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Rerouting a major Indonesian mining road to spare nature and reduce development costs

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Abstract

Road-infrastructure projects are expanding rapidly worldwide while penetrating into previously undisturbed forests. In Sumatra, Indonesia, a planned 88-km-long mining road for transporting coal would imperil the Harapan Forest, the island's largest surviving tract of lowland rainforest. Such roads often lead to increased forest encroachment and illegal logging, fires, poaching, and mining. To evaluate the potential impact of the proposed road, we first manually mapped all existing roads inside and around the Harapan Forest using remote-sensing imagery. We then calculated the expected increase in forest loss from three proposed mining-road routes using a metric based on travel-time mapping. Finally, we used least-cost-path analyses to identify new routes for the road that would minimize forest disruption and road-construction costs. We found that road density inside and nearby the Harapan Forest is already 3–4 times higher than official data sources indicate. Based on our analyses, each of the three proposed mining-road routes would lead to 3,000–4,300 ha of additional forest loss from human encroachment plus another 424 ha lost from road construction itself. We propose new routes for the mining road that would result in up to 3,321 ha less forest loss with markedly lower construction costs than any other planned route. We recommend approaches such as ours, using least-cost-path analysis, to minimize the environmental and financial costs of major development projects.

KEYWORDS

deforestation, environmental planning, Harapan Forest, infrastructure, nature conservation, roads, spatial planning, Sumatra, tropical forest

Abstrak

Proyek infrastruktur jalan berkembang pesat di seluruh dunia dengan mengorbankan hutan yang sebelumnya tidakterganggu. Di Sumatera, Indonesia, jalan tambang sepanjang 88 km yang direncanakan untuk mengangkut batu bara akan membahayakan Hutan Harapan, jalur hutan hujan dataran rendah terbesar yang masih ada di pulau tersebut. Jalan seperti ini sering menyebabkan peningkatan perambahan hutan dan penebangan liar, kebakaran, perburuan, dan penambangan. Untuk mengevaluasi potensi dampak dari pembangunan jalan yang

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diusulkan, pertama-tama kami secara manual memetakan semua jalan yang ada di dalam dan di sekitar Hutan Harapan menggunakan citra penginderaan jauh. Kami kemudian menghitung perkiraan peningkatan hilangnya hutan dari tiga rute jalan tambang yang diusulkan menggunakan metrik berbasis pemetaan waktu tempuh. Terakhir, kami menggunakan analisis jalur dengan biaya terendah untuk mengidentifikasi rute baru jalan yang akan meminimalkan gangguan hutan dan biaya konstruksi jalan. Kami menemukan bahwa kepadatan jalan di dalam dan di sekitar Hutan Harapan sudah 3-4 kali lebih tinggi dari yang ditunjukkan oleh sumber data resmi. Berdasarkan analisis kami, masing-masing dari tiga rute jalan tambang yang diusulkan akan menyebabkan hilangnya hutan tambahan seluas 3.000-4.300 ha akibat perambahan hutan oleh manusia ditambah lagi 424 ha yang hilang dari pembangunan jalan itu sendiri. Kami mengusulkan rute baru untuk jalan tambang agar hilangnya hutan berkurang hingga 3.321 ha dengan biaya konstruksi yang jauh lebih rendah daripada rute lain yang direncanakan. Kami mereko mendasikan pendekatan seperti pendekatan kami, menggunakan analisis jalur biaya terendah, untuk meminimalkan biaya lingkungan dan keuangan dari proyek-proyek pembangunan besar.

KATA KUNCI

deforestasi, perencanaan lingkungan, Hutan Harapan, infrastruktur, konservasi alam, jalan, tata ruang, Sumatera, hutan tropis

1 | INTRODUCTION

Road networks are expanding rapidly around the globe, with some 25 million kilometers of new paved roads anticipated by 2050 (Dulac, 2013). Many of these roads are being constructed in developing tropical nations (Laurance & Arrea, 2017), which harbor ecosystems with exceptional biodiversity (Sodhi et al., 2010), carbon storage (Baccini et al., 2012), and other environmental services (Carrasco et al., 2016). Such roads, if poorly planned or implemented, can provoke serious problems such as illegal deforestation, mining, poaching, and forest fires (Clements et al., 2014; Laurance, Goosem, & Laurance, 2009).

