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Mapping environmental risks and socio-economic benefits of planned transport infrastructure: a global picture

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Executive Summary

Study Purpose

Improving road and rail networks can have social and economic benefits but also significant environmental consequences on biodiversity and ecosystem services. Weighing the ecological consequences of building and operating transport infrastructure in specific locations against the social and economic benefits that would result is essential for making sound decisions.

This study aimed to produce a foundational, globally consistent assessment of the risks and benefits to people and the nature of currently planned, large-scale road and rail transport infrastructure projects. Ultimately this can help to improve regional, national, and global decision making. The study also included the development of a novel global database of planned roads and railways. Detailed results of the analysis can be explored using the Global Infrastructure Impact Viewer (GIIV), a web-based tool that was created for this project.

Key findings

The findings summarised here are taken from analyses in the main document and in Appendix 1 – Additional analyses.

Database:

- The database of planned roads and railways draws on 57 data sources.
- Nearly half a million kilometres (489,730 km) of road and rail development is currently planned or is being built (approx. 1.2% of existing global stock of road and rail). This is lower than other estimates for future infrastructure due to differing approaches, i.e., mapping available plans versus modelling future growth.
- China has the most road and rail planned (75,153 km), followed by Russia (38,370 km) and Brazil (23,814 km).
- The database coverage spans 137 countries and territories and overlaps with nearly half (422 of the 847) of the world's terrestrial ecoregions, primarily those in broadleaf and mixed forest biomes.
- We assume most of these planned road and rail projects will finish in the near future, i.e., within 10/15 years. However, the exact time frame is unknown, as is project fate – projects could be delayed, never constructed, or even abandoned once complete.

Risks to biodiversity:

Species

- Nearly 60% of the species in our study (2472 out of 4096) overlap with risk areas from planned transport infrastructure. Of these, 42 species are at risk of a >10% decline in their probability of persistence.
- Highest risks to species' persistence are found in the global tropics, especially Indonesia, Papua New Guinea and South America.
- As species selected in this study are already of conservation concern, and the loss (i.e., extinction) of any species is irreversible, the increased risks described here should be seriously considered.

Conservation areas

- Approximately 12% of planned transport infrastructure length crosses conservation areas (i.e., either protected areas, 7.3%, or Key Biodiversity Areas, 6.9%)
- Highest risk to conservation areas, based on length crossing into either PAs or KBAs, are found in Central and Western Europe (Poland, Germany), and South America.
- As well as risks to the biodiversity and/or ecological processes in these areas, new transport infrastructure may disrupt ongoing conservation management.

Wilderness areas

- 1.6% (approx. 8000km) of planned infrastructure crosses wilderness, i.e., areas largely undisturbed by human development.
- Highest risks to wilderness areas were found in North America (Canada) and South America (Brazil, Peru).
- Although not all countries have wilderness areas, for those that do, new infrastructure developments crossing into these areas can be a precursor to large scale land use change.

Risks to ecosystem services:

- The total direct risk of infrastructure development on carbon storage is approx. 883 million tonnes of carbon loss from vegetation biomass and soils (up to 1m depth). For context, in the year 2000, the carbon stocks held in aboveground biomass of Costa Rican forests was approx. 776 million tonnes of carbon (Harris *et al*. 2021). Highest risks are in boreal and tropical areas where large forests and carbon-dense peatland soils are found.

- Global infrastructure development potentially risks approx. 1.17 million tonnes of nitrogen no longer being retained by vegetation. Removal of vegetation can result in nitrogen pollution entering watercourses, affecting downstream water quality. These risks are greatest where areas of dense forests are found.

- Surface water and wetlands play a key role in the livelihoods of people and the movement and health of species, as well as global climate regulation, however, it was not possible to quantify the potential losses of wetland-related services resulting from infrastructure impacts. Infrastructure development coinciding with areas of surface water is greatest in boreal and tropical zones.

- Pollinator dependent food production is liable to be stressed by infrastructure development through land conversion and habitat reduction. Impacts are high in temperate regions (USA and Europe), as well as in India, China and Argentina.

- Indirect risks to ecosystem services could be significant. The development of road and rail infrastructure could allow access to new areas, resulting in illegal deforestation and land conversion (e.g., to agriculture or mining).

- As well as impacting our ability to protect carbon stores and mitigate climate change, infrastructure development may itself be vulnerable to climate-related hazards such as flooding, landslides and extreme weather events. Furthermore, infrastructure development may undermine our resilience to climate change by reducing the healthy functioning of ecosystems.

Economic benefit:

- GDP increase associated with planned road and rail infrastructure ranges from approx. 0.1% (17.4 billion USD) across North America and Australasia to 1.3% (4.4 billion USD) for the lower income countries (World Bank classification) outside Europe, North America and Australasia. The largest absolute benefits are expected in countries classified as upper middle income outside Europe, North America and Australasia. Here GDP gains of 0.9% or 212.2 billion USD (per year) are estimated.

- Highest GDP increases in absolute terms are in Saudi Arabia, China and Russia, driven by large, planned rail infrastructure investment. Similarly, Brazil and Argentina have large-scale rail infrastructure projects planned that may deliver significant wider economic benefits.

Employment benefit:

- Roughly 2.4 million new jobs globally (an increase of 0.19%) are associated with planned road and rail infrastructure.

- Significant positive effects on employment are projected in Pakistan, Tajikistan and India, Mali, and Uzbekistan, primarily due to planned rail infrastructure projects in these countries.

- The literature is mixed in terms of benefits to employment from increasing transport infrastructure

- The analysis focused on low and low to middle income countries where there is better evidence for transport infrastructure boosting employment.

Risk-benefit comparison:

When comparing combined environmental risk (i.e., risk to biodiversity and ecosystem services) to economic benefit, countries are grouped in four main categories.

- Higher risk – lower benefit: Bolivia, Peru and Hungary fall in this category for which infrastructure plans require highest scrutiny.

- Higher risk – higher benefit: examples include Indonesia, Russia, China, Brazil and Argentina – typically those with the largest quantities of planned transport infrastructure. Plans for this category should also be reassessed.

- Lower risk – lower benefit: majority of countries are in this category, spread mostly in Africa, northern South America, Australia, and parts of Asia. It is worth considering return on investment for these countries.

- Lower risk – high benefit: mostly in South and Central Asia, but also USA and Mexico, along with a few southern African countries. The favourable trade-off in this category should mean their plans are of least concern overall.


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Three main factors help explain why countries are in either of the above higher risk categories: 1) poor spatial planning and regulations/enforcement, 2) large lengths of planned infrastructure and/or 3) the countries are naturally environmentally rich.

There are various issues of inequality surrounding this comparison, including:

- historical inequities from developed countries typically having benefited from depleting their natural resources already – making lower risk scores more achievable, and
- distributional inequities where people that benefit from road and rail development may be different to those facing consequences of environmental damage (e.g., local economic benefits compared to global risks from depleting carbon stocks).

Key insights:

- Road and rail infrastructure is necessary but needs to be better planned to reduce negative climate and biodiversity impacts.
- Some of the risk metrics, currently using global data, can be adapted for use with national datasets and local planning assessments
- A web tool has been developed as an extension of this work for further exploration of the study's results
- Considering nature-related risks to infrastructure is a natural next step to this work.
- This study delivers a novel database and innovative metrics to give a global perspective on risks and benefits of near-future road and rail infrastructure. We hope this body of work can be built on to be of even greater benefit in future.

Future improvements:

- Planned road and rail database: potential improvements include greater geographic coverage, better data accessibility, increased update frequency. More involved changes for longer term feasibility include introducing requirements for data transparency for infrastructure developers, as well as providing details on progress and post-construction monitoring.
- Biodiversity: risk metrics could be improved by including species-specific impact distances, coupled with further research on how response to infrastructure varies by species. It would also be beneficial to incorporate less-studied indirect risks, e.g., connectivity, and cumulative risks from multiple projects.
- Ecosystem services: modelling land use change and settlements associated with new road and rail infrastructure, as well as estimating economic costs from lost ecosystem services would be useful for future analysis. Similarly, modelling services provided to 'downstream' beneficiaries and considering risks to infrastructure from depletion of services would also improve understanding of impacts.
- Socio-economic benefits: as the relationship between new infrastructure and economic growth is still not clear cut, further research is needed. This is also true for employment benefits where the evidence is especially mixed. Social impacts need more research, especially on how transport infrastructure impacts different groups, including those that may be more vulnerable, such as indigenous peoples.

Introduction: why map and model global transport infrastructure?

Background and Context

Infrastructure sits at the heart of the 2030 Agenda for Sustainable Development, influencing 92% of the 169 Sustainable Development Goal (SDG) targets across all 17 of the goals (Thacker *et al.* 2018). It provides essential services that allow our economies to function and grow and are critical for human health and wellbeing. At the same time, infrastructure in all sectors has negative impacts on the environment. Vast amounts of natural resources are required for its construction, it is responsible for 79% of global greenhouse gas emissions (Thacker *et al.* 2021) and is has direct and indirect impacts on nature. Of these, it is perhaps the latter that is least well understood, and this study seeks to further our understanding of the impacts that linear infrastructure in one sector – transport – can have on nature.

Why do we need roads and railways?

Transport infrastructure, such as roads and rail, facilitates economic and human development. Notably it decreases transportation costs and facilitates economic activity and human movement, thus stimulating demand for goods and services, which subsequently creates more jobs (Laurance *et al.* 2015; Laurance 2018). Additionally, constructing new or retrofitting existing linear transport infrastructure improves productivity, reflected by an increase in efficiency, ultimately generating higher GDP. There are other benefits including access to healthcare and education (Weiss *et al.* 2018).

What are the risks from transport infrastructure?

There are risks involved in the development and use of all types of infrastructure, and specific risks from linear transport infrastructure (i.e., road and rail) development. Some of the key concerns centre around negative impacts on the environment, especially in terms of biodiversity and ecosystem services (ES)[1] .

For biodiversity, the obvious direct negative impacts are habitat loss, degradation and fragmentation, and collision-related mortality (Laurance *et al.* 2014; Laurance *et al.* 2015; Laurance 2018; Hughes 2019; Giuliani *et al.* 2020; Vilela *et al.* 2020). In addition, construction and use of infrastructure can affect species through noise, pollution and dust (Ibisch *et al.* 2016; Carter *et al.* 2020). Indirect negative impacts on biodiversity from linear infrastructure development include increased hunting and poaching (Hughes, 2019; Benítez-López *et al.* 2017) and spread of invasive species and diseases (Hughes, 2019; Simmonds *et al.* 2020; Ibisch *et al.* 2016), in addition to opening new areas for habitation and agricultural expansion by enabling access to previously inaccessible areas.

Similarly, the loss and degradation of natural ecosystems caused by land conversion is a clear direct negative impact for ecosystem services. The direct negative impact on the structure and functioning of ecosystems is reflected in reductions of associated ecosystem services such as air quality regulation, climate regulation and climate change mitigation, flood and coastal protection, water quality regulation, and others (Laurance *et al.* 2014; Laurance *et al.* 2015; Vilela *et al.* 2020; Simmonds *et al.* 2020).

In the case of global climate regulation, for example, carbon storage loss results from soil sealing and the release of vegetation carbon stock in road construction (Tardieu *et al.* 2015). This negatively impacts global climate change mitigation efforts and contributes to the increase of greenhouse gases in the atmosphere. Road construction will have indirect negative effects on natural landscapes and their ecosystem service provision, including cultural and intrinsic values. For example, road development may open previously inaccessible forests to habitation and illegal logging (Barber *et al.* 2014). Infrastructure development may increase climate-related hazards, such as landslide risk in areas with steep slopes (Boston 2016; Larsen and Parks 1997).

In general, the short- and long-term risks and benefits are not adequately accounted for at the planning stage. Further details of impacts on biodiversity and ecosystem services are covered elsewhere in the main report and Appendix 1. An extensive literature covering these impacts exists but is only briefly summarised here to provide context to the study.

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[1] Ecosystem services are the benefits people derive from ecosystems and their functions which contribute to human well-being and economic activities (Millenium Ecosystem Assessment 2005; Brown *et al.* 2016).

What does the future suggest?

Paved road infrastructure is projected to increase globally by 3.0 to 4.7 million kilometres by mid-century, representing an increase of 14%–23% with respect to stocks in 2018 (Meijer *et al.* 2018), and some estimates are higher still (Dulac *et al.* 2013). Although such increases are largely predicted to occur in areas of urban expansion, notable infrastructure developments aiming to improve connections between urban areas are also being planned (Hughes 2019; Vilela *et al.* 2020; Carter *et al.* 2020).

Does international policy play a role?

The three Rio Conventions – the Convention on Biodiversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD) – provide a useful context in which to understand and from which to measure the potential environmental impacts from planned infrastructure (Convention on Biodiversity [CBD], 1992). Their scope covers some of the risk areas from transport infrastructure development, namely biodiversity loss, land degradation, and climate change.

Well-planned and developed transport infrastructure plays a key role in achieving the Sustainable Development Goals (SDGs), influencing 76 different SDG targets across all 17 goals (Thacker *et al.* 2018) and this study has brought together a set of coherent analyses that allows decision-makers to understand trade-offs associated with transport infrastructure investment across scales. The trade-offs and synergies between SDGs associated with transport infrastructure investment could be explored as part of national development planning.

In addition, a new resolution on sustainable and resilient infrastructure was adopted by Member States at the fifth session of the UN Environment Assembly (UNEA 5). This resolution details specific actions for UN Member States, UNEP and partners and provides a strong mandate for continued work on integrated approaches to sustainable infrastructure.

Targets, including those relating to the SDGs and the Post-2020 Global Biodiversity Framework (which is, at the time of writing, at a draft stage and subject to ongoing negotiation), are intended to be practical and useful instruments for prioritising and improving the health and sustainability of our environment and society. In turn, development mechanisms based on these targets and policies should enable government and industry to develop more sustainable transport infrastructure.

How can we ensure a sustainable transport infrastructure future?

Effective planning and decision-making require that potential risks and benefits of a given road/rail project need to be measured and predicted. Typically, relevant measurements are carried out on local and subnational scales, such as through strategic environmental assessments (SEAs), environmental impact assessments (EIAs) and life cycle assessments (LCAs). Recently as the scale of infrastructure initiatives has increased, so has the geographic coverage of studies measuring potential impacts. Studies include work on transport corridors in Africa (Laurance *et al.* 2015), the Development Corridors Partnership Project (Juffe-Bignoli *et al.* 2021.), the Belt and Road Initiative in Asia (Hughes 2019; Carter *et al.* 2020), the road network in Amazon (Vilela *et al.* 2020) and more. The mapping and modelling of future transport infrastructure, accounting for the economic, social and environmental project costs and benefits, needs to occur at local, regional, national, and transnational scales to enable sustainable infrastructure outcomes.

How is this study going to make a difference?

To date, there is no globally consistent assessment of the risks and benefits of planned large scale terrestrial transport infrastructure projects. This study aimed to create the foundation of such an assessment, a valuable piece for advancing regional, national and global decision making on infrastructure.

To achieve this aim, we:

1. developed a new global database of planned roads and rail,
2. created a suite of relevant environmental and socio-economic metrics,
3. estimated environmental risks at the global, country and project level,
4. compared environmental risks to benefits to the economy at the country level.

The study provides a more detailed view of the distribution of risks posed by global planned transport infrastructure, and could be relevant for informing national infrastructure and land use planning. However, these analyses do not provide a substitute for local scale assessments.

Audience, scope and structure

This report is aimed primarily at a non-technical audience and policy makers. Its scope is to provide a global picture of potential risks and benefits of planned transport infrastructure. We focus on (paved) roads and rail linking settlements and development centers (i.e., not within built up areas). These were considered an essential starting point considering the geographic scale, their potential impacts, and data availability. We note the importance of impacts from other transport infrastructure (e.g., ports, terminals, airports) but initiated this first effort with a focus solely on linear transport infrastructure: roads and rail. The study does not aim to replace sub-national and local level planning, but some of the risk metrics and approaches in this study will be useful at such scales.

Complex environmental relationships, economic costs of loss of ecosystem services, and detailed (e.g., local, gender disaggregated, etc.) socio-economic benefits were outside the scope of this study. We could not directly compare economic costs from roads and rail to their economic benefits, but instead focussed on risks. This was due to data limitations for construction and maintenance costs, along with complexities of modelling the monetary value of lost ecosystem services at a global scale. For brevity, at the country level we show total risks of all planned roads and rail infrastructure. Showing the values for risks and benefits per kilometre of new infrastructure can provide further insight, for which a separate web viewer (see information box) has been produced to accompany this study.

BOX 1 THE GLOBAL INFRASTRUCTURE IMPACT VIEWER (GIIV)

This is a web-based tool that allows users to explore the data from this study on an interactive map. Using the tool, it is possible to view the spatial results for different indicators alone or combined with others, at either the national or project scale.Website: https://www.giiviewer.org/

The main body of the report is structured around a series of questions. These are answered through spatial analysis of characteristics of planned transport infrastructure, or statistical relationships at the country level. Methods are described in text boxes, so as not to interrupt the flow of the main text. Similarly, text boxes are used for qualitative descriptions of aspects that were not feasible to include in the analysis, but are relevant to the broader topics, namely a comparison of road versus rail infrastructure and consideration of resource consumption and emissions from construction. For brevity, the Appendices are used to house relevant supporting details. Appendix 1 contains additional analyses that either feed into the metrics in the risk-benefit comparison in the main body of the report, or do not feed in but are still of interest (i.e., the benefits to employment analysis). Appendix 2 contains more detailed methods descriptions for the various risk and benefits metrics.


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Where are road and rail infrastructure projects planned?

Towards a Global Database

To know where new infrastructure is planned requires a substantial data-gathering exercise. Until this study effort no such global database existed. Therefore, one of the first key tasks of this study was to collate plans from around the world and format them into a single, consistent global database on planned roads and railways. Now the database exists, it can be added to and updated regularly should time and financial resources be available (not addressed at time of report publication). This database for near-future infrastructure would complement other spatial databases for existing transport infrastructure, such as the Global Roads Inventory Project (GRIP) (Meijer *et al.* 2018).

BOX 2 METHODS - GLOBAL DATABASE

We compiled global spatial data on planned linear road and rail infrastructure from numerous sources: through authors from scientific literature who have compiled data for regions/countries, online databases and by digitizing maps from reports and papers. It is important to note that even though we have complied data from across the globe, it is not a comprehensive global dataset. It does not include all planned road and rail infrastructure in the world, but just the large projects for which data/maps were available online. For example, it was difficult to find data in Russia (other than data already collected for the Belt and Road Initiative), North America and Australia. In the case of the USA, this may be because infrastructure funding is often at a state level, meaning data may be less likely to appear in national searches.

Only data on roads and railways that are either still in the planning stage or are under construction but not completed were included. Those that are under construction were included as their completion can still take considerable time, depending on the size of the project. We focused on large infrastructure developments, with the majority of datasets included (52 out of 57) being over 100km in length. Five smaller datasets were included, as the data were readily available and located in areas where data was lacking. The shortest of these was 40km. Developments occurring only within built-up areas, for example construction of a metro line in a city, were not included as these are likely to have a relatively low environmental risk on biodiversity but would take a considerable amount of time to include.

