected areas. We then calculated indices of impact for each, accounting for both scope and significance of damage.

Potential impact on species diversity was calculated using range maps of endangered amphibians, reptiles, birds, and mammals. For each cell that would be cleared due to the road project, we calculated the increased risk of extinction as the sum of each species multiplied by a weight assigned to its vulnerability status *SI Appendix*, Table S14 (b) according to the International Union for Conservation of Nature (IUCN) Red List (42), i.e.,

$$\sum_j s_j \cdot vulnerability_j,$$

where s_j is species j density (measured as the species count for each cell) and $vulnerability_j$ is the status of species j in the IUCN Red List, with weights corresponding to extinction risk (*SI Appendix*, Table S14; ref. 43). For each road, the total risk is given by summing the species diversity risk calculated in each cell that would be cleared.

To calculate the biome impact, we used ecoregions as reference (44). For each road, we calculated the risk to each biome as the area of that biome that would be deforested multiplied by the inverse of its total coverage in the study area, i.e.,

$$\sum_{ecoregion} \frac{1}{Area_{ecoregion}} \cdot (\textit{Area of the ecoregion that would be cleared}).$$

We then calculated the total biome-level damage score for by each road as the sum of the risk to each biome impacted.

We calculated the risk of interfering with hydrological processes using global surface water data (45). Risk was quantified as the sum of deforested areas with presence of surface water for at least 25% of the period of observation (1984 to 2015). This approach may underestimate risk in two ways. First, surface water obscured by standing vegetation cover can go undetected by remote sensing, such that heavily forested river segments may not be identified. Second, seasonally flooded areas will typically be excluded by the 25% presence threshold.

Impact on the global climate was represented by carbon emissions, calculated as the tons of carbon present in deforested cells (46). Finally, we calculated the area that would be cleared inside national protected areas, as a broader indicator of importance, independent of physical and biological features. Regional protected areas, whose management and management objectives vary dramatically within and between countries, were not included.

To combine types of environmental impact, we first normalized each of the five environmental risk variables as follows:

$$normalized\ risk_i = \frac{(risk_i - min_i)}{(max_i - min_i)},$$

where min_i and max_i are the corresponding statistics of the variable i. This normalization guarantees that the values are in the range [0,1], following one of several standard practices in statistics for normalization where the goal is to compare measurements that have different units. We then calculate a combined environmental damage score for each road by averaging the scores for each of the five normalized variables, assigning equal weights to each.

SI Appendix, Table S6, shows the final environmental damage score for all road projects, as well as the individual risk scores for each of the five variables.

Social Impact. To calculate social impact, we identified both positive and negative effects. We used spatial data to calculate three indicators of benefit related to improved access to health care and education: 1) the number of schools and health centers inside the 20-km buffer around each road, 2) the average distance between these and the proposed road, and 3) the total population of the municipalities through which the road would pass. The final nonmonetary social benefit measure is a linear combination of these indicators.

To calculate social costs, we used both spatial and survey data. We used the former to calculate the length of each proposed road that would pass inside the territory of indigenous people in voluntary isolation (i.e., indigenous people who do not maintain or have contact with other peoples). Specifically, we first identified which proposed roads would go through the territories of indigenous people in voluntary isolation by overlapping two relevant spatial layers. Second, we calculated the length of road (in km) that would pass through the indigenous territories. Third, using the same methodology as for the other indicators, we normalized the resulting lengths to combine this indicator with those for the additional social variables.

We also used data from a questionnaire given to experts in each country (n = 33) on two issues: 1) the degree of rejection by people directly affected by each road project and 2) violation of any legal norms. The former was defined according to five categories from "very low" to "very high" levels of rejection. To each category, we assigned a weight from 1 to 5 to capture the different levels of rejection: 1 for the lowest and 5 for the highest rejection. The answers were then combined linearly through a weighted average. The second question was posed as a simple yes or no choice. In this case, we assigned the value of 1 to roads with no legal violation and 5 otherwise. As before, the answers were linearly combined.

To create the unified social impact score, we follow the same normalization procedure used for environmental damage, allowing benefits to reduce the score and negative impacts to increase it. *SI Appendix*, Table S7, shows the final social impact scores for all road projects.

Economic Return. There are different methods to calculate the economic return from road investments. Approaches following the trade literature (47) estimate the welfare impact of a reduction in transportation costs in terms of reduced prices and increased economic activity. Other approaches parameterize explanatory regression models using cross-sectional data on gross domestic product with road density as an explanatory variable (*SI Appendix*, Table S14 (b–c)). A common approach among development banks is to calculate the increase in consumer surplus resulting from reducing transportation costs, based on the elasticity of demand for transport and other factors. For example, the Fourth Highway Development Model (HDM-4) and Roads Economic Decision (RED) model, both developed by the World Bank, are broadly used for this purpose (*SI Appendix*, Table S14 (d); ref. 48).