The current tsunami of road building is unprecedented in scope. Initiatives such as China's massive Belt and Road Initiative (Laurance & Arrea, 2017), the Programme for Infrastructure Development in Africa (African Union, 2015), the South American Council for Infrastructure and Planning (Bebbington et al., 2020), along with national development corridors in Indonesia (Alamgir, Campbell, et al., 2019; Sloan, Campbell, Alamgir, Engert, et al., 2019; Sloan, Alamgir, Campbell, Setyawati, & Laurance, 2019), Malaysia (Alamgir et al., 2020; Sloan, Campbell, Alamgir, Lechner, et al., 2019), and Papua New Guinea (Alamgir, Sloan, et al., 2019), could dramatically impact the environment.

In Indonesia, the megadiverse island of Sumatra has a number of planned road developments including the Trans-Sumatran Highway (Sloan, Alamgir, et al., 2019), Jantho Road (Hanafiah, 2020), and a major mining road through the Harapan Forest (Diana & Jong, 2021), the largest tract of lowland rainforest remaining on the island (Diana & Jong, 2021). All of these projects will traverse intact rainforests (Sloan, Alamgir, et al., 2019), increasing human access while triggering further forest loss and degradation (Clements et al., 2014; Laurance et al., 2009; Linkie, Smith, & Leader-Williams, 2004).

The mining corporation PT Marga Bara Jaya has gained approval from the provincial government to construct a 88-km-long paved road for transporting coal, which would bisect the Harapan Forest. This road would result in the destruction of an estimated 424 ha of forest during road construction (Diana & Jong, 2021). Further forest disruption is expected following construction, with incursions of loggers, miners, hunters, and small-scale cultivators along the road.

The environmental impacts of the new road are uncertain. The mining corporation PT Marga Bara Jaya has provided three potential road routes but has not published assessments of their respective expected costs or environmental impacts. It has not, moreover, considered alternative routes that would have potentially lower environmental impacts. While multiple previous plans to construct a road through the Harapan Forest were rejected (Hermawan, 2020), approval was eventually granted in October 2019, making this development an imminent threat to Sumatra's scarce lowland forest.

Rerouting roads with potentially wide-ranging environmental impacts can markedly improve outcomes for nature while reducing overall construction costs (Cannon, 2017; Mahmoud et al., 2017). Here we use least-cost-path analysis, a strategic planning method, to identify alternative routes for the Harapan Forest road in Sumatra, Indonesia. This type of analysis allows users to create a cost surface that quantifies landscape features, to generate routes that minimize cumulative costs of movement between locations (Adriaensen et al., 2003). The user-designated cost surface can represent various environmental or economic landscape features and importantly allows multiple features to be combined into a single cost surface. This makes least-cost-path analysis a flexible tool for environmental applications, such as identifying road routes that limit environmental and economic impacts. Our analysis identified several alternative routes for the PT Marga Bara Jaya road that would substantially reduce both the environmental impacts and construction costs of the development.

2 | METHODS

2.1 | Study site

The Harapan Forest, or "Forest of Hope," is an important conservation area in Indonesia, containing around 20% of Sumatra's remaining lowland rainforest (Diana & Jong, 2021). Spanning 986 km^2 in area, the Harapan Forest contains a mix of old-growth rainforest and selectively logged forest (Harrison & Swinfield, 2015). It hosts

TABLE 1 Least-cost-path cost-surface scenarios

Scenario	Name	Cost layer weights		
		Road cost	Forest value	Deviation penalty
All layers weighted equally	A	1	1	1
Forest value weighted higher	B	1	10	1
Forest value weighted much higher	C	1	100	1
Forest value and deviation weighted higher	D	1	10	10
Forest value and deviation weighted much higher	E	1	100	100

Note: Five separate cost surfaces were created by applying variable weightings to the three component layers. The road cost layer was given a weight of 1 in all scenarios as low values are given highest priority in least-cost-path generation.