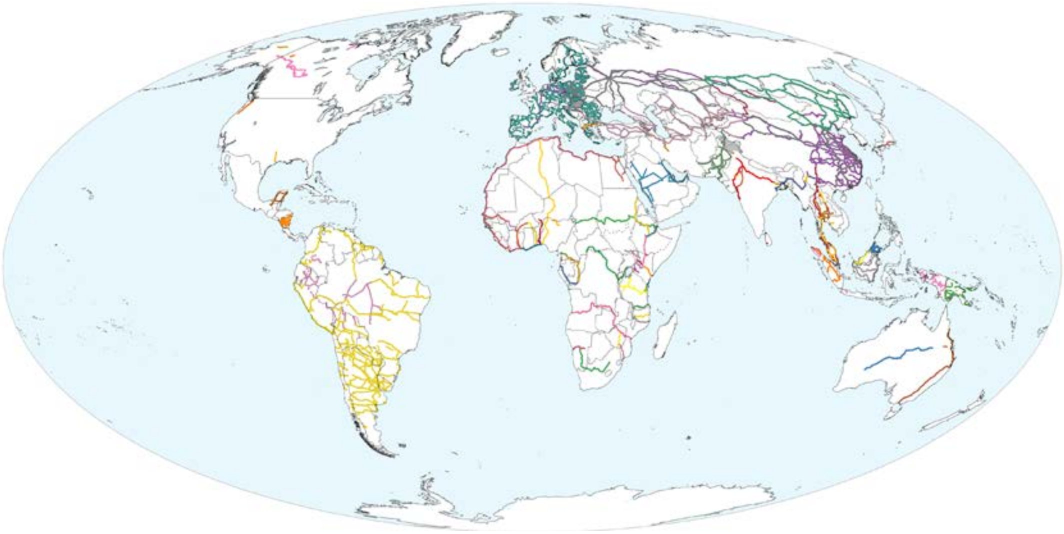
All data searches were undertaken between 2020 and 2021. We used the most recent information available to assess the time periods of the projects to try to ensure projects which have been completed were not included. Unfortunately many development projects did not have up-to-date information available online. We were able to assess 46 of the datasets using information ranging from 2011 to 2021 (although the majority was from within the past five years). The dataset for Europe was assessed against data on current roads/railways as the data was of sufficient spatial accuracy (see Appendix 2 for more details). The remaining ten datasets could not be assessed, either because they were too large to do so in sufficient detail, or information was not available. Some of the differences in accuracy may be due to the types of plans – some being intended to follow for on the ground implementation, whereas some are more indicative (e.g., a hypothetical corridor linking one area to another). We removed obvious cases of such indicative plans, such as straight lines between built up areas, but less noticeable apparently detailed ones may remain.

Due to the variety of sources and timelines for the different projects, assigning stage (e.g., planning, in progress) and type (e.g., upgrade, new) of development was problematic. These criteria were included and updated where possible, but for the analysis we chose to group these stages and types together. This approach was preferable to producing results based on potentially false distinctions.

Analysis - Global Database

- The database of planned roads and railways collated here uses 57 data sources (see Figure 1). Some of these sources are themselves compilations, such as the African Development Corridors Database (Thorn *et al.* 2022).
- We assume most projects will be complete in the near future, roughly within 10/15 years. However, this estimate is based on a small number of projects with start or end dates listed. The exact timeframe for completion of all projects is unknown, especially considering some will be postponed, or cancelled.
- Due to the difficulty of getting permission from this number and variety of sources, currently the database is not open access.
- The total length of infrastructure is nearly half a million kilometres (489,730km).
  - Of this, 55.3% of the length was road, and 44.7% rail infrastructure.
  - For context this represents 1.2% (16.6% rail; 0.7% road) of existing global stock (based on 136 countries for rail and 224 countries for roads).
  - Considering the ambiguity in the database for type of project (i.e., 'new' versus 'upgrade'), not all should be interpreted as an increase in infrastructure necessarily (see Appendix 2 – Supplementary Methods).
- In terms of coverage, the database spans 137 countries and territories, including 133 transboundary projects (~4% of the 3201 projects in the database). In terms of ecological coverage, we found that projects overlap with nearly half (422 of the 847) of the world's terrestrial ecoregions[2] (Dinerstein *et al.* 2017). Nearly a third of the length of the infrastructure falls in temperate broadleaf and mixed forest biomes, and a fifth in tropical and sub-tropical broadleaf forest biomes.
- The expanse of linear transport infrastructure included in the compiled dataset represents just a small fraction (6–9%) of the length of future infrastructure that studies have been projected for 2050. Meijer *et al.* (2018) estimated that 3.0–4.7 million kilometres of additional road length will be built. Their larger estimate results from a longer considered period and alternate methodology. While our dataset includes infrastructure projects whose construction is planned for the near future, the estimates in Meijer *et al.* (2018) result from modelled projections based on forecasts of human population density increase, and associated demand for roads.

Figure 1. Map showing location of planned roads and rail in the database. Each colour represents a different data source. Some of the 57 datasets were themselves collections from multiple sources (see Appendix 2 for details).



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[2] Ecoregions are defined as relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change (Olson *et al.* 2001)

What does infrastructure development mean for biodiversity?

Risks to biodiversity

Negative impacts on species' populations and habitats from transport infrastructure are well documented (e.g., Laurance *et al.* 2015, Bennett 2017). They range from the direct footprint of the project to more nuanced indirect effects from increased hunting and reduced habitat connectivity (Clements *et al.* 2014). Direct risks include habitat loss and, especially for roads, increased chances of mortality due to vehicle collisions. Infrastructure also poses indirect risks due to noise, light and air pollution and can cause avoidance behaviour and disruption to movement, breeding and migration patterns (Skarin & Åhman 2014). For example, traffic noise can negatively affect the breeding behaviour of mammals and amphibians and an increase in lights on roads can alter the foraging behaviours of bats (Polak *et al.* 2011; Tennessen *et al.* 2014).

Studies have shown that roads have negative effects on the abundance of amphibians, birds and large-sized mammals (Fahrig & Rytwinski 2009). Although it should be recognised that different species are affected differently depending on factors like body size, movement range and reproductive rate (Rytwinski & Fahrig 2011). Species with large body size, large movement range and low reproductive rates tend to be negatively affected by roads (Rytwinski & Fahrig 2011). Negative effects are also observed for species drawn towards roads for food/resources and those which cannot evade vehicles (Fahrig & Rytwinski 2009). Conversely, species that are positively affected by roads tend to be drawn towards roads for food/resources but can evade vehicles, or their predators are affected negatively by roads (Fahrig & Rytwinski 2009). For example, roads have been found to have a positive/neutral effect on the abundance of small-sized mammals like rodents (Fahrig & Rytwinski 2009).

Composite risk to biodiversity

To produce a headline map for risks to biodiversity, we created a composite metric from a combination of risk to species persistence and impacts on wilderness areas and conservation areas. Wilderness, as depicted here, represents areas of minimal human impact and disturbance from infrastructure and human populations. We use the term conservation areas to represent a combination of Key Biodiversity Areas (KBAs) and protected areas (PAs). KBAs are designated areas of global importance for biodiversity; whereas PAs are legally designated sites that are typically actively managed with the goal to conserve nature and its benefits.

For a detailed description of these input risk datasets and individual analyses, see Appendix 1 and specifically Figures 14-16.

Analysis - Composite risk to biodiversity

Global level

Global statistics for the three risk datasets used as inputs into the composite risk map for biodiversity (for details see Appendix 1).

- **Species:**
  - Approximately 60% of the 4096 species in our study overlapped with risk areas from planned transport infrastructure. 42 species declined in their species persistence score by >10%.
- **Conservation areas:**
  - 12% of the total length of the planned infrastructure crosses conservation areas (i.e., either protected areas (PAs), 7.3%, or Key Biodiversity Areas, 6.9%)
- **Wilderness:**
  - 1.6% of the total length of planned transport infrastructure crosses wilderness areas (~8000km).

Country level

Composite risk was highest in parts of South America, namely Brazil and Paraguay, and in parts of Southeast Asia, in particular Indonesia (Figure 2). The higher risk in countries in the Neotropics and the Southeast Asia tropics can be explained because these regions include countries where planned infrastructure was found to pose a high risk to species persistence and the preservation of wilderness area from a global perspective. Argentina, Ecuador and Peru, and Russia and China all showed a relatively high composite risk also. In the case of Russia, the overall risk is high due to the length of infrastructure although the risk of its projects per km is low (Figure 3). China presents a similar pattern though with even more projects, and larger total length of infrastructure – in keeping with its development in recent years.

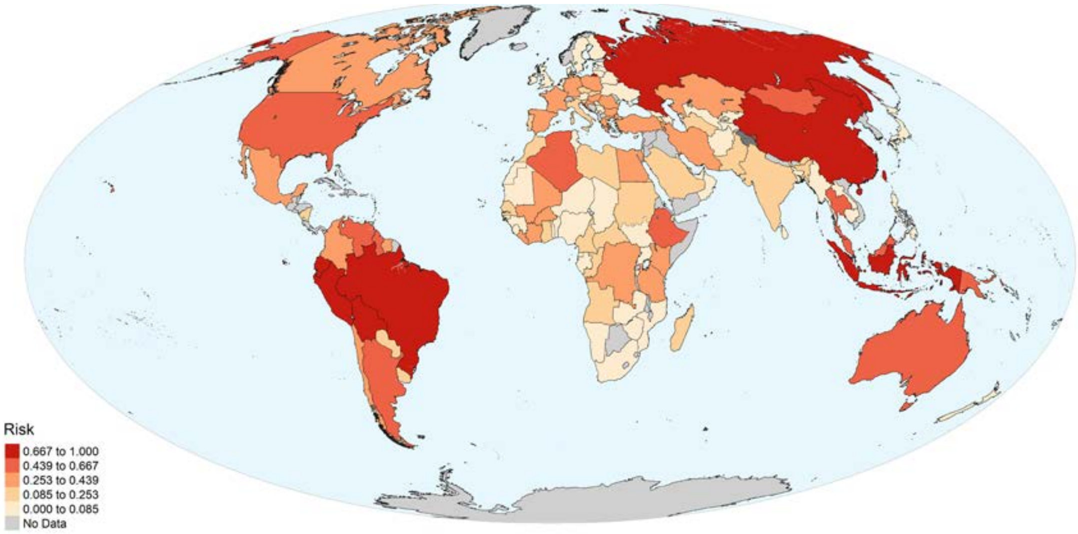
BOX 3 METHODS - COMPOSITE RISK TO BIODIVERSITY

To make risks comparable, we first produced normalised measurements for risks to species persistence, wilderness areas and conservation areas, by rescaling them from 0 to 1. We scaled values between zero and the 90th percentile in each variable, and values over that threshold were set to one. The 90% threshold was identified as it ensures adequate spread within the resulting range by missing out, i.e., bounding the values for outliers. Normalised measurements of risk to species, wilderness, and conservation areas, were then averaged to obtain the composite risk. To obtain composite risk at country level we combined each variable aggregated for all projects in a country, normalised. We produced a map for composite risk to biodiversity at the project level by combining project level normalised variable values.

We acknowledge that not all inputs datasets are equal or could substitute for any other. This approach does, however, provide a transparent and easily describable composite metric for use in a risk-benefit analysis.

The analysis section describes results at the: 1) global level – summary statistics of the three input risk datasets; 2) country level – comparing total composite risk for each country; 3) project level – comparing composite risk for each planned road/rail project.

Figure 2. **Map showing the composite risk to biodiversity from planned roads and rail, shown at the country level**



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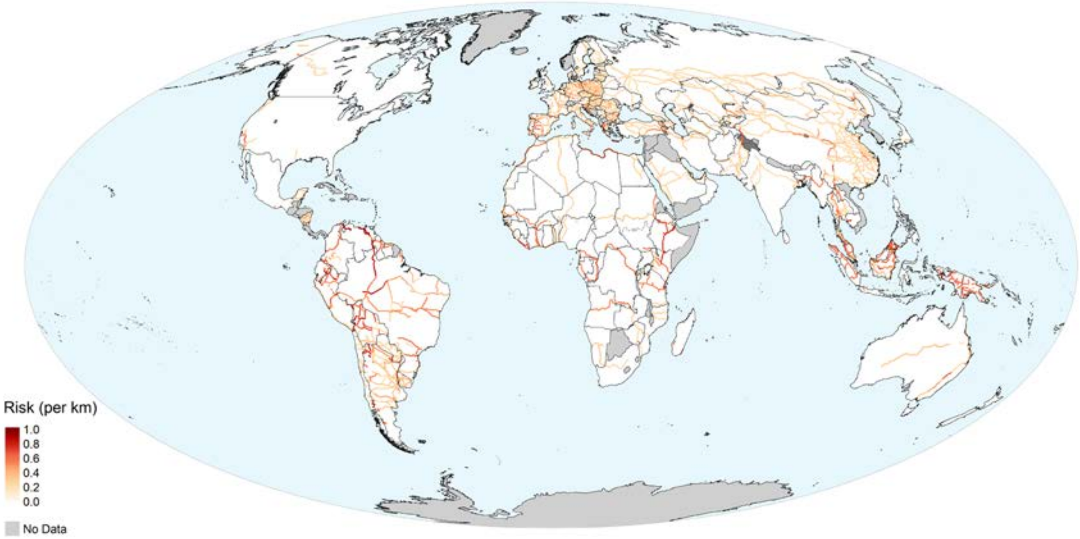
Project level

Importantly, projects in tropical Africa were found to represent a high risk to biodiversity per km, at a magnitude that is comparable to that of countries in the Neotropics and Southeast Asia (Figure 3). In fact, some projects crossing equatorial and tropical Africa, including parts of the Gulf of Guinea, the Congo basin, or the Great Lakes in East Africa, were amongst projects with the highest risk to biodiversity per km, globally. However, the planned infrastructure is not extensive compared to some countries. Therefore, most African countries are not appearing in the higher risk categories when results are summed to the country level (Figure 2). To see high risks at the sub-national level, please go to the GIIV website (http://giiviewer.org/).

Figure 3. Map showing the composite risk to biodiversity, per km of planned roads and rail, shown at the project level.



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What does infrastructure development mean for people?

To answer this question, we focus on two aspects that relate to people and society, namely the risks to ecosystem services and the socio-economic benefits from planned road and rail infrastructure.

Risks to ecosystem services

Infrastructure development will result in both the loss and degradation of natural resources and ecosystems, and increased pressure on ecosystem functioning and ability to provide services. People and nature depend on ecosystems for their livelihoods, health and wellbeing as well as for services related to global climate regulation, and the negative impacts disproportionately affect more vulnerable groups, including indigenous peoples and women and girls. Understanding the risks posed to ecosystem functioning by infrastructure development should be a crucial step in its development and planning, particularly where the level of disturbance may result in ecosystems collapse. This is critical if countries want to achieve national environmental commitments (e.g., CBD and UNFCCC targets) and minimise trade-offs.

Direct impacts from construction of road and rail infrastructure may result in the loss of vegetation biomass, impacting the provisioning of ecosystem services including carbon storage and sequestration, water quality regulation and clean water provisioning, as well as timber and non-timber forest products. Vegetation biomass removal and damage to associated soils, results in the loss of carbon stored and prevents further carbon being sequestered from ongoing biomass growth. This negatively impacts global climate change mitigation efforts and contributes to the increase of greenhouse gases in the atmosphere. Furthermore, loss and degradation of natural ecosystems will negatively affect their cultural, spiritual, and intrinsic values.

Ecosystem loss and degradation can occur beyond the immediate vicinity of infrastructure development. Chaplin-Kramer *et al.* (2015) demonstrated that the introduction of forest edges could result in further changes to forest aboveground biomass carbon up to 1.5km from the forest edge in tropical forests, due to, e.g., increased wind exposure and desiccation. Furthermore, infrastructure development may increase access to remote ecosystems (Sang *et al.* 2022). Several studies document a 'fishbone' deforestation pattern extending out from road developments with increased access leading to exploitation of the ecosystem (Frietas *et al.* 2010). Ninety-five percent of deforestation in the Brazilian Amazon occurs within 5km of a road or navigable river (Barber *et al.* 2014). Deforestation can affect local climate regulation, with areas often becoming drier and arid, significantly impacting local communities' clean water availability and crop production. The effects of vegetation loss may be felt over large distances from the infrastructure development.

Populations downstream may be impacted through reduced water quality and clean water availability as pollutants are no longer retained by vegetation and enter the watercourse (Nyumba *et al.* 2021). Vegetation stabilises soils, and its removal may lead to increased sediment exports, contributing to decreased water quality and potentially increased risk of landslides, depending on factors including climate, slope, and soil type (Larsen and Parks 1997; Boston 2016).

The impacts of infrastructure development on ecosystem services have not been widely studied over larger scales. The distance from development, over which the ecosystem service will be affected, will vary by ecosystem service, type of infrastructure, and factors including local topography and climate. However, understandably, little evidence of recommended distances exists in the literature.

Ecosystem services are the benefits people derive from ecosystems and their functions, which contribute to human wellbeing and economic activities (Millenium Ecosystem Assessment 2005; Brown *et al.* 2016). We use the term ecosystem services in this study for simplicity, but for water quality regulation, crop pollination and surface water, only the impacts on the stocks, i.e., natural capital assets (Brown *et al.* 2016), could be assessed. Estimating the actual service provided to people for these aspects could not be mapped due to complexities in linking the potential service (e.g., nitrogen stored in vegetation biomass) to the downstream beneficiaries (i.e., the realised service). Understanding the risk to the natural capital assets is important, as they may be critical to local communities both now and as population distributions change in the future. Carbon storage and sequestration is considered a global service and therefore not linked to local beneficiaries.

Composite risk to ecosystem services

Showing the individual risks to different ecosystem services is useful for understanding the patterns in each of the countries' planned infrastructure portfolios. But to understand where overall risks to ecosystem services are greatest, results can be combined into a single headline map – as shown at the country and project level in Figure 4.

NB: For description of the four input risk datasets (I.e., carbon stocks, surface water, water quality regulation and pollination) and individual analyses see Appendix 1, specifically Figure 17, and Appendix 2.

Analysis - Composite risk to ecosystem services

Global level

Global statistics for the four risk datasets used as inputs into the composite risk to ecosystem services map are provided here (for further details see Appendix 1).

- **Carbon storage:**
  - The total direct risk of infrastructure development on carbon storage is approximately 883 million tonnes of carbon loss from vegetation biomass and soils (up to 1m depth). For context, in the year 2000, the carbon stocks held in aboveground biomass of Costa Rican Forests was approx. 776 million tonnes of carbon (Harris et al. 2021). Highest risks are in boreal and tropical areas where large forests and carbon-dense peatland soils are found.
- **Nitrogen storage:**
  - Global infrastructure development potentially risks approx., 1.17 million tonnes of nitrogen retained by vegetation, which could negatively impact downstream water supply. These risks are greatest where areas of dense forests are found.
- **Surface water:**
  - Surface water and wetlands play a key role in the health and livelihoods of people and the movement and health of species, as well as global climate regulation. However, it was not possible to quantify the potential losses of services resulting from infrastructure impacts and instead the study focused on stocks (i.e., presence of water). Infrastructure development coinciding with areas of surface water is greatest in boreal and tropical zones.
- **Crop pollination:**
  - Pollinator dependent food production is liable to be stressed by infrastructure development through land conversion and habitat reduction. Impacts are high in temperate regions (USA and Europe), as well as in India, China and Argentina.

Country level

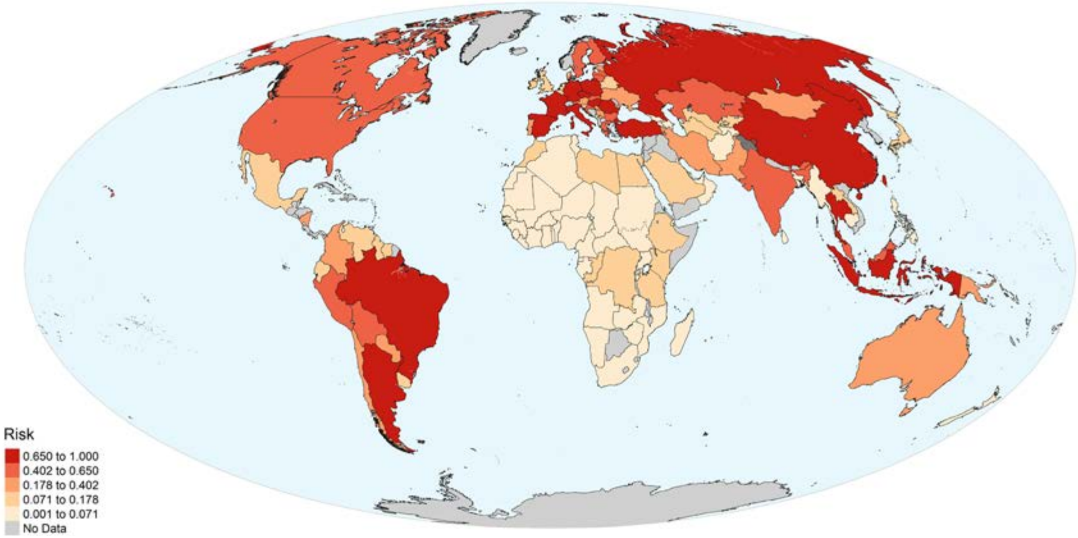
We found that, from a global perspective, planned linear transportation infrastructure has the potential to pose high risks to ecosystem services across much of the world, across tropical, temperate, and cold regions. These include countries in the Neotropics and the South-East tropic, and from temperate areas in central-Europe and the Northern hemisphere more widely (but also Argentina to the South) (Figure 4). In comparison with the composite risk map for biodiversity, cold regions stand as areas at a higher risk from planned infrastructure in terms of the ecosystem services they provide. These regions contain some of the greatest stocks of ecosystem services globally, particularly for carbon, due to the prevalence of carbon rich peatland soils. The tropics were also highlighted as areas of considerable risk due to high density of vegetation biomass and presence of peatlands in some areas.