In this study, we used the third approach. In particular, we applied the RED model, which estimates the NPV of building or improving rural roads with low traffic, as is the case for the road projects in this study (49). In the context of multiple theoretically valid approaches, this choice was made to facilitate use of the results by decision-makers, for whom the consumer surplus approach in general and HDM-4 and RED, in particular, are most familiar. The government of Brazil, for instance, directly uses these approaches.

The RED model evaluates one road at a time, comparing project implementation to a scenario in which the project is not implemented. For the road improvement projects, our without-project scenario was the road in its current state. For the new road projects, because current demand for transit could not readily be observed, we estimated transit in the without-project scenario based on a hypothetical road in the same location but in the worst possible condition.

Gross benefits are calculated based on reduced vehicle operating costs and travel time. Key inputs include the International Roughness Index (IRI) scores (based on road condition), which determines vehicle operating costs and travel speed, and AADT, which is used directly to calculate consumer surplus. To overcome the lack of data for the projects evaluated, we used econometric models based on existing observations to estimate road conditions and normal traffic in the with-project scenario. This estimation was done in two steps. First, we regressed road and local characteristics on observed AADT for all roads in the Amazon with such data. Second, we used the fitted model to predict traffic for all road projects in our analysis. Generated traffic (existing users driving more frequently or driving farther, as well as new users) was computed internally by the RED model based on a defined price elasticity of demand for transport. We used an elasticity of 1 for cars and buses and 0.6 for trucks (50).

Our model specification for AADT and IRI was

$$\log Y = \beta_0 + \gamma X_1 + \delta X_2 + error,$$

where Y is road condition or AADT, X_1 is a matrix containing variables related to road characteristics (length, surface type, and classification), and X_2 is a matrix containing local characteristics (population density, land cover, elevation, and gross domestic product in 2017 US$). Descriptive statistics are given in *SI Appendix*, Table S8. We used ordinary least squares regression for the traffic model and ordered logistic regression for the roughness model to account for a categorical dependent variable (very poor, poor, fair, good, and very good) in the latter case.

SI Appendix, Table S9, shows results for the traffic model. *SI Appendix*, Tables S10 and S11, show results for the road condition model. None of the roads for which we had observed roughness data were classified as in "very good" condition; as a result, estimated conditions also exclude this category. We transformed road condition predictions into IRI scores using the standard values in the RED model (*SI Appendix*, Table S12).

For the purpose here, the models seek only to estimating missing traffic and predict road conditions. There is no need to understand the precise causal relationship between coefficients on the regressors and the dependent variables (51). We note that our sample consists of 90 observations which could potentially lead to imprecise estimates. However, observed traffic data in the Amazon region are extremely scarce. The models for AADT and IRI could be improved if more data on traffic were available.

Road costs include initial construction and ongoing maintenance. Official data on initial investment were available for 65% of the roads analyzed. For the remaining projects, we used the average per km investment from our sample in the relevant country. Annual maintenance costs were estimated using standards reported in the World Bank's Roads Cost Knowledge System (ROCKS) database (52). These maintenance costs are the average among the 67 projects for which information was available in the ROCKS database (*SI Appendix*, Table S13).

The net economic benefit is calculated by RED as

$$Net\ economic\ benefit = -initial\ investment + \sum \frac{benefit_t - maintenance\ cost_t}{(1+d)^t},$$

where t is the year and d is the discount rate. We used a 20-y horizon and a discount rate equal to 6.87% per year, which is the long-term interest rate in Brazil, the country with the largest set of road projects in our sample.

Finally, we normalized the NPV following the same procedure used for the environmental and social damage scores, with the goal of obtaining a measure of economic benefits that is comparable to these other measures.

Efficiency. For road projects with NPV > 0, we first calculated a socioenvironmental damage score as the linear combination of environmental and social scores with equal weight assigned to each. Second, we calculated the efficiency with which a given project delivers economic benefit by dividing NPV by the socioenvironmental damage:

$$efficiency = \frac{Net\ economic\ benefit}{Socioenvironmental\ damage\ score}.$$

SI Appendix, Figs. S4 and S5, rank the NPV > 0 road projects from most to least efficient, considering all countries together and then individually. In each panel, efficiency is scaled from 0 to 1. We do not rank the efficiency of projects with NPV < 0, as there is no rational basis for spending scarce public resources to generate not only socioenvironmental harm but also economic loss. We acknowledge that national and local governments may continue to prioritize and implement road projects that lead to apparent lose–lose situations. Understanding why these proposed roads remain on the agenda is an important area for study. In the meantime, we hope the framework and improved information presented here can support movement toward better infrastructure decisions for people and the environment.

Data Availability. All data used in this study are publicly available from the sources mentioned in the text. The combination of these different datasets, used to create our database, is presented in *SI Appendix*, Tables S1–S3, S6 and S7, and S11–S14.

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