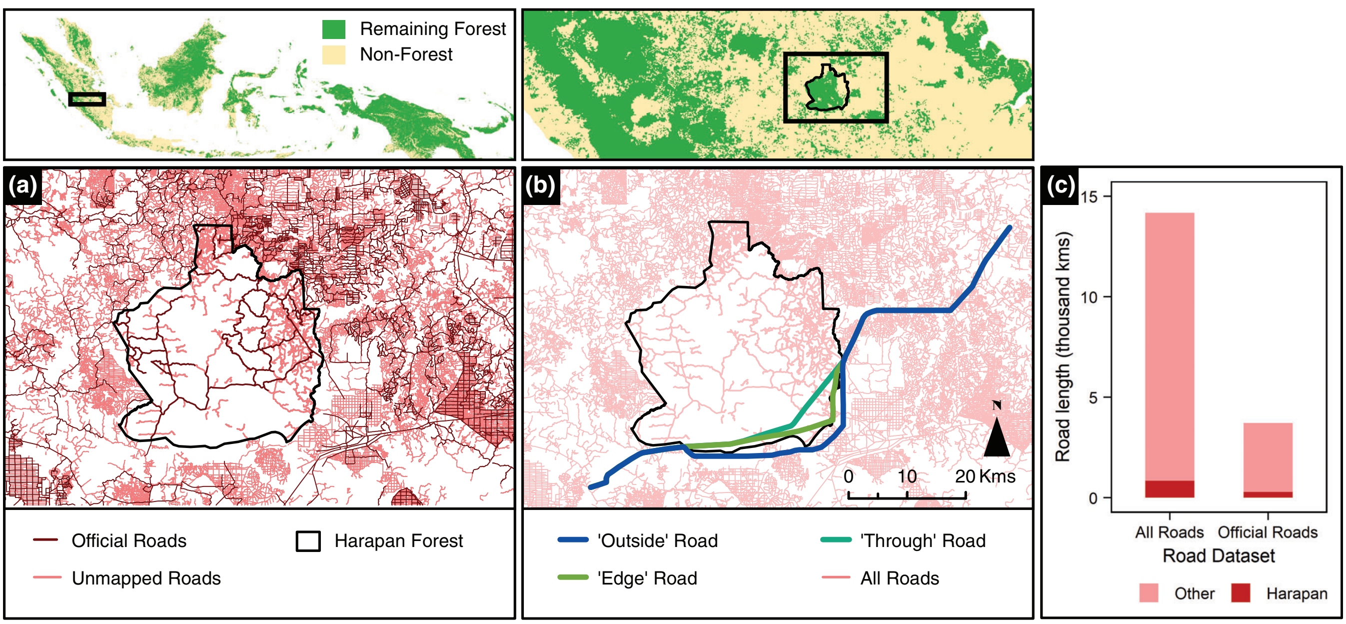

FIGURE 1 Existing road networks within and around the Harapan Forest in Sumatra, Indonesia. (a) The many unmapped roads digitized in this study were not recorded in Indonesian official road data; (b) locations of three proposed mining road routes: "outside" the forest; along the "edge" of the forest; and "through" the forest; (c) mapped road lengths in the Harapan Forest and the surrounding region as a whole

exceptional biodiversity, including 55 of Sumatra's 77 known frog species and many endangered mammal, bird, and plant species (Diana & Jong, 2021; Swinfield & Harrison, 2015). The forest is also an important refuge for large-mammal fauna, including the Sumatran tiger (*Panthera tigris sumatrae*), Asian elephant (*Elephas maximus*), Malay tapir (*Tapirus indicus*), and a diverse assemblage of primates (Utomo & Walsh, 2008). Despite its biological importance, the Harapan Forest has lost a significant portion of its area, and almost all of its adjacent forest, in the last 20 years (Hansen et al., 2013).

2.2 | Roads

We manually digitized three proposed locations for the mining road from a figure in the Indonesian Ministry of Environment and Forestry's EIA documentation (Hermawan, 2020). The image was georeferenced in ArcMap 10.7 using a projective transformation, with a total root-mean-square error (RMSE) of 178 m. Additionally, we digitized all previously unmapped roads in the Harapan forest and surrounding areas using the highest-quality satellite imagery available through Google Earth, following methods described in Sloan et al. (2018).

2.3 | Least-cost-path analysis

To propose new construction locations for the mining road, we conducted least-cost-path analysis using ArcMap 10.7. Least-cost-path analysis utilizes a user-designed cost surface to generate routes that minimize the cumulative cost of movement between locations (Adriaensen et al., 2003). As the cost surface is user-designated, it can represent various landscape features such as habitat quality (Sawyer, Epps, & Brashares, 2011), dispersal limitations of wildlife species (Balbi et al., 2019), or construction costs (Atkinson, Deadman, Dudycha, & Traynor, 2005), among others. Crucially, least-cost-path