BOX 4 METHODS - COMPOSITE RISK TO ECOSYSTEM SERVICES

We produced a composite metric measuring the combined risk that planned linear infrastructure poses to ecosystem services. This included the direct risks estimated for carbon stocks, surface water, water quality regulation and pollination (see Appendix 2). As with the composite metric for biodiversity, we started by producing normalised measurements for each of the four risks by rescaling them between 0 and 1 (with values above the 90th percentile set to 1). Once we had normalised measurements of risk to the four ecosystem services, we averaged them to obtain a composite risk on a scale of 0 to 1. The composite risk at the country-level was calculated from the combination of normalised values of total country stocks. For the map showing composite risk at the project level, we combined normalised values of stocks at the project level.

The analysis section describes results at the: 1) global level – summary statistics of the four input risk datasets; 2) country level – comparing total composite risk for each country; 3) project level – comparing composite risk for each planned road/ rail project.

Figure 4. **Map showing the composite risk to ecosystem services from planned roads and rail, shown at the country level.**



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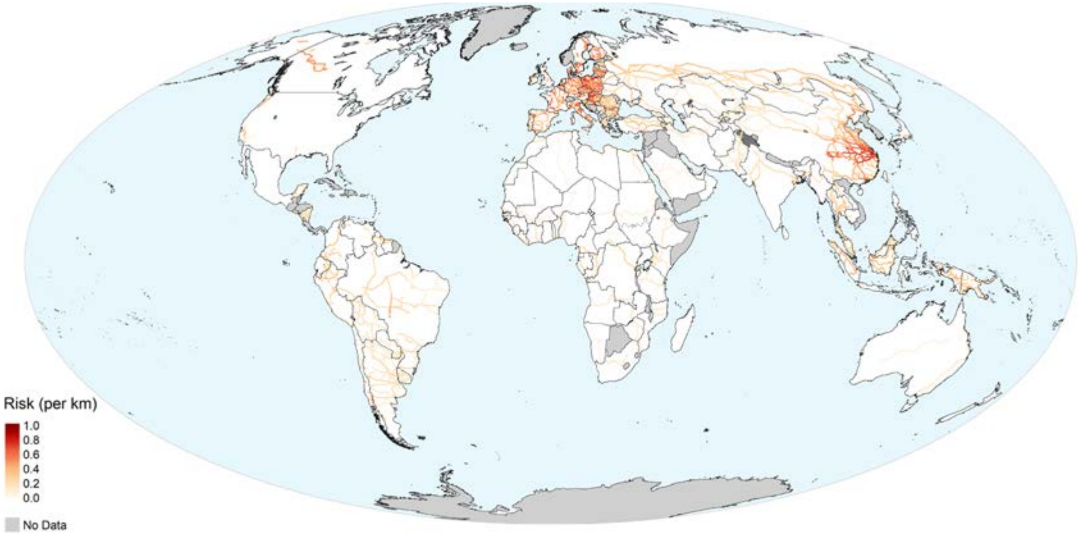
Project level

Some of the high-risk countries are large and have extensive plans of infrastructure expansion, such as Russia and China. Other examples come from regions with concentrated, large stocks of ecosystem services, resulting in planned projects that were found to pose a high risk per km. Examples in this case are Canada and Central and Northern European countries. South American countries also show high composite ecosystem services risk (Figure 9) due to high water and carbon ecosystem services values, combined with widespread infrastructure development plans and associated pressures. Contrastingly, apart from Indonesia, countries highlighted in the tropics tend to have a comparatively lower overall risk per km (Figure 5). This may be due to planned infrastructure not intersecting with areas of high vegetation biomass (likely the case for North Africa, the Middle East and Australia).

Figure 5. **Map showing the composite risk to ecosystem services per km of planned road and rail, shown at the project level.**



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Socio-economic benefits

Improving transportation infrastructure is often presented as a catalysing development investment to improve economic output, raise incomes, and increase social wellbeing and access to public facilities and services. Yet, in the absence of accompanying and enabling policies and conditions, there is a risk that these benefits are not realised, in addition to well documented ecological risks from the construction of roads and railways. This section provides a broad analysis of the socio-economic benefits of transport infrastructure investment, to provide context in which to view such ecological risks. Data availability and methodological challenges limited the socio-economic analysis to GDP and employment benefits, and they are provided primarily to help put the environmental impacts into context; the study is not intended to give a detailed or nuanced view of these aspects of sustainable infrastructure development. For brevity we have focused the discussion here on the economic benefits in terms of potential increases in GDP – for the Benefits to Employment analysis see Appendix 1.

Increases in economic activity (which would be captured in GDP) associated with transport infrastructure construction may arise both directly and indirectly. Direct increases arise from spending on the construction, operation, and maintenance of the infrastructure (these are the project costs – which also yield employment benefits, see Appendix 1). There are also Wider Economic Benefits (WEBs) that accrue beyond the users of the transport infrastructure project (i.e., indirect benefits). These benefits arise due to the restructuring of the economy as linking different areas stimulates trade, employment and communication across them and as direct economic benefits are invested elsewhere in the economy. Users of the road or rail links also directly benefit from new transport infrastructure, essentially savings in travel costs and travel time, which can increase productivity, and so influence GDP indirectly.

Countries, often with the help of the international community, invest in transport infrastructure to boost economic growth and social welfare. Increasing the number of transport corridor initiatives is often justified based on their potential (but uncertain) wider socio-economic benefits.

The empirical evidence for demonstrating that investment in infrastructure has this significant, positive effect on production and economy is, typically, grounded in demonstrating a positive elasticity of GDP to transport infrastructure investment. In short, what is the increase in economic output per year given a quantified increase in the 'stock' of transport infrastructure in the country. These positive outcomes of effective transportation system are proposed to be more pertinent to developing countries.

This focus on wider economic benefits in the benefits analysis is justified as public infrastructure investments are intended to establish a development pathway that delivers public economic benefits that bring improved social welfare outcomes. Hence, focusing solely on direct, private benefits (i.e., to the individual) is not considered appropriate as the fundamental trade-off considered is across two public goods, namely, environmental resources against an increased national economy.

BOX 5 METHODS - ECONOMIC BENEFITS:

Estimating returns from transport infrastructure investment in terms of increases to national GDP

The change in gross domestic product (GDP) is derived based on a meta-analysis of elasticity estimates (Melo *et al.* 2013) which relate the percentage change in the stock (i.e., length) of infrastructure to an estimated percentage change in national income. The meta-analysis provided different elasticity estimates for different regions (US, Europe, Other) and, separately, different modes of transport (of relevance to this project – road and rail).

Collating data on the current stock of road and rail infrastructure and GDP, meant these elasticity estimates from Melo *et al.* (2013) could be used to estimate changes in national GDP associated with the planned increases in transport infrastructure stock. National GDP (2019) was obtained from the data series in table 4.2 of the World Bank's World Development Indicators (World Bank 2022) and national road and rail infrastructure stocks from the CIA World Factbook (Central Intelligence Agency [CIA] 2021a; CIA 2021b).

Where countries have a low stock of transport infrastructure, even a small transport infrastructure development can give rise to a high proportionate change in that stock. In such case, applying the elasticities of Melo *et al.* (2013) would lead to unrealistic GDP responses. This was particularly the case for rail infrastructure investments in countries where the current stock of infrastructure is particularly low (implying a potentially spuriously large change in GDP might be expected, as the percentage change in infrastructure stock would be exceptionally high). To mitigate these instances, generalised elasticities were applied that had been derived at the world bank income group level for the country in question.

As increases in GDP in this analysis are linked to the length of planned road and rail infrastructure, we assume that the analysis considers such benefits would be the same wherever the infrastructure is placed within a country. Therefore, local differences and non-linearities are not incorporated (e.g., the first kilometre of planned road/rail between two cities would be calculated as giving equal GDP benefit as the last kilometre), although we acknowledge that they exist.

The analysis section describes results at the: 1) global level – summary statistics of GDP increases; 2) country level – comparing total GDP benefit for each country. Project level results for economic benefits were not possible in this analysis (see Appendix 2 for details).

Analysis - Economic benefits

Global level

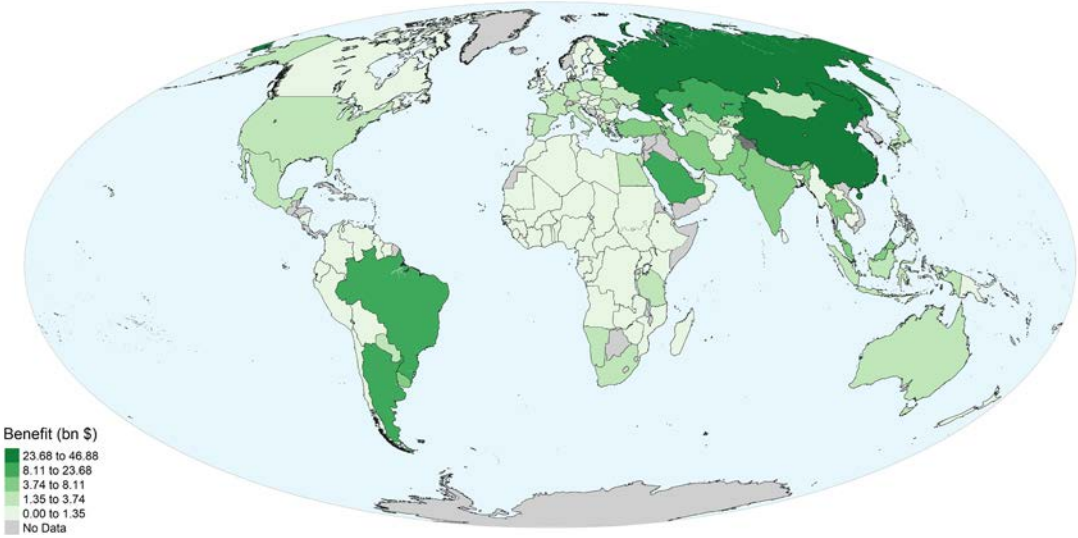
The global estimate associated with planned road and rail infrastructure investments (once the infrastructure is in place and operational) is an annual increase in GDP of 0.34% across those countries increasing their stock of infrastructure in the database.

The increase in GDP varied by region. Benefits in terms of the proportion of GDP were expected to be smallest in North America/Australasia (0.1%) and Europe (0.2%). The rest of the world divided (for analytical purposes) into World Bank income categories showed benefits between 0.7% and 1.3% of GDP. This higher range reflects a combination of factors, including the impact of having smaller original stocks of infrastructure, greater potential benefits from improvement of infrastructure in some cases, as well as greater absolute increases in infrastructure.

Country level

The highest GDP increases in absolute terms are noted in China and Russia (Figure 6). This is driven by the large amount of rail infrastructure investment planned in these two countries. The situation is similar for Brazil and Argentina, with comparatively low current stocks of infrastructure, suggesting that it may be reasonable to expect wider economic benefits that would register at the national level.

Figure 6. **Benefits of infrastructure on GDP.**



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BOX 6 WHAT ARE WE NOT INCLUDING? RESOURCE USE AND EMISSIONS

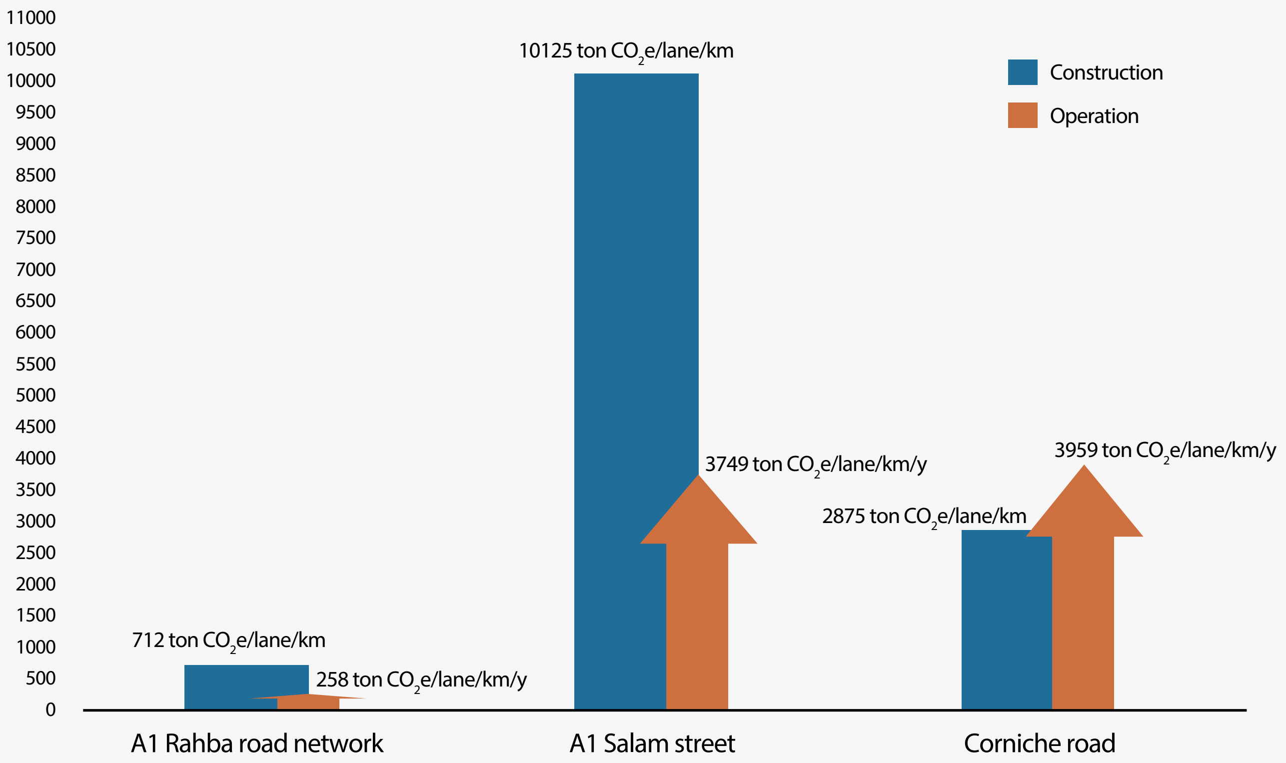
Infrastructure development is particularly resource intensive (United Nations Environment Programme [UNEP] 2019). The construction of roads, for example, consumes a variety of resources, particularly land resources (Laurance et al. 2014). In addition, rock, sand, etc. as the fundamental components of concrete play a vital role in the construction of most infrastructures. These materials are scarce, non-renewable resources. Additionally, the mining of these resources, especially excessive mining, has high socio-economic and environmental costs. Not only are human labour and time costs extensive, but also the potential environmental impacts caused by exploitation such as biodiversity loss, soil erosion, water and soil pollution, and the subsequent costs of control (Ibisch et al. 2016; Ascensão et al. 2018; Hughes 2019; Leal Filho et al. 2021). If resources are not utilised properly, future infrastructure development will be at risk of resource scarcity.

The construction process itself can cause negative impacts from air pollution, greenhouse gas (GHG) emissions and noise (Ibisch et al. 2016; Vilela et al. 2020), it also causes soil and water pollution, habitat damage and carbon stock released (Ibisch et al. 2016; Hughes 2019). Road construction generates multiple carbon emission pathways, for example, releasing embodied carbon in raw building materials and vehicles' emissions during supplies transport and construction work (Laurance et al. 2015; Hughes 2019; UNEP 2019; Vilela et al. 2020).

Global values for emissions from road construction are hard to calculate due to variation with road type, as illustrated by Figure A. This figure shows the estimated GHG emissions from construction and operation phases of three cases.

These three cases in Abu Dhabi illustrate how the type of upgraded and constructed road, as well as the materials and equipment used in construction process, can result in different final GHG emissions. Here, the lane-kilometre method (i.e., lane/km) is introduced. This is because only a new lane that is built can be counted. Moreover, carbon emissions from the operation stage are counted on an annual basis compared to the fixed carbon emissions from the construction stage.

Figure A. showing Greenhouse gas emissions during main stages of construction in Abu Dhabi: Case 1 involves the construction of a secondary road network (two-lane roadways with 30 km length) near A1 Rahba area. Case 2 involves the improvement of A1 Salam Street, including constructing a tunnel. Case 3 involves the upgrading of Corniche Road. Source: Alzard *et al.* (2019).



How do countries compare in terms of risks versus benefits of infrastructure?

A risk-benefit comparison aims to provide a global picture of trade-off patterns, as well as identify countries with plans that show poor risk-benefit trade-offs. We recognise that nature is diverse, and thus the variability in the global patterns of biodiversity, habitats or ecosystem services create a picture in which some regions and countries will find it exceedingly difficult to avoid incurring severe environmental risks. As a result, these countries have higher probabilities to score among those where development plans will impose higher risks. For this reason, it could be argued that another meaningful approach would be to compare to the individual country's 'best possible' development plans, i.e., incurring least risks. Nonetheless, the comparison of development plans for countries remains relevant from a global perspective. Therefore, it is offered here with the aim to highlight the regions where it is particularly important to balance expected benefits with projected environmental risks, so that sustainable development is achieved.

BOX 7 METHODS – RISK VERSUS BENEFIT

To attempt to answer this question, we weighed the estimated environmental risk posed by planned road and rail infrastructure in each country, against the potential economic benefits.

We averaged the two composite risk maps for (1) biodiversity, and (2) ecosystem services into a final 'all-environmental' composite risk map (see Appendix 1 – Additional Analyses, for corresponding map). This dataset provides an overall estimate of risk, where species persistence, wilderness, areas of importance to conservation and ecosystem services are represented in a balanced manner.

To explore how countries compare in terms of risks versus benefits of their planned linear infrastructure, we represented country-level estimates of composite risk against our evaluation of potential economic benefit. We used normalised economic benefits in the comparison. As both variables to compare are on a scale 0 to 1, we classified countries on four quadrants. The threshold of 0.5 was used to classify countries as 'higher risk' or 'lower risk', and as 'higher benefit' and 'lower benefit' countries.

This analysis is useful to identify countries in the different risk-benefit trade-off groups from a global perspective.

Analysis - Risk vs. Benefit

Trade-off categories

When highlighting countries in different trade-off categories, it is worth reiterating that although the approaches used in this analysis are aiming to estimate broad patterns of risk and benefit, the economic benefits, along with environmental risks, are extremely dependent on local context. Therefore, results shown are not attempting to substitute local assessments of individual projects.

Higher risk – lower benefit: When comparing risks versus benefits, three countries (Bolivia, Peru and Hungary) with the poorest, least desirable trade-offs can be seen in the top left corner of the chart in red (Figure 7) and corresponding map (Figure 8). These countries' plans risk not only high environmental damage but may provide little economic benefit in return. The road and rail project plans that may be most in need of reassessment fall in this category.

Higher risk – higher benefit: There are thirteen countries with high environmental risks coupled with high benefits. The environmental risks may be worth the economic benefits for some countries in this category, although it will depend whether there is institutional capacity and the will to manage these risks. The plans in these countries should be scrutinised further, especially as the top five highest risk countries overall are in this category: Indonesia, Russia, China, Brazil and Argentina. Of these, Indonesia stands out as having joint highest risk but much reduced economic benefits, in fact, it borders with the neighbouring 'higher risk – lower benefit' group.

Lower risk – lower benefit: Most countries fall in the lower risk – lower benefit category. These are found throughout Africa, northern South America, Australia, and parts of East and Southeast Asia. As these are lower risk, if planned roads and/or rail were built for one of these countries, based on these metrics it should cause less environmental damage than the higher risk categories. However, considering that these infrastructure projects may provide low or limited economic benefit, it is worth assessing if such projects are worthwhile.

Lower risk – higher benefit: These countries have the best risk to benefit trade-off. The geographic distribution of this result is concentrated in South, West, and Central Asia, including Saudi Arabia, the country with the best overall trade-off. These countries have both a low (or zero) existing infrastructure stock and a large, planned infrastructure increase (such as the planned Gulf Railway in Saudi Arabia), which helps to explain their high benefit scores.

In other regions of the world, this category is more scattered, with a few in the neotropics (Mexico and Paraguay) as well as Southern and Eastern Africa (Tanzania and Namibia). Some of these findings are surprising, but also highlight the potential for countries with rich natural resources such as Tanzania. The various caveats, such as the reliance on global data and focus on wider economic benefits should be considered here (see Economic Benefits section and Appendix 2 for details).

There is an issue of distributional inequity when considering these trade-offs, namely that benefits may accrue to different people than those impacted by the increased risks. A relevant example here is that we are considering national scale economic benefits but some of the environmental risks, such as loss of carbon storage or biodiversity, are relevant on the global scale. Similarly, the distribution of socio-economic benefits amongst various social groups may not be even and often require accompanying policies to address issues of equity. The location and operation of transportation infrastructure systems needs to account for the different service needs of different groups. Women and men, for example, use transportation infrastructure differently, and misalignment between service delivery and service needs can result in lower wider economic benefits (WEBs) than expected. Thus, the question of who gains and who loses from a specific road or rail project, or set of projects, is an important consideration that is worthy of further study.

Figure 7. **Chart comparing composite environmental risk to economic benefit at the country level for roads and rail. Countries are listed by ISO3 code for brevity.**

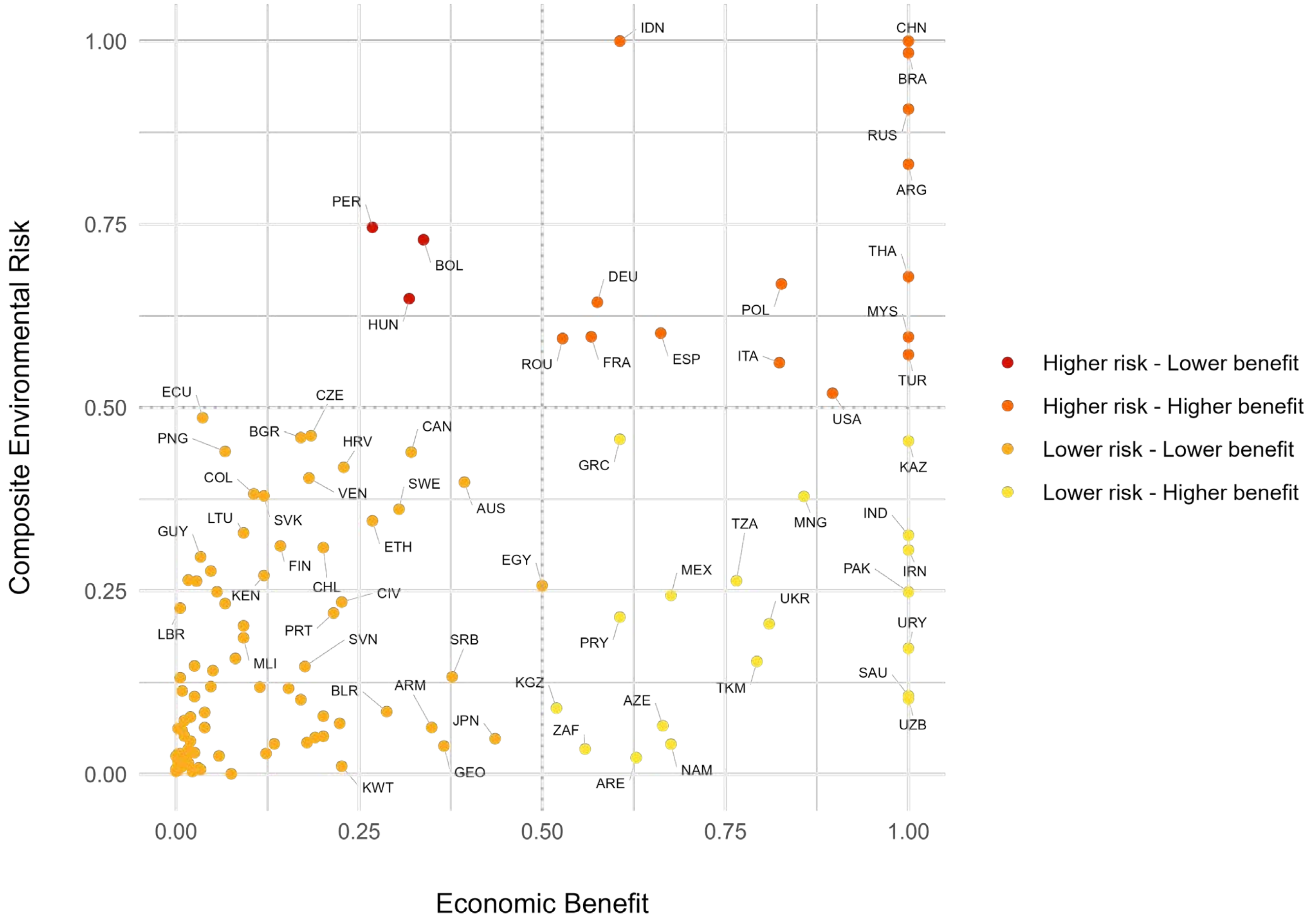
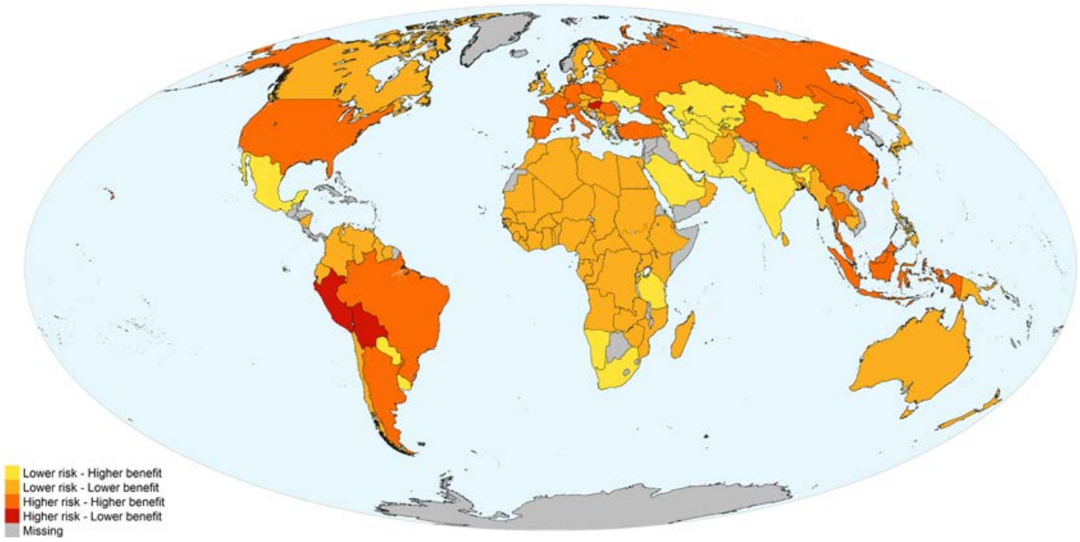


Figure 8. **Map showing main groupings for the composite environmental risk to economic benefit comparison for roads and rail.**



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How do we understand patterns of environmental risk?

As risk versus benefit was not possible at the project level due to limitations in the economic modelling at the global scale, we investigate the various metrics contributing to the risk scores for the countries of most concern, i.e., the two higher risk categories.

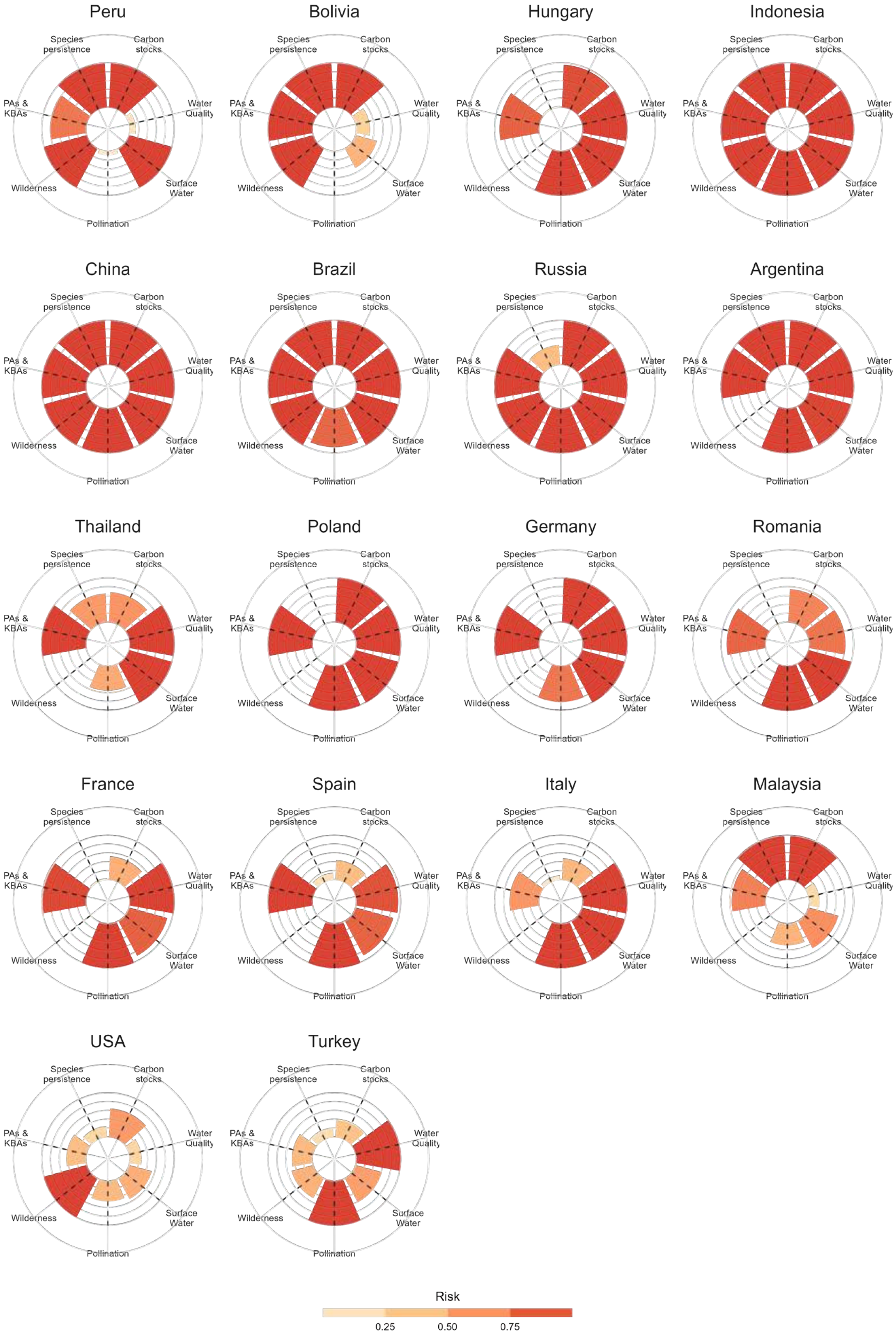
Western European countries show similar patterns of ES scores, characterised by higher risks to ecosystem services including carbon stocks, water quality regulation and pollination (Figure 9). In these developed countries, characterised by high agriculture and urban land uses, it is unsurprising that there are low scores for risks to species, wilderness areas and carbon stocks.

Central and Eastern European countries (including Romania, Hungary and Poland) also have similar patterns to each other, characterised by lower risks to wilderness and species persistence (Figure 9). Unsurprisingly, the countries with the highest risk scores overall (Brazil, Indonesia, China, Russia, and Argentina), have high scores for nearly all metrics.

There is a historical inequity that should be noted here, with more developed countries typically incurring smaller risks to wilderness areas and species persistence scores for example, due to having already exploited natural resources in their own countries, lowering the likelihood of higher risk scores for these metrics.

Apart from the above general patterns, some of which are likely to be due to similar biogeography and/or levels of development, the variety of findings is curious. For example, some neighbouring countries, such as Malaysia and Thailand, have notably different patterns of risk. To understand these aspects better would require further investigation of project placement and contributing factors at the project level. Such analysis is outside the scope of this report, but can be explored in the online tool that accompanies this study (global-infrastructure-impact-viewer.org).

Figure 9. **Plots of the different risks from planned roads and rail, for countries in the ‘higher risk – lower benefit’ and ‘higher risk – higher benefit’ categories. The environmental metrics include three biodiversity metrics – species persistence, wilderness, conservation areas (PAs and KBAs); and four ecosystem services metrics – carbon stocks, surface water, water quality regulation, and pollination.**



Explaining high environmental risk scores

There are several reasons why a country's linear transportation infrastructure development plans could have high composite environmental risk.

- The first reason is environmental impacts not being adequately considered in the planning of new infrastructure (or upgrades to existing infrastructure). Sometimes, development plans are driven by reasons such as perceived economic and social benefit and disregard environmental (and other) risks. Examples of this case are the projects identified that cross through protected areas and Key Biodiversity Areas (described as conservation areas in this study). Although it could be viewed as poor planning, it should be noted that planning is extremely dependent on each country's environmental regulations and enforcement capacities, which will vary greatly.
- The second reason is the length (in distance) of planned infrastructure projects. Our database of planned infrastructure includes countries with development plans that include up to ~75,000 km of new road and rail, and other countries with plans limited to a few kilometres. Countries may have larger or smaller development plans due to their size and population (large and highly populated countries will tend to have larger infrastructure networks) and their current infrastructure stocks (countries with smaller stocks of road and rail may have the need for a larger expansion). Additionally, the size of countries' planned transport infrastructure captured in this study is influenced by the accessibility and transparency of data for their development plans (i.e., some countries may not share their development plans at all or may share it through channels and languages that are difficult to access, while other countries freely share detailed description of their plans), the accuracy of their plans' spatial data, and by the amount of external effort put into assessing their plans (e.g., recent efforts from various conservation and scientific networks made possible a comprehensive documentation of plans for roads in the Amazon and between African countries).
- The third reason is their naturally rich environmental characteristics. As mentioned previously, countries that hold large expanses of wilderness, with high richness of threatened species, or extensive amounts of carbon and water resources, may find increased difficulties to avoid incurring high environmental risks. In this context, it is possible that countries score among the group with highest risk even if their plans were carefully designed to avoid the most sensitive environmental assets. Moreover, our approach at the global scale made it impossible to capture local-scale measures aimed at avoiding environmental damage such as the use of certain technology and design features to build more sustainable infrastructure. In this context, our analysis should be understood as an assessment from a global perspective aimed at highlighting regions that are particularly relevant in terms of their risks.

BOX 8 WHAT ARE WE NOT INCLUDING? ROAD VERSUS RAIL

Roads and railways, as two typical linear transport infrastructure types, are often compared. The methodology used in this study did not allow for a meaningful comparison of the different metrics due to data limitations – primarily the lack of information on the impacts of rail. However, there are various take-home messages from comparisons in the literature.

Rail transport is more cost effective, reflected in lower fuel costs, and has lower greenhouse gas (GHG) emissions (Nelldal & Andersson 2012; de Miranda Pinto *et al.* 2018; Tamannaei *et al.* 2021). Burning the same amount of fuel, rail transport can haul larger loads and travel longer distances than road transport. Moreover, railways have more standardized transit schedules, which can reduce traffic congestion. Studies have shown that carbon dioxide emission can be reduced by improving traffic conditions, particularly by reducing traffic congestion (Barth & Boriboonsomsin 2008; Barth & Boriboonsomsin 2009; Zhang *et al.* 2019). In contrast to more environmentally friendly railways (de Miranda Pinto *et al.* 2018; Tamannaei *et al.* 2021), the advantages of road transport lie in its lower economic construction cost and construction flexibility. Maintenance costs of roads are also much lower than that of railways (Affuso *et al.* 2003; Yang *et al.* 2021). Also, roads can traverse more undulating topography while railways cannot. Moreover, road transport is economical in transporting few passengers and relatively lower volumes of freights over short distances (Sahin *et al.* 2014).

What can we do to make roads and rail impact assessment better?

This study was a first attempt at global infrastructure mapping and modelling of environmental (biodiversity and ecosystem services) risks and socio-economic (economic and jobs) benefits. In addition, this study enabled the development of a global roads and rail database. As with any study, this effort contains some caveats in its application to decision-making. These caveats also highlight ways to improve future analyses and ensure a more robust database.

Database of planned roads and railways - improvements

The global roads and rail database can be improved in several ways:

- more complete (globally), detailed, and up-to-date coverage,
- making the data publicly available,
- inclusion of more non-English data via global partners and translation effort,
- globally standardised and frequently updated status categories in infrastructure planning data - to enable more detailed analyses and understanding,
- support (financial and time) for regular updating (and eventual partial automation),
- requirements for spatial planning data to be made open access should be written into infrastructure funding agreements, and
- monitoring infrastructure development, including real impacts after construction, to feedback and, in time, improve assessment process.

Risk to Biodiversity - future analysis and improvements

- Our analysis of the risk imposed by infrastructure on species, measured through projected change in their persistence score, represents a novel attempt to estimate the impact of future development on species conservation. It required some assumptions and simplifications: we based our analysis on metrics of abundance response to roads observed for bird and mammal species groups. In practice, species responses to infrastructure are more nuanced and species across other taxa (i.e., amphibians) as well as within mammal and bird species, respond differently across habitat types. In addition, these responses will vary by distance and with different intensities, to new infrastructure and types of infrastructure. Incorporating species-level estimates of impact distances would allow more reliable estimates of changes in likelihood of persistence.
    - > Expanding our knowledge on the response of species, such as accounting for more detailed taxonomic responses, impact of traits such as body size, diet or ecological preferences (e.g., specialists and generalists, rare and common species) in influencing response, would improve estimates of risk.
- Species' persistence probabilities may be affected by infrastructure in ways not considered in this study. Some of the less-studied indirect threats may be particularly relevant in certain regions; these might not have been considered by the studies from which we extracted impact distances and are more difficult to measure and forecast. For example, impacts resulting from secondary land-use change triggered by the increased accessibility resulting from infrastructure, changes due to reduced ecological connectivity, or cumulative risks in the context of global change (Juffe-Bignoli *et al.* 2021). Cumulative risks can be in the form of multiple impacts from the same project, combined risks of multiple transport (and non-transport) developments, as well as risks over time.
    - > Such impacts may add to the risk that infrastructure presents to species' likelihood of persistence – therefore, more research on how to include these additional risks in future studies could improve risk measurement and provide an earlier warning for species at risk of extinction.
- The wilderness areas metric could be improved with newer data, as the current dataset has not been updated for a number of years.
- The conservation areas metric currently contains protected areas and Key Biodiversity Areas (KBAs) data but could in future include data on Other Effective area-based Conservation Measures (OECMs). Currently data on these are only available for a few countries but this is growing.