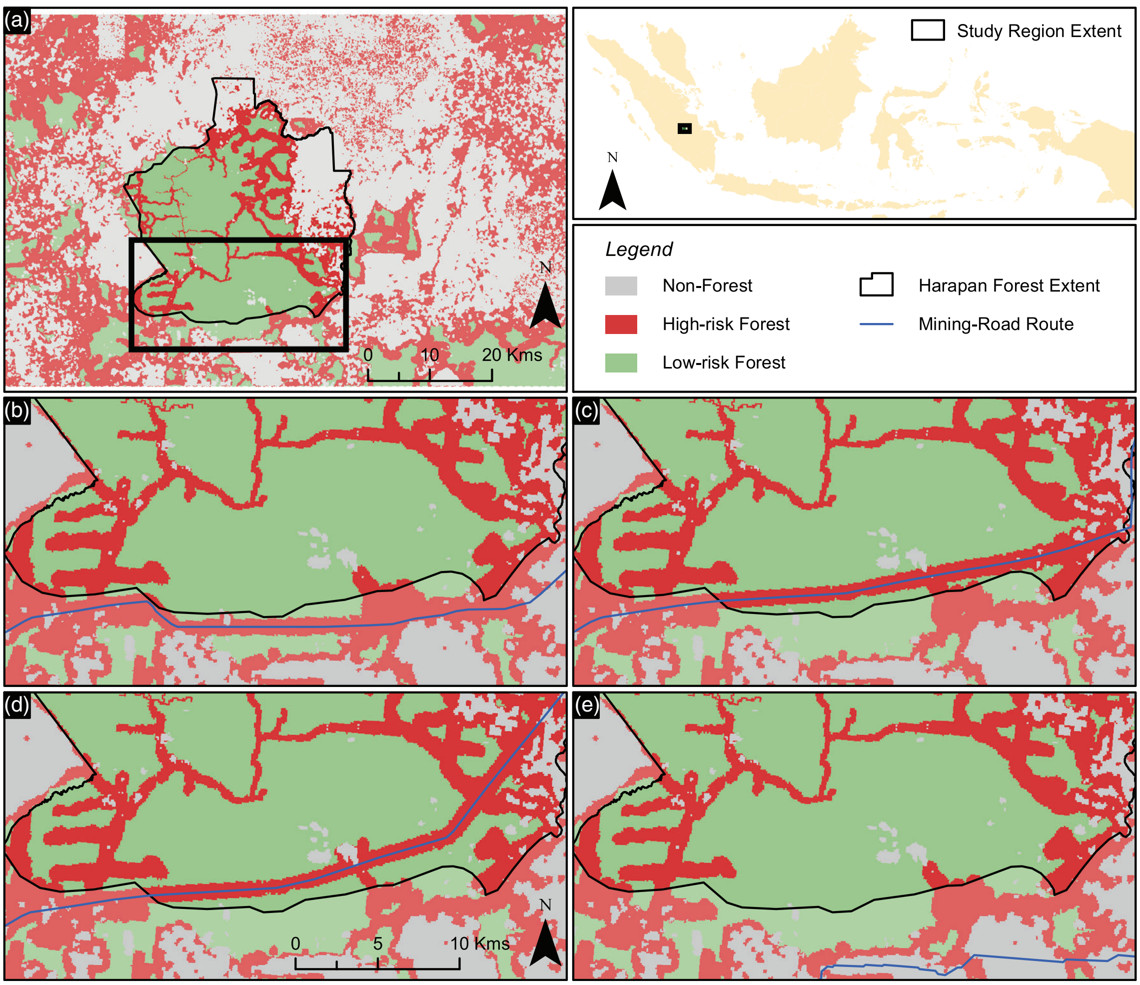

FIGURE 2 Travel time maps of the Harapan Forest in Sumatra, Indonesia. Maps show estimated travel times based on least-cost-path analyses for (a) no mining-road development; (b) an "outside" road route; (c) an "edge" road route; (d) a "through" road route; and (e) the least-cost route "B" for road development

analysis allows for multiple variables to be combined into a single cost surface, with flexibility to apply varying weights to each factor, making it a useful method for multiple ecological and environmental applications.

Our user-defined cost surface consisted of three main components: (a) a relative index of forest value; (b) a relative index of road-construction cost; and (c) a factor to penalize routes that deviate from the original proposed road locations (see Figure S1, Supporting Information). All cost surfaces, as well as all other geospatial analyses, were calculated at a 1-ha cell resolution (100 × 100 m). We used the origin and destination for the mining road, digitized from EIA documentation for the project (Hermawan, 2020), as the start and end points. The forest value layer was calculated using landscape-scale metrics to determine forest integrity and intactness (Table S1). Forested cells scoring above 0.65 in the forest-value layer were considered "high value" forest due to their high forest integrity (see Supporting Information). We calculated relative road costs using landscape metrics related to current level of development and ease of construction (Table S1). While land acquisition may factor into road construction costs, there is limited reliable information on land tenure in Indonesia, and often competing claims over land ownership and land occupancy (Gaveau et al., 2017; Guild, 2019). Hence, we did not include land-acquisition costs in our model. Finally, the deviation-penalization metric was calculated as the normalized distance from the original mining-road locations from the EIA document.