Risks to ecosystem services – future analysis and improvements

- Simulated future land use change (based on modelled historic deforestation) together with biophysical and socio-economic variables (e.g., Vilela *et al.* 2020) would be of value for understanding risk and benefits and informing decision making. Indirect effects of infrastructure development on deforestation and forest carbon storage could be included, improving the planning stages of infrastructure development. Such effort was beyond the scope of this study.
- Inclusion of assessment of infrastructure development related settlements or urban areas would be important given the further increased pressure on ecosystems.
- Vegetation along or near infrastructure provides valuable ecosystem services (e.g., air quality regulation, buffering the effects of noise from infrastructure use, reducing the risk of landslide events, and providing habitat and refugia for species). This could not be mapped in this study due to limitations in modelling these ecosystem services at global scales.
- Including economic values for loss of ecosystem services would enable a cost-benefit analysis using the same units. Currently this is only feasible for carbon at this scale of analysis. National scale modelling of such values is possible for some of the other ecosystem services, however, so more work could help scale these approaches up.
- Modelling effects of land use change on ecosystem service provisioning and effects on downstream users of the service would be a beneficial addition. Due to computational requirements, it is not possible to model this at a global scale. Therefore, where possible (due to data constraints, etc.), this should be done at the project scale to improve estimates of impacts on the services, and to model downstream effects which may affect more distant users of the service.
- Increased coverage of ecosystem services based on their importance for local areas and populations. Modelling ecosystem services at a global scale presents several challenges: the number of services which can be modelled is limited and output datasets are coarse. Choosing services important to the development area and local people will provide a better picture of risks to these services and allow opportunities to minimise and mitigate negative impacts.
- The services modelled in this analysis are found in terrestrial and freshwater realms. However, infrastructure will also impact ecosystems in coastal areas (e.g., coastal vegetation protection). Expanding ecosystem services to include those delivered in these realms would be useful in future.
- Inclusion of risks to infrastructure from depletion of ecosystem services. Various nature-related ecosystem services (e.g., flood protection, soil stabilisation, etc.) are key to the sustainability and stability of infrastructure. Nature-related risk assessments would include, for example, measures of climate change, loss of ecosystem integrity and natural capital and ecosystem services depletion. Furthermore, efforts to combat these risks could potentially be assessed, for example, restoration and nature-based solutions.

Socio-economic and employment benefits – considerations for further analysis

- Further investigation of the relationship between transport infrastructure development and per capita GDP growth is needed because several papers in the literature do not find a causal relationship (e.g., Holmgren & Merkel 2017; Rubaba *et al.* 2015).
- A key challenge will be disentangling whether transport infrastructure stimulates economic growth in an area, or the current and potential economic activity leads to the construction of transport infrastructure in the first place.
- Some evidence exists to support the notion of a positive relationship between job creation/employment and transport infrastructure in low – low to middle income countries (Gannon *et al.* 2022). However, effects appear to be mixed in the literature. Further investigation is therefore warranted.

- The link between poverty reduction and transport infrastructure is not clear in a number of studies, and with other factors also being relevant. In Cameroon, Najman *et al.* (2010) demonstrate that investing uniformly in tarred roads in Africa is likely to have a much lower impact on poverty than expected.
- Further exploration of social impacts and the way that the development of transportation infrastructure impacts – both positively and negatively – different communities and segments of society, including more vulnerable groups such as indigenous peoples and women and girls.
- Transport infrastructure development and investment has often been justified on somewhat spurious national development grounds. A clear framework that allows for the socio-economic benefits of such national investments, at a spatially explicit scale, is needed to bring consistency to the analysis of the economic rationality of such public spending. This must critically also include assessment of the impacts on nature and associated ecosystem services supply to identify if such spending truly delivers net public benefits.

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What have we learned from this study and what is next?

Infrastructure, including roads, railways, other transport systems and associated supporting infrastructure, is essential in our interconnected world. We rely on roads and rail to connect and transport goods and services and people and provide economic and social benefits.

We cannot be without infrastructure, but we can and must ensure better planning of infrastructure given the associated multi-faceted environmental risks as outlined in this study. Our world is facing dual climate and biodiversity crises and we need to tackle these in an integrated way across all sectors and with coordinated policy engagement.

Road and rail environmental risks can be assessed as we have demonstrated. Analyses of regions showing increased risk of infrastructure development on species fit with knowledge of biodiversity patterns.

The GIIV web tool has been developed to accompany this report, which enables policymakers, scientists, and others to look in more detail at the potential risks and impacts of new transportation infrastructure. This is intended to increase the impact of this study through improved knowledge and awareness, and consequent generation of additional, more focused risk assessments and policy uptake.

For making informed decisions, indicators can be useful tools. The work started here for example may help contribute towards sustainable infrastructure indicator development.

The database of planned road and rail projects, created as part of this study, provides a foundation and it can be expanded, improved, and utilised more widely. However, the costs (time and effort) of attempting to make such a database open access and consistently up to date would have to be considered.

Ideally, more fine-scaled metrics and assessment at local and regional levels for national use would be a beneficial next step. Also, as part of this package of work, we are working on a country-level case study in Mongolia.

Additionally, as this was the first global study of this kind, we highlighted in the previous section potential improvements that will allow future work in this area to advance. Some suggestions have immediate potential, and others depend on advancement of data and knowledge. One of the most critical for enabling more circumspect, future-proof understanding is the inclusion of nature-related risks (i.e., climate change impacts, ecosystem integrity loss and natural capital/ES functioning/depletion) and mitigation to infrastructure development and investment. This would build on the impact and utility of the work begun here and enable it to go beyond a business-as-usual perspective, which is needed if we are to understand how to create a sustainable future.

The global planned road and rail database development and the novel risk and benefit metrics and analyses have allowed important progress in understanding global road and rail infrastructure development from a biodiversity, ecosystem service and socio-economic perspective. We hope that this foundation of work can be further developed and improved upon to be of even greater benefit in future.


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Appendix 1 – Additional analyses

Biodiversity - Risks to species

Understanding the magnitude of risks to species is a key step towards making informed planning decisions. At the macro level, assessments use coarse metrics, such as simple buffers around infrastructure and species ranges. As we now have knowledge of how impacts on populations typically decline with distance (Benitez-Lopez *et al.* 2010), we can attempt to represent this by applying impact kernels to species distribution data. Similarly, novel metrics allow us to estimate the risks of infrastructure-related land conversion to species in terms of their probability of persisting (Duran *et al.* 2020) (see Methods box below). We combine these approaches in an easily communicated metric to provide greater ecological realism in understanding the infrastructure risks to biodiversity.

BOX 9 METHODS – RISK TO SPECIES

Average change in species' persistence scores

The persistence score (Duran et al. 2020), aims to measure how likely a species is to persist based on changes in their Area of Habitat (AOH) (Brooks et al. 2019). The score ranges from 0 to 1, with 1 indicating the maximum persistence probability for a species, resulting from no contraction of its distribution range from human threat. We calculated the average projected change in persistence when planned infrastructure is built for each project for mammals, birds and amphibians likely to be sensitive to changes in habitat (i.e., Critically Endangered (CR), Endangered (EN), Vulnerable (VU) and Data Deficient (DD), according to the International Union for Conservation of Nature [IUCN] Red List 2019).

To simulate the change in species distributions resulting from planned infrastructure, we assumed that distributions will be affected near new roads and railways. As infrastructure can affect species in several ways, we designed a combined measurement of risk that aims to account for both direct and indirect impacts (Table 1) - where components extend different distances from infrastructure. The risk from each planned project was calculated as the difference in the species' persistence scores before and after the infrastructure is built. Results for all species were summed to give a score per project, and values for all projects in a country were aggregated to provide country-level estimation of risk.

Table 1. Approaches used for modelling impact of infrastructure on species

Impact type	Taxonomic group	What does it represent?	Impact distance	How does the impact decline?	Reference
Strong, short-distance	Mammals	Habitat loss, habitat degradation, increased mortality, pollution, noise – contributing to a decline in mean species abundance.	5km	Species abundance starts declining at the impact distance (5km is the distance for mean species abundance = 0.9)	Benitez-Lopez *et al.* (2010)
Strong, short-distance	Birds / amphibians	Habitat loss, habitat degradation, increased mortality, pollution, noise - causing a decline in mean species abundance. In the absence of estimations for amphibians, we assumed a similar risk as that estimated for birds.	1km	Species abundance starts declining at the impact distance (5km is the distance for mean species abundance = 0.9)	Benitez-Lopez *et al.* (2010)
Indirect – short-distance	All taxa	Selective logging, fuelwood collection, hunting; spread of fires and invasive species, pollution, and livestock grazing.	5km	Declines exponentially approaching zero at 3km and truncated at 5km	Grantham *et al* (2020)
Indirect – long-distance	All taxa	Over-exploitation of high socio-economic value animals and plants, changes to migration and ranging patterns, and scattered fire and pollution events.	12km	Declines linearly up to a conservative threshold of 12km (and slow intensity)	Grantham *et al.* (2020)

Analysis – Risk to species

Which species are at risk?

Of all threatened amphibian, bird and mammal species globally (n = 4074), 2396 were found to be in areas that will be crossed by planned roads (Figure 10 and 1514 from rail (Appendix Figure 12). For species that are within the impact area of roads or rails, amphibians (768 species, 46% of study species from the group), mammals (914 species, 70%) and birds (851 species, 77%) have broadly similar total numbers. The spread of species in the highest threat status categories (Critically Endangered, CR; and Endangered, EN), were also quite similar. Within the species intersected, 198 were Critically Endangered (CR, 48% of all analysed species in the category); 583 were Endangered (EN, 60%); 1012 were Vulnerable (VU, 76%), and 740 were Data Deficient (DD, 55%).

Figure 10. Number of study species impacted by planned roads shown by IUCN threat status category and taxonomic group.

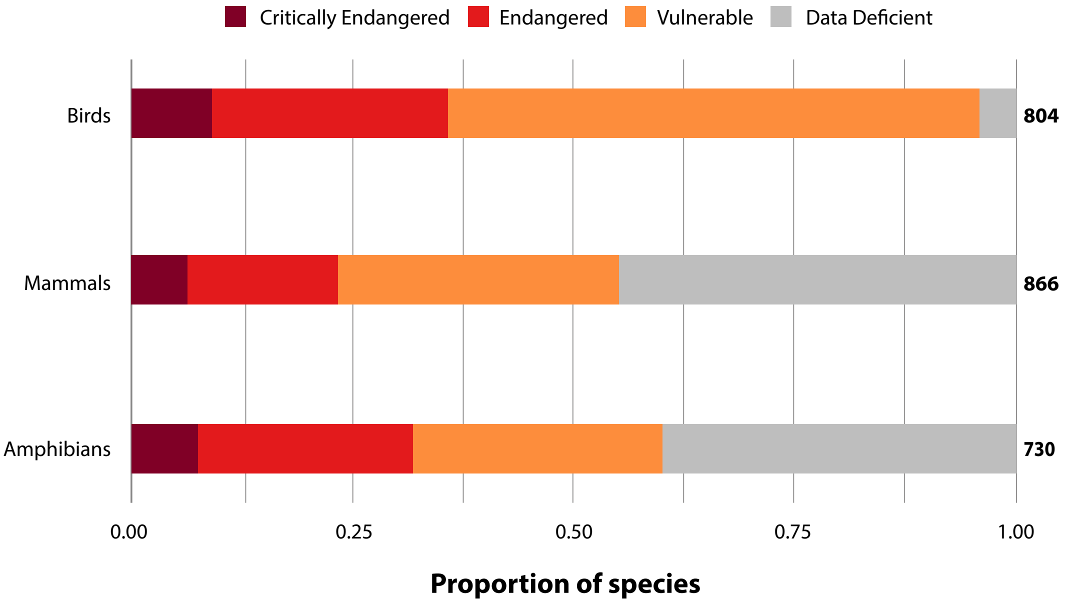
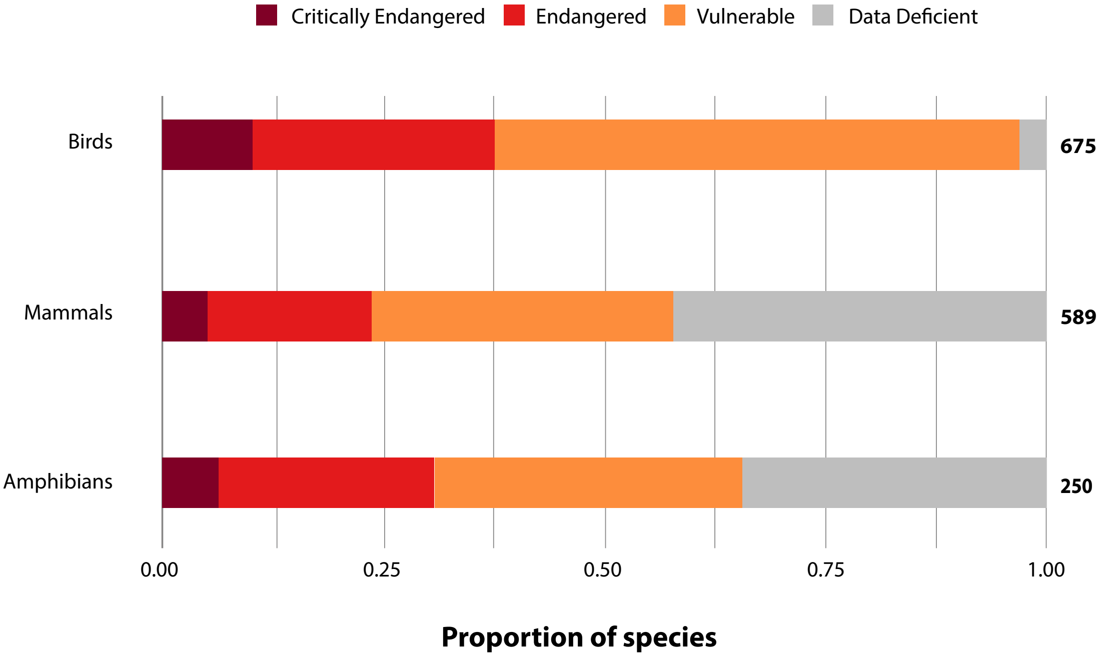


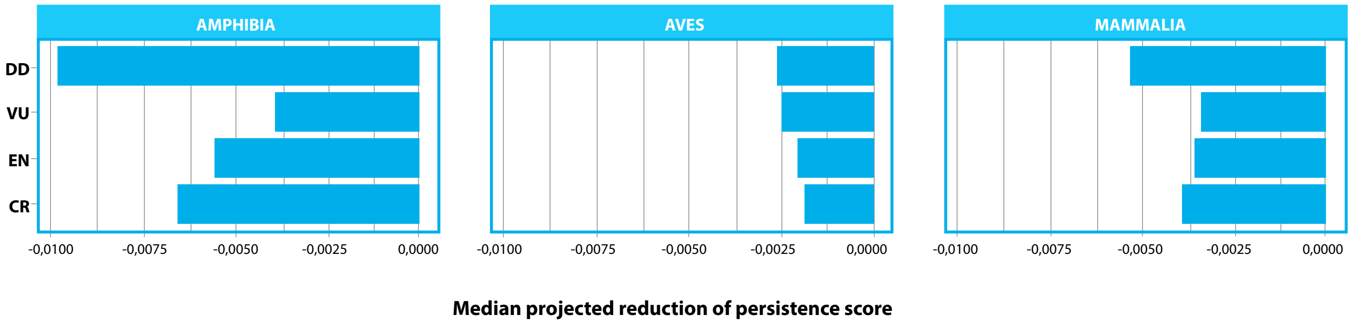
Figure 11. Number of study species impacted by planned rail shown by IUCN threat status category and taxonomic group.



How big are the risks to different groups of species?

Among the different species groups, at the global level, risks to persistence from planned infrastructure were similar. The decrease in median persistence scores, were most notable for amphibians and mammals: 2.57% and 1.96% larger declines, respectively, than birds (Figure 12).

Figure 12. **Global change in species' persistence scores for mammals, amphibians and birds resulting from planned linear infrastructure. Shown by taxonomic class and threat status.**

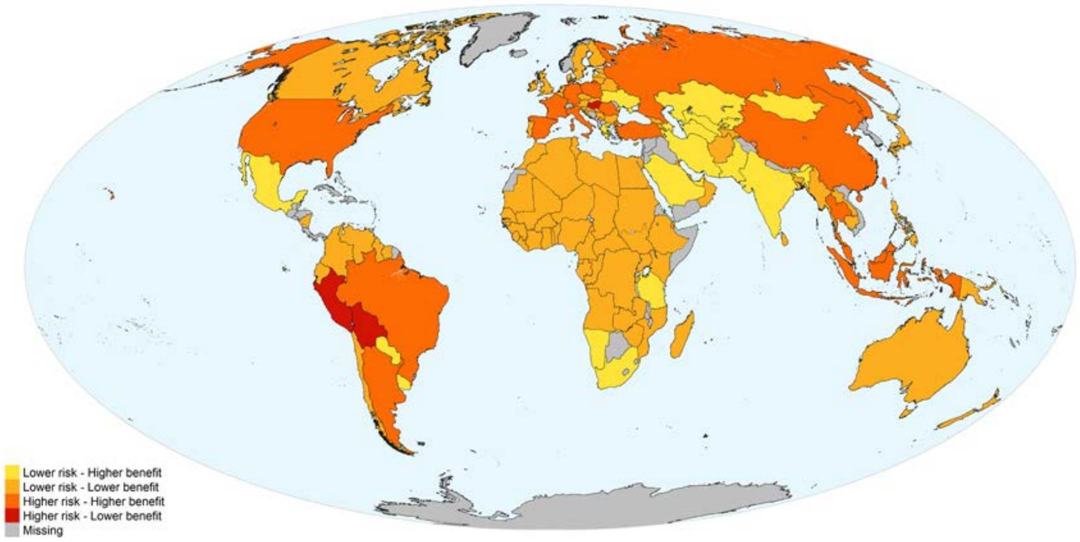


The different IUCN status categories each show similar risks from new infrastructure (median decrease in species' persistence score: DD = -0.006; CR, EN, VU = -0.003). However, the Data Deficient (DD) category showed a notably larger drop in persistence. This highlights the need for more information for such species. If Red List status can be ascertained, appropriate conservation mechanisms may be able to better protect these species from future threats, such as infrastructure development.

Where are the risks greatest?

The largest risks to species from planned roads and rail were found across the global tropics, with emphasis in Indonesia, followed by Papua New Guinea and several South American countries (including Brazil, Bolivia, Peru and Colombia) (Figure 13). Other notable areas of loss include several countries in Sub-Saharan Africa, Thailand and China. These patterns generally occur in areas with known high biodiversity and endemism (Jenkins *et al.* 2013). In addition, these regions agree with those found in studies that highlight key areas for expansion of the global conservation network (Jung *et al.* 2021).

Figure 13. **Map showing risks to threatened and Data Deficient species from planned roads and rail, aggregated to the country level.**



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Biodiversity - Risks to conservation areas

In addition to focusing on risks to species, we also consider risks to areas that are important for biodiversity conservation – namely protected areas (PAs) and Key Biodiversity Areas (KBAs).

Key Biodiversity Areas are designated areas of global importance for biodiversity, based on a set of explicit criteria. The criteria typically involve the site containing greater than a certain percentage of a species' global population. The thresholds for which depends on various factors such as threat status and size of their geographic range (KBA Standards and Appeals Committee 2020). Currently there are 16,356 sites globally, making up 8.85% of the world's terrestrial surface. Historically, site identification was focused upon birds, but has now widened to include mammals, reptiles, amphibians, plants, freshwater fish species, insects, and marine biodiversity.

Protected Areas are legally designated sites that are typically actively managed with the goal to conserve nature and its benefits. There are 251,947 protected areas globally which cover 15.73% of the world's terrestrial area (UNEP-WCMC and IUCN 2022). They may be designated for various purposes from protecting threatened biodiversity to preserving cultural values and ecosystem services. Many protected areas are in fact designated for more than one reason, with a quarter of them having multiple overlapping designations (Deguignet *et al.* 2017).

KBAs and protected areas often overlap. In the datasets used in this analysis (data for the countries for which the database of planned transport infrastructure has data), 44% of KBAs were also inside protected areas. Correspondingly, 29% of protected areas included habitats that are designed as KBAs.