We combined the three cost metrics using varied weights to create five different cost surfaces for least-cost-path scenarios (Table 1). We carried out least-cost-path analysis using each of these five cost surfaces, to create new proposed mining-road routes. These proposed routes were then overlaid onto the existing travel time cost surface, and travel time was calculated to create new estimates of risk of forest encroachment. We also calculated, for all potential mining-road routes, a "Road Cost Index" by summing the relative cost for each cell over the total length of the road. Finally, we determined the number of cells that already contain roads (and therefore might require only improvement of existing roads) and the number of cells that did not (and hence would require new-road construction).

2.4 | Travel time

To quantify accessibility of forested areas before and after mining-road construction, we used an adapted version of the travel-time metric developed by Weiss et al. (2018) (see Supporting Information). Travel time is a useful metric for estimating the spatial extent of environmental impacts as it considers both distance to sources of threats (i.e., human populations) as well as the ability of the landscape to limit or facilitate access (Jusys, 2016; Rideout, Joshi, Viergever, Huxham, & Briers, 2013). We calculated travel time for the region surrounding and inside the Harapan Forest under nine different scenarios to estimate the influence of the road on potential forest loss. These nine scenarios were (a) a control scenario (no road); (b) road route outside the Harapan Forest; (c) road route along the margin of the Harapan Forest; (d) road route through the Harapan Forest (Figure 1), and five alternate routes developed using least-cost-path analysis (Table 1). These travel-time maps were used to compare the potential deforestation provoked by road development.

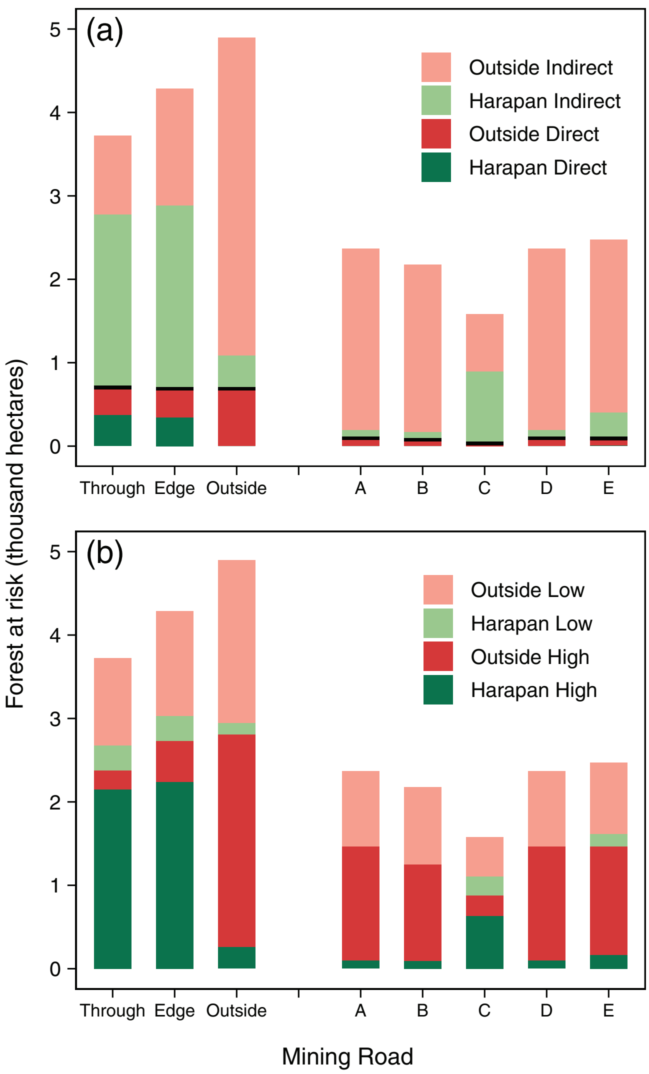

FIGURE 3 Potential increase in at-risk forest following development of different mining roads in the Harapan Forest in Sumatra. (a) Comparison of the magnitude of potential direct and indirect forest loss, where the former occurs within 1 ha cells the road will bisect. (b) The quantity of high-value and low-value forest loss inside and outside the Harapan Forest. At-risk forest was calculated as the number of low-risk forest cells that became high-risk following road construction