New infrastructure projects, such as roads and rail, inside protected areas and KBAs can cause habitat fragmentation and pose various direct and indirect risks to biodiversity (as described in the Risks to biodiversity section).

BOX 10 METHODS – RISK TO CONSERVATION AREAS

We estimated the total length of roads and rail in protected areas and Key Biodiversity Areas (KBAs). We downloaded spatial data for protected areas, obtained from the World Database of Protected Areas (WDPA) (protectedplanet.net, data accessed in Nov 2021), and KBAs from the World Database of KBAs (IUCN 2016 2021 dataset). We excluded protected areas with 'proposed' or 'not reported' status, and those of international designation, following the methodology used to calculate global estimates of protected area coverage (UNEP-WCMC 2021). To avoid double counting areas where PAs and KBAs overlap spatially, which are significant, we used a 'flattened' layer combining both datasets. As no definitive distances have been defined for impacts from roads/rail on such areas, we chose to calculate length of infrastructure that falls inside these areas. These conservation areas contain multiple environmental components that can be impacted in several ways. Some of these components are captured in the Risks to Biodiversity and Risks to Ecosystem Services results. However, these sites warrant inclusion as they also represent conservation efforts and the possibility of legal ramifications.

Caveats:

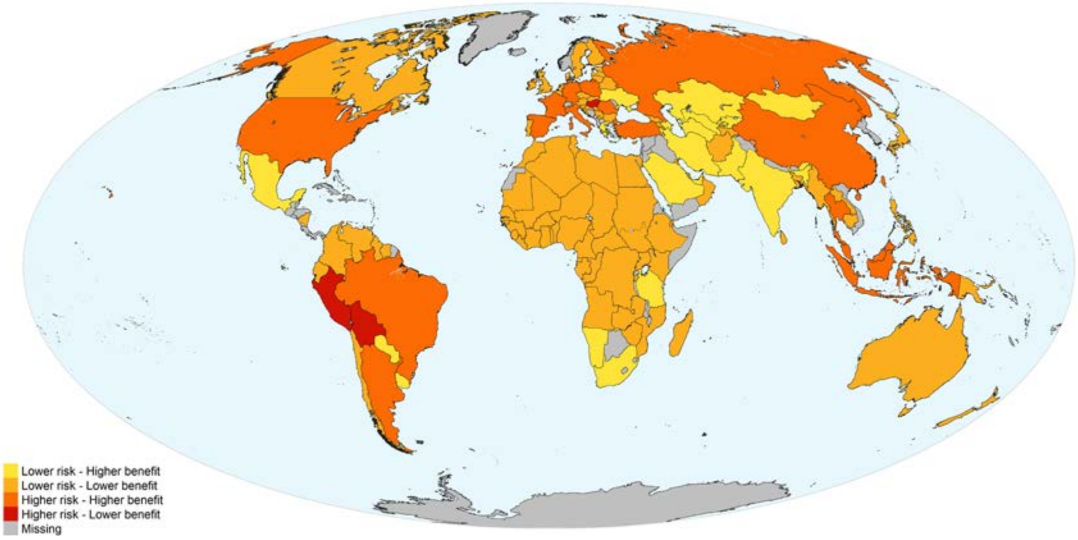
- The WDPA is the most coherent global picture of protected area coverage available. Updates are provided from country focal points, but sections can be out of date (see the WDPA Manual (UNEP-WCMC 2019)).
- Currently the KBA dataset is biased towards birds and the terrestrial realm given its historical focus, however, expansion of the KBA network is ongoing and taxonomic coverage is increasing.
- Other Effective Area Based Measures (OECMs) were not included in this analysis, but we recommend they are included in any future analyses. Currently only a few countries have been collated for the World Database on OECM (WDOECM) database (protectedplanet.net), but this is increasing rapidly.

Analysis – Risk to conservation areas

Overall, 12% of total infrastructure crosses conservation areas, 7.3% in PAs and 6.9% for KBAs.The highest risks from planned roads and rail crossing through conservation areas are found in Central and Western Europe, and South America. In Poland, the country with the highest risk, ~2700km is within conservation areas - 18% of the length of all planned roads and rail (Figure 14). Such figures are not surprising considering nearly 40% of the country is protected, roughly 2.5 times the global coverage for terrestrial areas (UNEP-WCMC and IUCN 2022). In a similar example, Brazil also has a high-risk score for this metric and protected area coverage of approximately 30%. In such countries and regions, planning infrastructure that avoids conservation areas may be particularly challenging.

However, several other more obvious factors exist that account for variation in scores. These range from spatial inaccuracy of planning data (see Appendix 2 Global Database of Planned Roads and Rail) to the type of designations, and – particularly for KBAs – a lack of awareness of distribution and global importance of the conservation area.

Figure 14. Map showing risks to protected areas and Key Biodiversity Areas from planned roads and rail, aggregated to the country level. In this case, risk is determined by the length (km) of planned infrastructure intersecting PAs or KBAs per country.



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Biodiversity - Risks to wilderness areas

Wilderness areas as depicted here represent areas of minimal human impact and disturbance from infrastructure and human populations. The presence of transport infrastructure in such areas can have disproportionately large impacts in some of these ecosystems. Increased accessibility combined with previously unexploited natural resources, as in the case of forests, can lead to large scale land use changes. For example, the propagation of new roads branching off from a single new logging road can give rise to the fishbone deforestation patterns seen in parts of the Amazon Rainforest (Freitas *et al.* 2010).

BOX 11 METHODS – RISK TO WILDERNESS AREAS

We estimated the length of planned linear infrastructure crossing wilderness areas. A map of wilderness areas was produced for 2013 identifying the terrestrial areas with a human footprint of zero, following Williams et al. (2013). This map was then overlaid with the database of planned linear infrastructure to identify projects that intersected wilderness area and the length of this intersection was calculated.

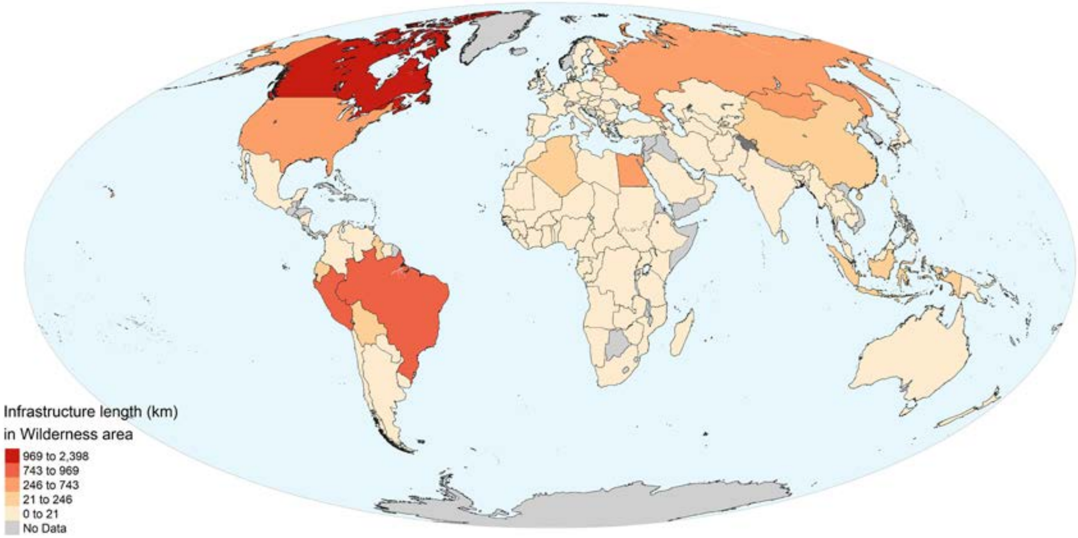
Caveats:

- In the eight years that have passed since the wilderness layer was produced, it is highly likely that there has already been a reduction in the coverage.
- Roads passing near but outside such areas will show no increase in risk – relevant mainly to datasets with lower spatial accuracy (see Appendix 2 Figure 19).
- Wilderness does not necessarily indicate the presence of high biodiversity, but the metric used here is included as a simple, easily understandable proxy for high ecological intactness. When combined with conservation areas and species persistence metrics it helps provides a more rounded risk metric for biodiversity.

Analysis – Risk to wilderness areas

We found that planned terrestrial transport infrastructure may pose a risk to wilderness area in at least 23 countries (mean wilderness area intersected by infrastructure of 332±517km). The patterns of risks to wilderness areas from planned infrastructure can be seen in Figure 15. Roads and rail in Canada cross the largest length (~2400km) of wilderness, corresponding to almost 60% of the total planned infrastructure in the country. Similarly, Brazil and Peru face high wilderness risks with 960km and 969km of infrastructure, respectively, potentially opening up previously undeveloped regions.

Figure 15. **Map showing risks to wilderness areas from planned roads and rail, aggregated to the country level.**



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Risks to ecosystem services

BOX 12 METHODS – RISKS TO ECOSYSTEM SERVICES

For the following ecosystem services there was little support for calculating risk beyond direct impacts.

All input datasets were resampled to ~30 arc second resolution (approx. 1km). Risk per project was then calculated based on summing the ES values for the pixels that touched the planned infrastructure lines (see also Appendix 2 for further details).

Carbon

Carbon stock: We estimated risks to carbon stocks resulting from the construction of planned infrastructure by combining 1) a global layer of soil carbon data (1-metre depth) from the Harmonized World Soil Database and 2) vegetation biomass from the UNEP-WCMC above and belowground carbon density layer (Hiederer and Kochy 2012). Datasets were summed together to show total carbon stock that might be at risk from infrastructure construction (Soto-Navarro et al. 2020).

Water

Surface water: We followed methods in Vilela et al. (2020) to highlight roads that intersect with surface water and that could pose a risk for flooding and water quality. For this we used a global layer of surface water produced by JRC (Pekel et al. 2016).

Water quality regulation: We estimated nitrogen retention provided by nature (kg/ha nitrogen), using layers calculated by Chaplin-Kramer et al. (2019) using the InVEST modelling framework. The maximum potential benefit layer (nitrogen pollution loads requiring retention) was multiplied by the proportion of nitrogen retention provided by nature to estimate the nitrogen retained by vegetation in each cell (kg/ha nitrogen). The dataset represents total potential nitrogen retained by vegetation per cell (tonnes).

Crop pollination

Crop pollination: for this we used maps of nature's contribution to pollinator-dependant micronutrient production. This layer was produced using layers from Chaplin-Kramer et al. (2019) which were developed using the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) modelling framework. The maximum nutrient production requiring pollination layer was multiplied with the proportion of nature's contribution to this service to estimate the maximum nutrient production requiring pollination provided by nature in each cell.

Caveats

- For services such as water quality provisioning and pollination-dependant crop production, the impact of the potential losses could not be linked to the number of people using them due to limitations in the scope of the analysis.
- Carbon storage is a global ecosystem service, and therefore the realised service is not linked to those directly using it.
- Due to challenges involved in mapping and valuing ecosystems at a global level, the analysis only focuses on a limited number of services.
- The types and importance of ecosystem services will vary by local climate, landscape, and socio-economic factors.
- The distance over which ecosystem services are affected will vary by service, infrastructure type and local context, it was not possible to account for this at a global level.

Analysis – Risk to ecosystem services

Risk to carbon stocks

Potential carbon stock losses are greatest across countries with high forest coverage, including boreal countries such as Canada, Finland and Russia, temperate and subtropical countries including Germany and China, as well as tropical countries with dense rainforest including Brazil and Indonesia (Figure 16). Several of these countries (particularly Canada, Russia, and Indonesia) have large extents of peatland soils, which store some of the densest carbon stocks on land. Infrastructure development displacing these soils could result in significant soil organic carbon (SOC) emissions alongside any losses of vegetation biomass. The transport sector is one of the fastest growing sources of emissions globally (Intergovernmental Panel on Climate Change [IPCC] 2014). The results demonstrate that large stores of carbon could be at risk from infrastructure development. Therefore, opportunities to minimise and mitigate this risk should be of high priority, particularly where carbon-dense ecosystems (such as forests and peatlands) may be lost or degraded because of development. This is particularly important as the global climate crises continues to worsen and net-zero emissions targets are being made across sectors and at national levels.

Risk to water quality regulation

Risks to water quality regulation are greatest where there are large densities of vegetation biomass, which retains nitrogen pollution, improving water quality for downstream users. The loss of this service may threaten the health, wellbeing and livelihoods of several downstream users who depend on clean water being produced by nature.

Risk to surface water

Areas of permanent surface water are found across the world, but are particularly prevalent in the Northern Hemisphere, notably in Canada, Nordic countries, and North Russia, where prevailing climate and wetland ecosystems allow for permanent coverage (Figure 16). The results of this analysis followed this trend, with infrastructure development having the largest impact in these countries. These ecosystems are also found throughout temperate and tropical regions, and the considerable number of developments in China, South America, and Asia-Pacific (particularly Indonesia) have highlighted large areas of risk to permanent water coverage. Risk to these ecosystems could threaten the quality of water (e.g., drinking water) if levels of pollutants rise, increasing risk of conflict in water stressed areas, threatening the livelihoods of those who depend on them and influencing the movement of both people and migrant species. The presence (or absence) of water also greatly influences global climate regulation. Depending on their condition, wetlands can be either significant sources or sinks of carbon dioxide and methane emissions and water coverage influences these processes (Pekel *et al.* 2016).

Risk to crop pollination

Finally, risks on pollination-dependant crop production as a result of land-use change were highest in countries where crop production is high, including the USA (particularly California), Europe, Russia, China, Indonesia and Argentina (one of the world's largest producers of soy, maize, sunflower, barley and cotton) (Figure 16). The loss of natural ecosystems which provide habitat for important crop pollinator species could result in food insecurity both at the local level and across global supply chains if major crop production is impacted.

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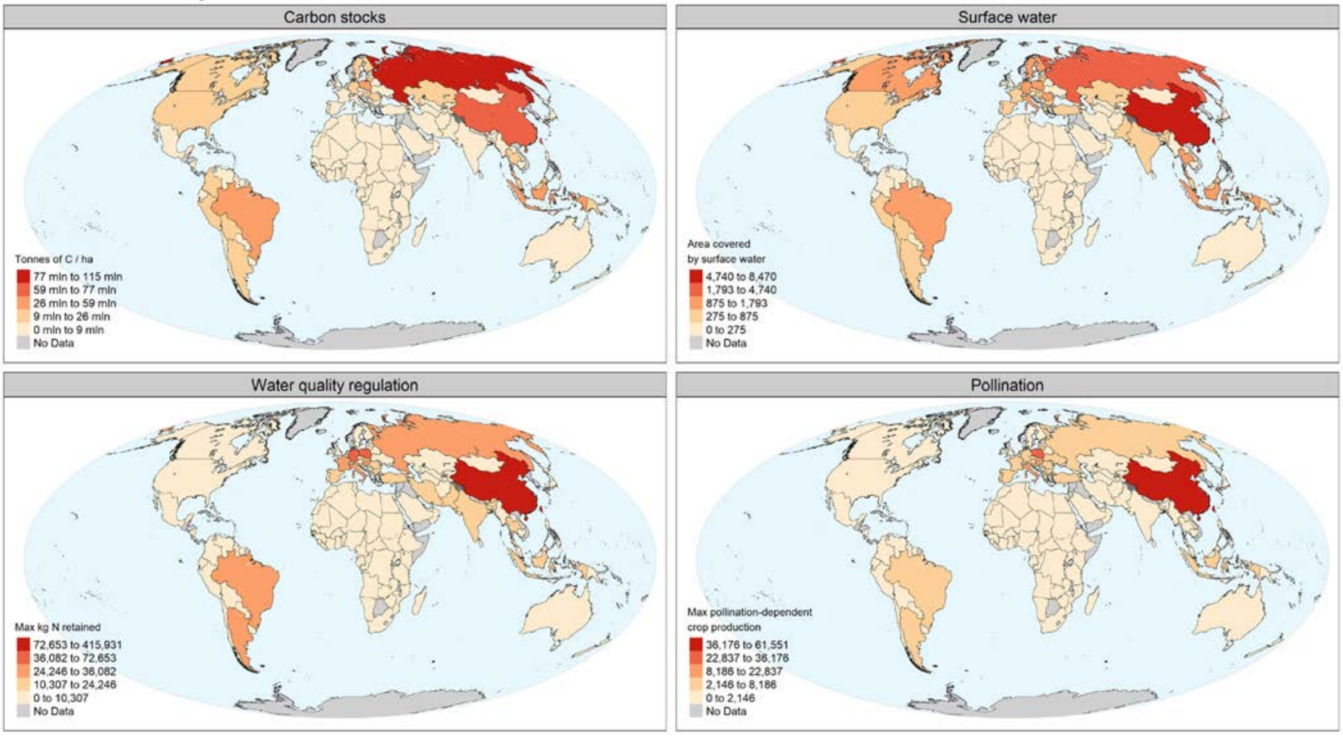
Figure 16. **Risks to ecosystem services from planned roads and rail, shown at the country level. Ecosystem services include carbon stocks (top left, units: tonnes of C/ha), surface water (top right, units: area covered by surface water), water quality regulation (bottom left, units: maximum kg of N retrained by vegetation) retention and crop pollination (bottom right, units: maximum pollination-dependent crop production).**



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Socio-Economic - Benefits for employment

When understanding the impact of developing rail and road infrastructure in a region, it is important to understand the consequences this would have on employment. The relationship between infrastructure and net employment can be unclear. Some studies have identified significant employment benefits from infrastructure development (e.g., Gálvez Nogales 2014). However, rises in unemployment or no effect in employment levels have also been observed when examining increased infrastructure in different areas and countries (e.g., Rubaba *et al.* 2015 and Laborda & Sotelsek 2019).

The general evidence suggests that any positive relationship between employment and infrastructure will be realised in low and low to middle income countries (Laborda & Sotelsek 2019). Accordingly, the employments benefits analysis focuses purely on these countries (i.e., investment in transport infrastructure has zero impact on jobs in the other countries of the world). In this approach, GDP employment elasticities have been used to derive data relating to the relationship between infrastructure and employment, with the aim to quantify the connections between the two.

BOX 13 **METHODS - EMPLOYMENT BENEFITS**

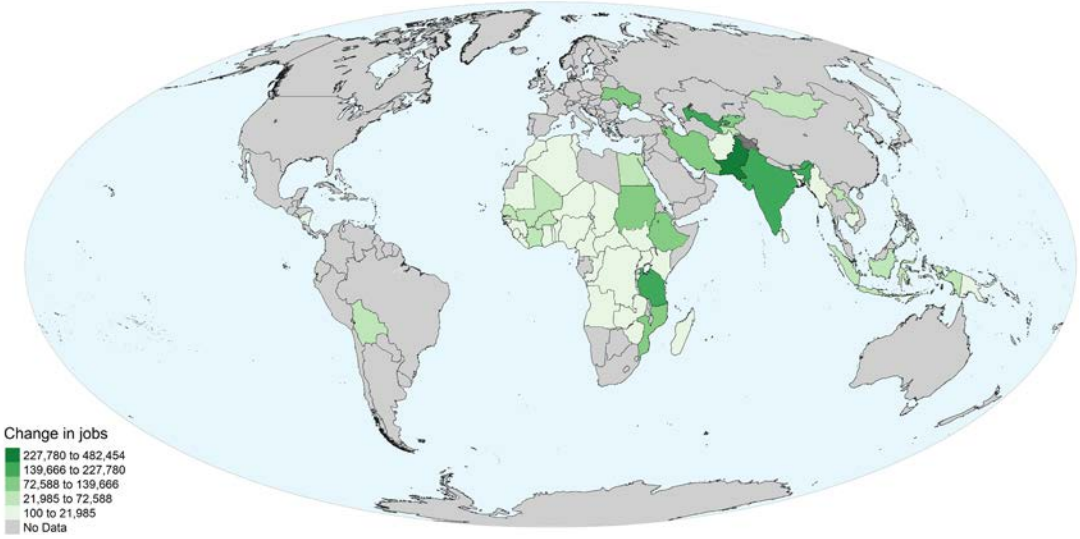
Estimating change in employment

The approach to estimate the changes in employment in a country associated with derived GDP increases from transport infrastructure development is based on using the elasticity of employment to GDP for non-OECD countries estimated by Anderson & Braunstein (2013). The estimated by Anderson & Braunstein (2013) is relevant to the working age population of countries. This is 0.155 (based on average of female and male elasticities), implying that a 1% increase in GDP leads to a 0.155% increase in employment in the working age population. We applied this elasticity to the relative changes in GDP estimated for the 82 low - low to middle income countries. As with the economic benefit analysis, results were only reasonable at the country level as there are no sub-national GDP estimates to spatial focus the analysis.

Analysis - Employment Benefits

Figure 17 reveals that planned infrastructure development could have significant positive effect on employment in Pakistan. This reflects the focus on rail infrastructure development in that country, which has a greater impact on GDP than road. A similar result is observed for Tajikistan. Elsewhere, relatively high employment returns on transport infrastructure are observed on India, Mali, and Uzbekistan. Again, associated with planned rail infrastructure.

Figure 17. **Benefits of infrastructure on employment. Only low - low to middle income countries with infrastructure are shown as the relationship with infrastructure is only supported for these countries (see Methods).**



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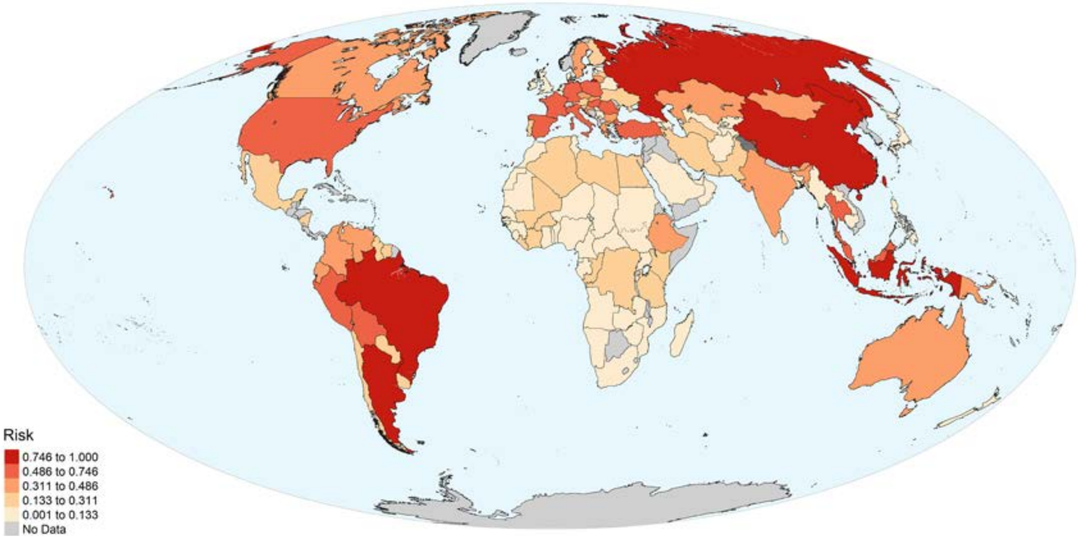
Biodiversity & Ecosystem Services - Composite environmental risk

The composite environmental risk map shows broadly similar patterns to the composite risk to ecosystem services map. However, combining with the composite map of biodiversity, has altered the pattern. Higher risk scores occur in the tropics (western South America and East Africa) and northern Africa – from high species risk and wilderness scores, respectively (Figure 18). In some of the northern hemisphere, such as Canada and parts of Europe, risk scores have reduced – due to lower risks to species and conservation areas, and lower wilderness scores, respectively (Figure 18). The data shown in this map were used in the risk-benefit analysis in the main body of the report (Figures 6 and 7).

BOX 14 **METHODS - COMPOSITE ENVIRONMENTAL RISK**

We averaged the two composite risk maps for (1) biodiversity, and (2) ecosystem services into a final 'all-environmental' composite risk map. This dataset provides an overall estimate of risk, where species persistence, wilderness, areas of importance to conservation and ecosystem services are represented in a balanced manner.

Figure 18. **Composite environmental risks from planned roads and rail, shown at the country level. The map displays the average of two composite risk maps: 1) biodiversity, conservation and wilderness areas and 2) ecosystem services: carbon stocks, water quality regulation, surface water and crop pollination.**



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Appendix 2 - Supplementary methods

Global Database of Planned Roads and Rail

Non-systematic searches were undertaken to find infrastructure projects and associated spatial data. First scientific literature was searched (using Google Scholar) and authors were contacted to request access to data. Subsequently, regular Google searches were undertaken to identify large infrastructure projects on government websites, project websites and other grey literature. Initially searches were general with no location specified, they were then narrowed down to continents and regions, and in some cases countries where there were large gaps, e.g., the USA or Australia.

If possible, spatial data were downloaded online, but in most cases, it was not available. Where this was the case, emails requesting access to data were sent to relevant contacts (e.g., the bodies managing the projects). Where we were not successful in obtaining the spatial data from either of the previous two methods, maps of the project routes were downloaded. If these were a high enough quality to show accurately the routes, they were georeferenced in ArcGIS Pro. We then produced spatial data for the projects using these georeferenced maps as guides. So that weblinks to data sources were available after the study completes, we archived them on the WayBack Machine (https://archive.org/web/).

Status and type

Each project was assigned a status (the stage at which the infrastructure project was at) and type (type of development) category. These categories were:

Status

- Operational – The infrastructure is completed and in operation
- In progress – The infrastructure is currently under construction
- Planning – New infrastructure that is still at the conceptual stages and yet to be implemented
- Unknown – it is not known what stage the infrastructure is at

Type

- New – A completely new development where the infrastructure is being built from scratch. On land that was not previously used for that type of infrastructure.
- Upgrade – upgrades to existing infrastructure e.g., widening a road or tarmacking a dirt road.
- Existing – The road already exists, and no improvements are being made.
- Unknown – it is not known what type of development is happening.

Some additional categories were also included where it was not entirely clear what the category should be. For example, new/upgrade where it was not clear whether it was a new development or an upgrade to an existing one. Or planning/in progress where it was not clear whether the project was still in the planning stage or if construction had begun.

Datasets that we received that have been published in scientific literature already had status and type information included. Datasets provided by other sources also often had this available. Maps that were georeferenced also often included information on status and type. On the occasions when this information was not available, searches were undertaken (e.g., on project websites) to try to determine the status and type of project. If it was not possible to find information, they were recorded as unknown.

As the information on status and type was often several years out of date, searches were undertaken for most project to attempt to identify more up-to-date information. Were there was no information available, satellite imagery was used to see if the road/railway already existed (in the case of new roads/railways). The status and type information were updated based on the results of these checks. This was not possible for some of the large datasets, however, such as the datasets for Europe and the Belt and Road Initiative (BRI). An automated approach was used to check the Europe dataset. The amount of overlap between them and existing roads/railways was calculated. Any planned new roads/railways in the dataset that had a high overlap with existing roads/railways were assumed to have already been completed. This method did not work for the BRI and other datasets as they were not as spatially accurate as the Europe data.

Spatial accuracy

Each dataset was given a spatial accuracy of high, medium or low. This was done differently for spatial datasets that we downloaded/were provided with and for the datasets that we georeferenced. For the datasets we downloaded/were provided, as the majority of datasets included existing and/or to be upgraded roads/railways, the accuracy could be compared to basemaps/satellite imagery. A spatial accuracy score was not possible where the dataset only included new roads. The criteria for the categories were:

- High – the lines followed the roads/railways on the basemaps/satellite imagery exactly.
- Medium – the lines followed the road/railway route on the basemaps/satellite imagery well but deviated from the exact route slightly (less that 1 km).
- Low – the lines followed the route of roads/railways on the basemaps/satellite imagery but were off by a kilometre or more, but no more than 3 or 4 kilometres.

For the datasets we georeferenced, a judgement was made based on how well the image could be georeferenced and the resolution of the image. The width of the road/railway line on the georeferenced image was measured. The thickness of this indicated how accurate the resulting spatial data produced would be. If the line was only a few meters wide, the spatial data produced was more likely to be accurate than if the line was 10km wide. The same high, medium, low categories were used.

Datasets that clearly were not depicting the actual route of the infrastructure, such as straight lines between cities were not considered.

Figure 19. **Roads and rail according to spatial accuracy.**

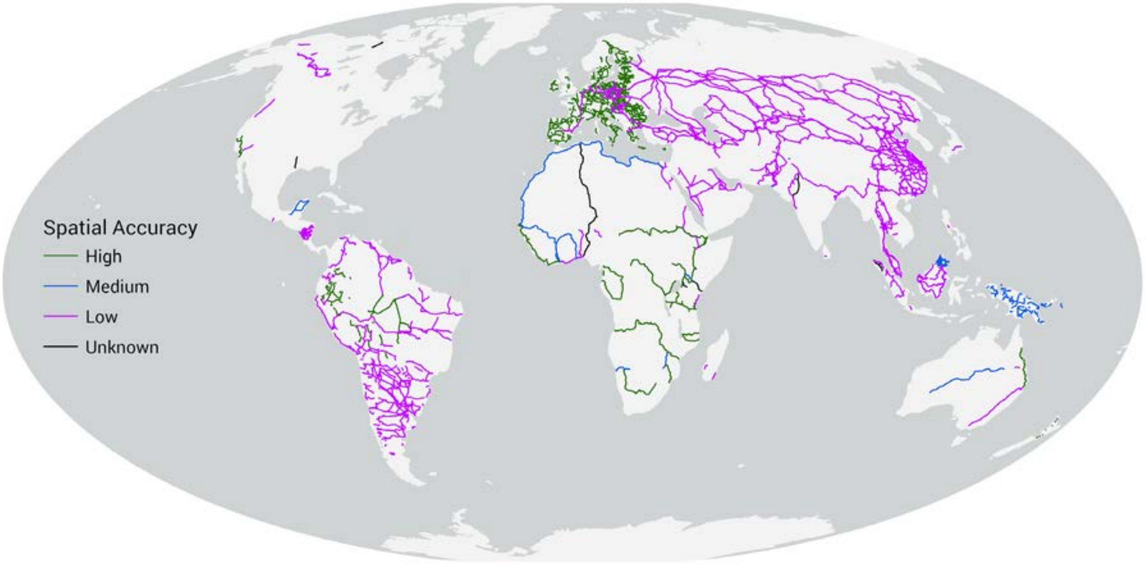

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*Table 2. **Number of roads projects in each combination of the Type and Status categories.***

		Type					
		new	**new/upgrade**	**upgrade**	**upgrade/existing**	**unknown**	**Total**
Status	in progress	118	1	201		6	326
	planning	254	2	697		15	968
	planning/in progress			8			8
	unknown	1	323	120	38	1	483
	Total	**373**	**326**	**1026**	**38**	**22**	**1785**

*Table 3. **Number of rail projects in each combination of the Type and Status categories.***

		Type				
	Row Labels	**new**	**new/upgrade**	**upgrade**	**unknown**	**Grand Total**
Status	in progress	23		83	1	107
	planning	220	1	788	15	1024
	planning/in progress			4		4
	unknown		280		1	281
	Grand Total	**243**	**281**	**875**	**17**	**1416**

Caveats

- The dataset is not a comprehensive global dataset, it only includes infrastructure projects where data could be found. Distinctions between 'new' and 'upgrade' are not reliable as they are subject to being out of date or potentially misinterpreted due to differences in terminology used. For example, some datasets may class a highway being built on top of a single carriageway as a 'new' road, whereas others may call this an 'upgrade'. Up to date information was also difficult to obtain for whether roads were still in the 'planning' stage, were 'in progress' or had already been completed. We checked and updated this, as stated above, as best as possible with online information and satellite imagery, but these were both often outdated. Therefore, the data in the status field are also not reliable. For example, there may be infrastructure down as 'planned' or 'in progress' which has in fact already been completed. It is also important to note that we assume projects will be completed in the relatively near future. However, it may be the case that some are never completed, have long delays or are abandoned once completed.
- Overlapping projects – a small number of overlapping sections for projects in different stages were discovered. As this was found after analysis was complete, for each metric we compared impact values for the full length of both projects and then adjusted these based on the length of road/rail overlapping. Whichever value was highest was chosen to represent the overlapping section as we are interested in potential risk. The duplicate was then removed from the section in the latest project stage.
- Type – distinctions between 'new' and 'upgrade', even when classed as such in the project datasets we collated are not reliable. As they are subject to being out of date or potentially misinterpreted due to differences in terminology use within the infrastructure sector, or to what is required for our analysis (i.e., where a "new" road/rail project is not a replacement of another road with effectively the same footprint).
- Project status – not always recorded and when it is may not be accurate. Efforts were made to carry out checks on these against satellite imagery, for example to see if a planned road is going into a new area.

- Geographic coverage – despite efforts to achieve an unbiased geographic spread (including targeting countries/regions where initially little data were available), we were limited to plans published and available in English (with Spanish translation for some project data).
- Temporal limitations – the database is a snapshot in time of planned linear transport infrastructure and without effort to maintain it, will be outdated.
- Spatial accuracy – accuracy depends on how the spatial data were created and mapped (e.g., digitizing). We estimated spatial accuracy for each dataset but acknowledge that results are less reliable where uncertainty is highest (see Figure 20).
- Defining a project – some data in datasets were not divided explicitly into infrastructure projects. For these we applied an approach to split the dataset. This enabled fairer comparisons for project-level results. Remaining heterogeneity in project length may influence project-level results to some extent as risks typically increase with length. However, this influence is expected to be minor as project-level results are normalized by length (i.e., per kilometre results) and aggregate country-level results should not be affected.

Risks to biodiversity - methodology

To assess potential impact of transport infrastructure development on biodiversity we used existing global layers on the distribution of species, protected areas and other important conservation areas (including Key Biodiversity Areas), as well as wilderness area based on a global database of biodiversity response to anthropogenic pressure. Analyses were conducted at the project level, and summary statistics at global, regional and national scale were produced for each biodiversity aspect. In this appendix we only cover species persistence methods in detail as this analysis was more involved than those for wilderness and conservation areas.

Species persistence. By quantifying the overlap between planned linear transportation infrastructure and species distributions, we estimated changes in the likelihood of species to persist. To do this, we applied the approach described in Duran *et al.* (2020).

- We conducted the analysis for threatened (i.e., included in the global Red List of Threatened species in the categories Vulnerable, Endangered or Critically Endangered) and Data Deficient species of vertebrates. Specifically, we included mammal, bird and amphibian species ranges from the IUCN Red List database (IUCN 2019) as these were the only comprehensively assessed terrestrial taxonomic groups.
- The analysis is based on maps representing area of suitable habitat (AOH; Brooks *et al.* 2019) for the species. AOH maps result from using species' habitat preferences and elevation requirements and to refine IUCN range maps. We developed AOH maps for each available species with range data following methods in Power & Jetz (2019) and Jung *et al.* (2021) and refined them further using infrastructure data for two scenarios (near-current and projected future). We applied impact kernels to areas around infrastructure so that areas directly within the footprint lost habitat and areas a little further away lost a proportion of habitat (see distances in Table 1, Appendix 1). Source of data: self-produced species AOHs in Google Earth Engine. Original resolution: 30 arc-sec.
- We then calculated persistence scores (P) for each species using the following equation:

$$P = (E)^z$$

where E is the remaining proportion of species AOH at a given time, relative to the historic range size (i.e., pre-industrial). We calculated P for species "current" range and projected a future P after linear infrastructure is built by simulating the impact of this in species AOH. Then, we used a second equation to estimate the change in persistence score:

$$\Delta P = [(Et0)z - (Et1)z]$$

Where $t0$ and $t1$ are times before and after planned infrastructure has impacted species range. The parameter z is the extinction coefficient. We used a z-value of 0.25 based in Duran *et al.* (2020), which calibrated this value based upon its ability to predict proportions of species becoming extinct or threatened as a result of habitat loss.

- Understanding the distance at which linear infrastructure impacts species ranges and the intensity of this impact was not trivial. Different types of transport infrastructure are likely to impact species differently, and species with different characteristics are impacted in distinct ways. Moreover, these impacts are likely to be habitat and taxa specific. Lastly, the bibliography on these impacts is still scarce, granting us with no clear and easy values to apply within the scope of the study globally and across a wide range of taxa and habitat types. We reviewed literature to identify the approaches that previous attempts have used to estimate the impact of linear infrastructure on species ranges (see Appendix 1, risk to species for more detail). Analyses were conducted in R.

- We studied the impact of planned infrastructure on species persistence scores in two ways:
  - At the infrastructure project level: we calculated the impact of each infrastructure project on all the species whose AOH overlaps with the project. To do this, we calculated ΔP for each species and the footprint of the specific infrastructure project and summed the impact across all species potentially affected.
  - At the species level: To do this, we calculated species-specific ΔP as a result of all infrastructure projects that overlap with the species AOHs. We then aggregated these species-specific results by taxonomic group, country and/or biome to provide insight on where and which groups are likely to be more affected by planned infrastructure.

Input data. This analysis required data on species distribution at present and historic times. At the global scale, we used species' Area of Habitat. We obtained the data by refining species range data from IUCN and birdlife. Each species range was modified to remove areas that do not overlay with suitable land cover and elevation preferences of the species, as catalogued in the IUCN database of threatened species metadata. We took the elevation from a digital elevation model, and land cover was taken from a global habitat map (Jung *et al.* 2021). We used a map of potential natural vegetation (PNV) to produce historic AOHs by identifying the most likely natural cover in the absence of human land cover. For species with seasonal distributions, we calculated the change in persistence score for each season independently and selected the seasonal score indicating a higher decrease in persistence as indicative for the species as a precautionary measure.

  - Global data resolution: this was determined by original species ranges, which is often uncertain and variable among species and taxa. Refinements were calculated at 100m resolution (this is the resolution of elevation and land cover data used), and then resampled to 1km for further analyses.
  - Species coverage: we conducted global analyses for threatened and near threatened species from the taxa birds, mammals and amphibians, for a total of 4074 species. Such a large number of species were studied thanks to analysis automation through scripting.
  - Country scale analysis

- The same data may be used at the national level. In general, data resolution is adequate for a country scale analysis and often represents the best available data. However, species ranges might lack enough detail in some regions.
- Alternatively, if better species distribution data are available, they may be used instead. Ideally, such a dataset might include estimations of species distributions in the absence of human land cover, or else the same method used at the global level might be adapted to obtain this.
- This analysis likely requires applying scripts because it maybe lacks enough interest if restricted to a short number of species. If calculating on a large number of species is not an option, the adequacy of this analysis should be discussed.

Risks to ecosystem services – methodology

Chaplin-Kramer *et al.* (2015) demonstrated the introduction of forest edges could result in further changes to forest aboveground biomass carbon up to 1.5km from the forest edge in tropical forests, due to factors including increased exposure to wind and desiccation. Furthermore, infrastructure development may increase access to remote ecosystems including tropical forests. Several studies have documented a 'fishbone' deforestation pattern extending out from road developments as increased access leads to exploitation of the ecosystem through logging (Freitas *et al.* 2010). Large areas of deforestation can affect local climate regulation, with deforested areas often becoming drier and arid, having significant impacts on local communities in terms of clean water availability and crop production. However, this effect could vary significantly by location and would require simulating future land change based on modelling of historic deforestation trends whilst taking biophysical and socio-economic variables into account (Vilela *et al.* 2020). Due to the size and global extent of the dataset this was out of scope for the analysis. Therefore, the indirect effects of infrastructure development on deforestation and forest carbon storage are not estimated but should be considered in the planning stages of infrastructure development.

To assess potential impact of transport infrastructure development on ecosystem services we used existing global ecosystem service layers from Chaplin-Kramer *et al.* (2019; developed using the InVEST model (Sharp *et al.* 2020)), Harris *et al.* (2021), Soto-Navarro *et al.* (2020), Hiederer and Kochy (2012) and (Table 4).

For each ecosystem service we identified a road effect zone and assessed the potential change in ecosystem service due to the infrastructure in biophysical terms where possible.

Summary statistics at global, regional and national scale were produced for each ecosystem service.