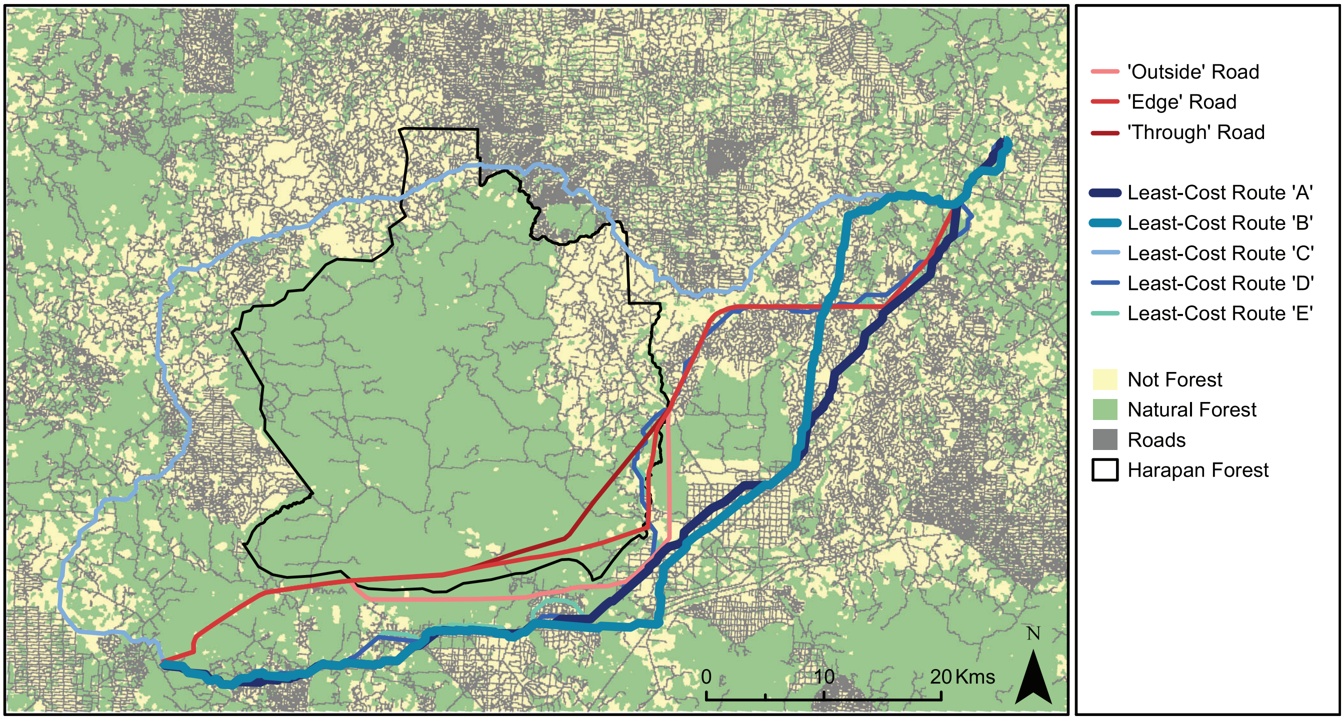

FIGURE 4 Mining-road routes for both the three initial proposed routes and our five potential alternative routes generated using least-cost-path analysis. Roads "A" and "B" (displayed using a heavier line) are considered the best potential routes from environmental and construction-cost perspectives

2.5 | Forest-risk threshold

To quantify the extent of remaining natural forest cover, we downloaded Version 1.8 of the Global Forest Change forest cover dataset (Hansen et al., 2013). We further delineated natural forest cover by removing deforested areas from the Global Forest Change dataset and masking out palm oil plantations mapped by Xu, Li, Ciais, Cheng, and Gong (2020). To compare the area of forest under greatest risk of deforestation following mining-road development, we identified a threshold travel time at which forest loss diminishes substantially. For each travel-time value, we calculated the percentage of cells that were no longer natural forest (Figure S3). At an estimated travel time of 46 min from populated areas, the chance of a cell undergoing conversion from natural forest was <5%, and we used this threshold to distinguish "high-risk" and "low-risk" forest.

3 | RESULTS

3.1 | Current threat level

We digitized 562 km of formerly unmapped roads inside the Harapan Forest, bringing its total interior road length to 848 km. Additionally, we digitized 9,908 km of previously unmapped roads in the region immediately surrounding the Harapan forest, bringing the total road length there to 13,333 km (Figure 1).

To date, the Harapan Forest has lost 18.2% of its natural forest extent, whereas the area surrounding the Harapan has lost 52.6% of its natural forest (Figure S1). Of the remaining natural forest, 74.5% (55,475 ha) inside the Harapan Forest is considered high value, whereas only 13.7% (26,113 ha) of the forest outside is high value.

The Harapan Forest is under serious threat. Overall, 50.3% of its remaining natural forest area (22,676 ha) lies within the high-risk travel-time threshold of 46 min from a populated area. Additionally, 77.9% of the surrounding natural forest is within this high-risk zone.

3.2 | Road construction and forest risk

Construction of a high-speed paved road in the Harapan Forest (such as the proposed mining road) will further increase the forest area with a high risk of encroachment (Figure 2). For all proposed road routes, forest under high risk of encroachment following human incursions dwarfed the amount of forest loss caused by road construction itself (Figure 3a). Direct forest losses from planned road construction were typically a few hundred hectares, whereas forest at risk from human incursions along the road ranged at least an order of magnitude higher, ranging

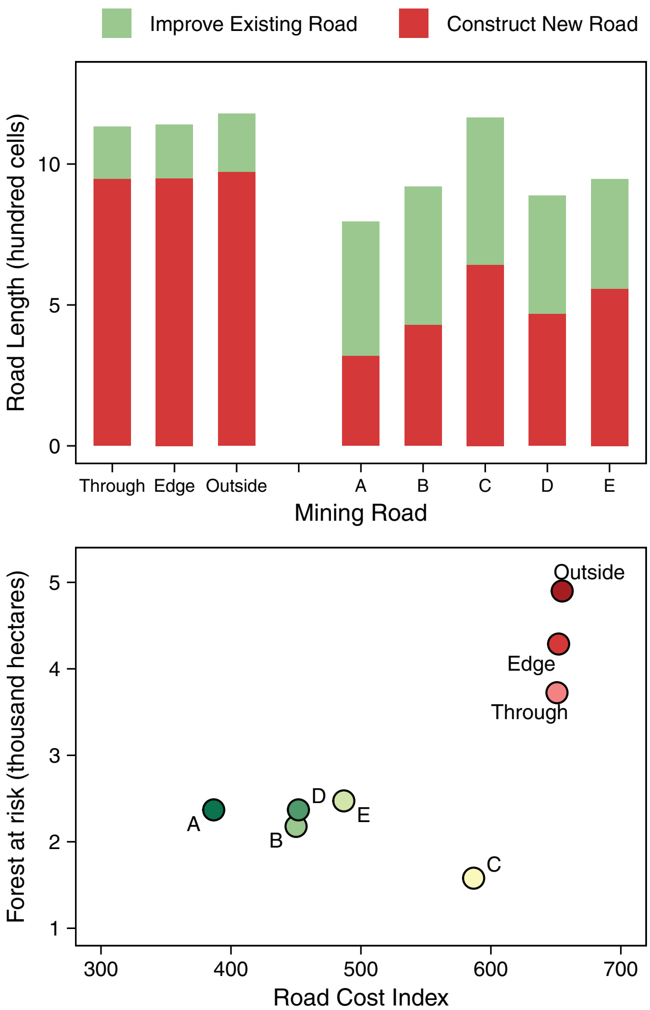

FIGURE 5 Road construction costs for each of eight proposed mining-road routes in southern Sumatra, Indonesia. (a) Number of 1-ha cells in each roads route that currently have roads or lack roads. (b) Relative road construction-costs summed across the length of each road (Road Cost Index), compared to potential increases in at-risk forest. Roads with low values on each axis are favored, having both lower development costs and less potential forest loss

from 3,000 to 4,300 ha (Figure 3b). For all proposed road routes, most of the forest that experienced an increased risk of conversion was high-value forest (Figure 3b).

3.3 | Alternative road routes

All of the alternative mining-road routes we devised using least-cost-path analysis (Figure 4) resulted in less forest being categorized as high-risk, especially high-value forest within Harapan Forest (Figure 3b), compared to the proposed mining-corporation routes. All of our alternative routes would result in <100 ha of direct forest loss from road building, and all but one resulted in no direct loss inside the Harapan Forest (Figure 3a).

The two best performing least-cost-path roads, “A” and “B,” resulted in 2,369 ha and 2,178 ha of forest becoming high-risk, respectively. Moreover, only 101 and 94 ha of high-value Harapan forest, respectively, was expected to become non-forest cover. Even when we included a high penalty for deviating from the original proposed routes in the least-cost-path analysis, our proposed route “E” resulted in 2,473 ha of forest becoming high-risk, but with only 166 ha of this being high-value Harapan forest. Despite a nontrivial risk to existing forests, this route is a marked improvement on all three of the original proposed mining-road routes in terms of its environmental impact.

3.4 | Road construction and relative costs

Our route prioritization method resulted in proposed routes spanning shorter distances (aside from road “C”) (Figure 5a) and hence having lower potential travel times. The three proposed mining-road routes required construction of new roads across between 946 and 971 cells, while our least-cost-path analysis identified new routes that would require new road construction across between 318 and 642 cells (Figure 5a). By summing the relative costs of construction across the length of each proposed road route, we demonstrate that our proposed alternative routes would have both lower impacts on forests and lower relative construction costs (Figure 5b). By prioritizing areas that already have roads, especially larger roads, we could avoid areas where construction costs would be high—such as sites with steep slopes or those that lack existing bridgeworks or river crossings.

4 | DISCUSSION

With only 3% of Sumatra's lowland rainforest surviving as of 2019 (Hansen et al., 2013), new road developments on the island need not, and should not, intersect the last few remaining areas of intact forest (Laurance & Balmford, 2013; Laurance, Clements et al., 2014; Sloan, Alamgir, et al., 2019). Construction of a high-speed, high-traffic-volume mining road through the Harapan Forest would almost certainly result in a spike in illegal forest loss and degradation (Barber et al., 2014), with serious impacts on rare fauna and flora. Fortunately, strategic planning methods, such as the least-cost-path analysis employed here, allow one to identify alternatives to existing development plans with markedly lower environmental and construction costs.

If the Indonesian mining firm PT Marga Bara Jaya prevails and one of its proposed road routes (Figure 4) is selected, the Harapan Forest could become an environmental crisis in the making—with sharp increases in road-related poaching (Clements et al., 2014), mining (Laurance, 2008), forest clearing, and logging (Barber et al., 2014). Human encroachment along the road is expected to cause major forest loss (3,000–4,500 ha), dwarfing that from road construction itself (424 ha). The Harapan Forest's status as an ecological-restoration concession is unlikely to provide real protection from illegal forest exploitation (Spracklen, Kalamandeen, Galbraith, Gloor, & Spracklen, 2015) or degazettement (Golden Kroner et al., 2019) after road building, as it has already suffered considerable unofficial roading and conversion for palm oil.

The Harapan Forest represents a new policy structure for forest conservation in Indonesia and globally. This model of lowland rainforest conservation, whereby industrial selective-logging concessions are managed for ecosystem restoration, has inspired further restoration-license applications covering over 40,000 km^2 worldwide (BirdLife International, n.d.). The Harapan Forest therefore has unique value from both biodiversity and conservation-policy perspectives. Yet the planned mining road could fragment and further disrupt the Harapan Forest, greatly diminishing its success as a conservation model (e.g., Burivalova, Şekercioğlu, & Koh, 2014). Fortunately, we see prospects for rerouting the Harapan road to skirt the main forest block while traversing nearby lands that are largely deforested. Similar efforts in Nigeria led to the successful rerouting of a major planned highway to avoid bisecting the country's largest remaining rainforest tract (cf. Cannon, 2017; Mahmoud et al., 2017).

New roads are often touted for their capacity to yield economic growth and other benefits for rural populations (Hettige, 2006). However, poorly planned roads often fail to meet either of these goals (Alamgir et al., 2017; Collier, Kirchberger, & Sonderbom, 2016; Mahmoud et al., 2017; Messick, 2011). Well-located roads can improve a range of outcomes by increasing access for rural residents to urban markets, education, and healthcare (Bryceson, Bradbury, & Bradbury, 2008; Laurance, Sayer, & Cassman, 2014; Weiss et al., 2018) but the Harapan mining road, as presently planned, would yield few such benefits. Further, the road would notably be expensive to construct because it fails to take advantage of existing roads that could be improved to allow heavy-vehicle traffic (Collier et al., 2016; Kaliba, Muya, & Mumba, 2009). It is difficult to escape the impression that plans for the Harapan mining road were devised with little attention to their environmental and socioeconomic impacts and overall cost.

Using a relatively simple least-cost-path analysis, we were able to identify alternative routes that would allow a major mining road in Sumatra to proceed with markedly reduced costs and environmental impacts than presently planned. Strategic planning like this can improve socioeconomic outcomes for rural residents and indigenous peoples, by ensuring that new roads improve their access to markets, education, and healthcare at the lowest cost (Laurance, Clements, et al., 2014). Strategic planning can also reduce the environmental toll of new road projects by avoiding critical ecosystems and wildlife habitats (Alamgir et al., 2017; Laurance & Balmford, 2013). With more than 500,000 km of new roads expected in the Asia-Pacific region by 2025 (Coordinating Ministry For Economic Affairs, 2011; Eleventh Malaysia Plan, 2015), the need for proactive road-planning cannot be overstated.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Jayden Engert: Conceptualization (lead); formal analysis (lead); investigation (equal); methodology (lead); writing – original draft (equal); writing – review and editing (equal). **Yoko Ishida**: Investigation (equal); data curation (lead). **William Laurance**: Supervision (lead); funding acquisition (lead); writing – original draft (supporting); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

Roadmaps and meta-data generated for this study have been uploaded onto Open Street Map (https://www.openstreetmap.org), a publicly available global-road archive. Additional datasets pertaining to the study are available upon request.

ETHICS STATEMENT

Institutional ethics review was not required.

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SUPPORTING INFORMATION

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