We rescaled all layers used to approximately 30 Arc Seconds (~1km) spatial resolution to harmonize methods.

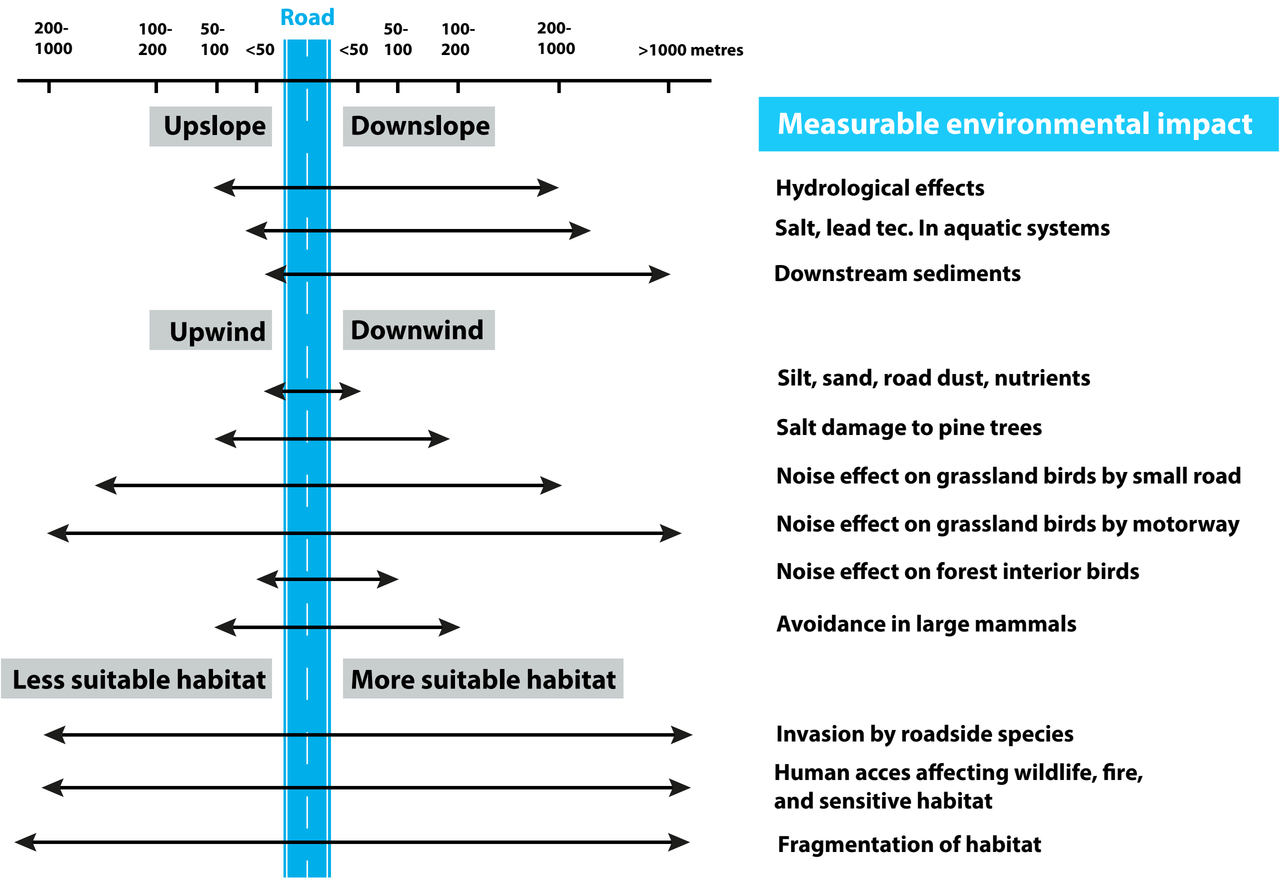
Table 4. ***List of ecosystem services that were evaluated, source of data, units and spatial scale of datasets.***

	Ecosystem service	Source of data	Original Units	Original resolution	New Units	Data format
1	Nitrogen retention for water quality regulation	Chaplin-Kramer *et al.* (2019), InVEST	Maximum kg/ha nitrogen to be retained * proportion nature contributes to retention	10 arc-sec (~300 m)	Tonnes of nitrogen retained/pixel	Raster
2	Crop pollination	Chaplin-Kramer *et al.* (2019), InVEST	Maximum crop production requiring pollination * proportion nature contributes to crop pollination	10 arc-sec (~300 m)		Raster
3	Carbon storage (Vegetation biomass)	WCMC vegetation biomass carbon (Soto-Navarro *et al.* 2020)	Tonnes of carbon/ha (for terrestrial ecosystems) stored in above ground and below ground biomass	10 arc-sec (~300 m)	Tonnes of carbon/pixel	Raster
4	Soil organic carbon	HWSD soil organic carbon (up to 1m depth). (Hiederer and Kochy, 2012)	Tonnes of carbon/ha stored in the first meter of soil	30 arc-sec (~1km)	Tonnes of carbon/pixel in first meter of soil	Raster
6	Surface water	JRC (Pekel *et al.* 2016)	Area covered by surface water with an occurrence of >25%	30m	Presence or absence of water per pixel	Raster

Road effect sizes:

Little literature was available which demonstrates potential effect sizes for a range of ecosystem services, particularly at large spatial scales. Studies estimating road effect size generally focused on biodiversity or downstream hydrological modelling, which would require a lot of data and computing power at the global level. Furthermore, road effect size will likely vary based on the size of roads (e.g., single track or motorway development), topography and type of vegetation and disturbance (see Figure 20). Studies measuring the effects of roads typically measure them up to 1km from the road. However, the effect size is likely to vary by ecosystem service as well as the interaction between distance from the road and the impact on the ecosystem service. For example, deforestation may occur as a result of a road being built, in some areas fragmentation of the forest may extend beyond the direct impact as a result of increased access for logging. Similarly, road development which creates forests edges may increase desiccation from wind exposure and reduce forest biomass towards the forest edges (Chaplin-Kramer *et al.* 2015). However, this effect is often only quantified at local scales and varies by location. Therefore, it was not possible to include these effects in this analysis. These effects have not been studied at large global scales. Therefore, we investigated only the direct risks of infrastructure development on ecosystem services where spatial layers were available at a global scale.

Figure 20. Figure from Seiler (2003). Redrawn based on Forman *et al.* 1997.



We assessed ecosystem service loss over a range of buffer sizes. A conservative estimate was made assuming an infrastructure's direct impact on ecosystem services is approx. 100m. As analysis at the global scale was taking place at a 1km resolution, we multiplied cells which intersected with an infrastructure development by 0.9 to estimate the remaining ES. The potential loss of the ecosystem service is calculated as the difference between the original layer and the layer of remaining ecosystem service.

The effects of infrastructure development on ecosystem service provisioning were likely to occur over large distances. However, these effects were likely to be downstream and modelling would be required to understand these impacts.

Direct impact of infrastructure development on carbon storage

Carbon storage analysis was split into vegetation biomass (above and belowground; Soto-Navarro *et al.* 2020) and soil organic carbon (up to 1m depth; Wieder *et al.* 2014). Per pixel carbon storage was estimated by rescaling layers to 1km where required.

The vegetation biomass carbon density layer was rescaled to 1km. The original layer was at a 300m resolution with units in tC/ha, when rescaling to 100m the mean value of the cells was calculated and then multiplied to convert values from tC/ha to tC per pixel (km2).

The soil organic carbon (SOC) layer was already at a 1km resolution and therefore did not require rescaling before use. However, two separate layers were available, SOC 0-30cm depth and SOC 30-100cm depth with units in tC/ha.

Direct risks of infrastructure development on carbon sequestration

Alongside the loss of carbon already stored in vegetation biomass, infrastructure development may reduce ongoing carbon sequestration into vegetation biomass. Forests represent a large sink of atmospheric carbon, sequestering 7.6 ± 49 GtCO2e yr−1 annually (Harris *et al.* 2021). We estimated the potential loss of this service by calculating the total CO2 sequestered annually in each pixel and estimating the losses where these intersected with new infrastructure.

We rescaled data from Harris *et al.* (2021) on gross forest removals between 2001 and 2020 (tCO2e/ha) from 30m to approximately 1km spatial resolution and converted to per pixel. We then divided these values by 20 to produce an annual estimate of carbon sequestration within each cell.

Direct risks of infrastructure development on nitrogen retention for water quality

We used data from Chaplin-Kramer *et al.* (2019) to calculate the total modified nitrogen load retained by vegetation per pixel at an approximately 1km spatial resolution. This represents the loss of potential nitrogen retention from pixels where they intersect with infrastructure development. However, this does not include the impact of reduced nitrogen retention on downstream water quality. This would require further modelling which would not be possible at this scale.

First, we multiplied the modified nitrogen load per pixel layer (maximum potential mitigation benefit, layer available under 'nutrient_potential_10s_scenario' for current [2015] scenario) with the layer of proportion nature contributes to retaining nitrogen in vegetation. This layer was rescaled from an approximately 300m spatial resolution to 1km. The null values were replaced by 0. Following this, we multiplied the layer was by 100 to convert units to kg/cell. Finally, we divided the layer by 1000 to produce an estimate of total modified nitrogen load retained in tonnes/cell.

Risks to on crop pollination

Infrastructure develop may remove habitat for crop pollinators and available agricultural land.

We used data from Chaplin-Kramer *et al.* (2019) to calculate the potential pollination-dependent nutrient production per pixel at an approximately 1km spatial resolution. First, we multiplied the potential pollination-dependent nutrient production per pixel layer (maximum potential benefit for crop pollination) with the proportion nature currently contributes to this service. This layer was rescaled from an approximately 300m spatial resolution to 1km. The null values were replaced by 0 to produce a final layer of micronutrient production (KJ for energy, IU for Vitamin A, mcg for Folate, normalised and averaged across the three nutrients) per cell.

Calculating ecosystem service loss from direct impact of road development

For each layer we assumed that ecosystem services were to be lost in cells which intersected with an infrastructure project polyline. We multiplied these cells by a value of 0.9, assuming that infrastructure projects will have a 100m direct effect zone. The total value of the ES before and after the road development were compared total ES loss.

The limitations of this approach include that an equal distribution of each ecosystem service exists across the cell, which at a 1km resolution may not be the case. Furthermore, the direct effect zone of infrastructure development will likely vary depending on the type of infrastructure being built. For example, a wide highway development will likely have a larger effect size than a smaller road.

Risk from infrastructure development on surface water

An analysis by Vilela *et al.* (2020) used data from Pekel *et al.* (2016) to highlight where roads intersect with surface water and could therefore pose a risk for flooding, decreased water quality and increased infrastructure costs. We took a similar approach in this analysis by identifying cells which have a surface water occurrence of at least 25% since the 1980s. These were then rescaled from an approximately 30m spatial resolution to 1km for the analysis. Rescaling the data to a 1km resolution likely results in loss of some detail in the dataset, and cells with surface water present may be relatively rare. Therefore, the risk posed by some infrastructure projects to surface water may be underestimated in some areas.

This ecosystem service cannot be summarised and valued specifically (due to the binary dataset) but could be useful in demonstrating where infrastructure projects could have negative impacts on surface water storage and pose threats to local communities. Therefore, we only assessed the potential direct impact of infrastructure development on surface water at the 1km scale, by summing the number of cells containing surface water intersected by infrastructure.

Indirect risks of infrastructure development on forest carbon storage

Alongside direct impacts, infrastructure development can also introduce forest edge effects. Chaplin-Kramer *et al.* (2015) demonstrated that changes to forest aboveground biomass carbon could be seen up to 1.5km from the forest edge in tropical forests, due to increased exposure to wind, desiccation etc. They estimated that within the first 500 m of the forest edge the aboveground biomass is on average 25% lower than in forest interiors. They also suggest reductions of 10% extending up to 1.5 km from the forest edge.

Forest aboveground biomass estimated for the year 2018 (Santoro and Cartus 2021) was aggregated from 100m to 1km spatial resolution and multiplied by 0.47 to estimate biomass carbon content. Analysis at a scale fine enough to apply a distance decay function. Furthermore, the size and scale of the database mean that it was not possible to establish whether a forest edge is already present where the infrastructure is being developed. Cells intersecting with the new road were expected to have a decrease in AGB carbon of 25%, with neighbouring cells decreasing by 10%. Due to the coarse spatial resolution of the analysis this approach may oversimplify the effects seen. Analysis at a higher spatial resolution would require the use of a distance decay function to estimate loss which would be difficult to produce at a global level. Furthermore, this relationship has only been shown for tropical forests and varies depending on location within the tropics. This analysis would be applied globally, assuming that this effect will be seen in forests globally where infrastructure development intersects them. However, this is likely to vary depending on the type of forest and the density of forest structures. Therefore, indirect loss of forest biomass carbon may be overestimated.

Studies have also demonstrated that road development may also lead to increased deforestation in highly forested areas. However, this effect could vary significantly by location and would require simulating future land change based on modelling of historic deforestation trends whilst taking biophysical and socio-economic variables into account (Vilela *et al.* 2020). Due to the size and global extent of the dataset this was out of scope for the analysis. Therefore, the indirect effects of infrastructure development on deforestation and forest carbon storage are not estimated. Instead, the direct impact of infrastructure on forest aboveground biomass carbon storage is assessed using a 50m buffer (100m in total).

Socio-economic benefits – methodology

The economic benefits associated with transport infrastructure construction accrue in both direct and indirect ways. These are summarised below.

- Direct economic benefits that accrue to the firms (and individuals employed) involved in the construction of the roads. However, these benefits are also reflective of project costs, which are typically from public funds.
- Direct economic benefits that accrue to users of the road or rail link. These essentially comprise savings in travel costs and travel time. These are often the focus of individual transport project appraisals, where the economic rationale for public investment is demonstrated when these benefits sufficiently exceed project costs.
- Wider Economic Benefits (WEBs) that accrue beyond the users of the transport infrastructure project (i.e., indirect benefits). These benefits can arise for example, because of the restructuring of the economy as agglomeration effects emerge from linking different areas and stimulating trade, employment and communication and as direct economic benefits are generated from complementary investments elsewhere in the economy. A competent transport system also enables/encourages tourism and foreign investment.

Countries, often with the help of the international community, invest in transport infrastructure to boost economic growth and social welfare. The increasing number of transport corridor initiatives is often justified based on their potential (but uncertain) WEBs. The empirical evidence for demonstrating investment in infrastructure has this significant, positive effect on production and economy is, often, grounded in demonstrating a positive elasticity of GDP to transport infrastructure investment. In short, what is the change in economic output per year given what would be expected relative to a change in the 'stock' of transport infrastructure in the country. These positive outcomes of effective transportation system are proposed to be more pertinent to developing countries.

This focus on WEBs in the benefits analysis is justified as public infrastructure investments are intended to establish a development pathway that delivers public economic benefits that deliver improved social welfare outcomes. Hence, focusing on direct, private benefits is not considered appropriate as the fundamental trade-off considered is across two public goods. Namely, environmental resources against an increased national economy.

The approach proposed is also pragmatic, in that it will allow transport infrastructure investments to be set in a broad economic context to give an approximation of the opportunity costs associated with not implementing transport corridor projects with high environmental costs. This approach is also considered appropriate to the aims of the study.

Methodology to quantify WEBs

As indicated above the aim of quantifying the wider economic benefits of transport infrastructure is to provide context to the more rigorous examination of the ecological risks. This will help to understand why countries are interested in transport infrastructure from an economic perspective, but also appreciate the scale of the trade-off that is incurred to achieve this, which is less often measured and less well understood.

A review of the WEBs literature revealed several assessments that looked at the output elasticity of investments in transport infrastructure (the percentage change in GDP derived from a percentage change in the stock of infrastructure), most were country specific, but one particularly valuable paper provided a meta-analysis of studies (Melo *et al.* 2013).

We found this was particularly useful as it provided average elasticity estimates for different regions (US, Europe, Other) and mode of transport (road, rail, air, port/ferry). The average elasticity across all studies was 0.06 – implying that a 1% increase in the infrastructure stock would lead to a 0.06% increase in the country's GDP. Melo *et al.* (2013) also examined the studies statistically but focussed on the impact that the method of the studies they examined had on the results rather geography or the mode of transport invested in, so the results of this analysis were less readily applicable to our problem.

To use the elasticities summarised in the paper, relatively few inputs were needed:

- GDP at a country level
- The current stock of road and rail infrastructure
- Planned changes on the stock of road and rail infrastructure

The latter of the three is an output of this study. GDP data are readily available. In this instance the data series in table 4.2 of the World Bank's World Development Indicators was used (The World Bank 2022), using GDP estimates for the most recent year available – 2019. The current stock of road and rail infrastructure (measured in terms of length, km) is collated in the CIA World Factbook (CIA 2021a; CIA 2021b)).

Selecting the elasticity to use from those analysed by Melo *et al.* (2013) was more complicated as the paper provided average elasticities for either of the variables of interest (geographical location or mode of transport) but not the combination, i.e., results were not presented for the average elasticity of investments in roads in Europe, just for roads OR Europe. As such, to allow a differentiation between both variables, we calculated the deviation of the road and rail elasticities from the overall mean across all transport modes and then applied to the average elasticity for each of the different regions. The results of this are presented in Table 5.

***Table 5.* GDP Elasticities for Road and Rail Infrastructure Development.**

Variable	Average Elasticities from papers review	Magnitide of Road / Rail elasticities relative to average across all papers	Place based elasticity adjusted for Road / Rail differentiation	
			Road	Rail
Europe	*0.039*		**0.0572**	**0.02405**
USA	*0.069*		**0.1012**	**0.04255**
Rest of World	*0.083*		**0.121733333**	**0.051183333**
Road	*0.088*	1.466666667		
Rail	*0.037*	0.616666667		
Total	***0.06***			

We could then apply the elasticities in the right hand two columns directly to give percentages changes in GDP as a result of the percentage increase in stock of transport infrastructure at a country level where new roads and railways were planned.

It is notable that the elasticities found for road and rail in the meta-analysis (and therefore those proposed for use in this assessment) are quite different. Although it might first appear that a lower expected impact on GDP might be anticipated as a result of a change in rail infrastructure, it should also be noted that the stock of rail infrastructure is significantly lower (there are more than 28km of road for every kilometre of rail globally, based on the CIA World Factbook data). This means that a 100km increase in rail infrastructure will translate to a higher percentage change in the rail stock, and thus even with the lower elasticity, the impact of new rail versus new road is larger on a per kilometre basis which may not be immediately apparent from the elasticities.

An additional complication arises where improvements to the current stock of infrastructure are planned. Here the stock in terms of length remains unchanged, but the quality improves. It is reasonable to assume (based on the review of literature) that fewer overall benefits accrue to the investment in infrastructure quality as compared to those which might arise from an entirely new connection.

To get to an order of magnitude benefit of improvement, based on the elasticities and data available, a pragmatic approach seemed to attribute a proportion of the benefits that would be accrued to a new road or railway to the improvement.

It also seems reasonable to expect that this proportion may be higher where the starting condition of roads and railways are lower. As part of its Global Competitiveness Index the World Economic Forum provides data on the quality of the road and rail network on a country-by-country basis. As such, the most recent accessible data for road and rail quality were used (2019) (The Global Economy 2021a; The Global Economy 2021b). The data attributes scores from 1 to 7 to road and rail infrastructure at a country level. To estimate the proportion of the benefit of a new road or railway that could be attributed to infrastructure stock improvements, we used the change from the current country average condition up to the world leading score. Whilst imperfect, this at least allows greater benefits from quality improvements to be estimated where the starting conditions are worse.

The benefits of road and rail improvements were therefore calculated in the same way as the benefits of new infrastructure, but with only a proportion of the benefits used, which varied with the starting condition of infrastructure based on a country average.

Having completed an initial run of this analysis, it became apparent that the application of the relationship summarised in the elasticities lead to some potentially spurious results where the stock of a particular infrastructure type was very low or non-existent (as it is for rail infrastructure in some countries and regions of the world). This meant that percentage changes in rail stock were very high (or infinite where no rail previously existed) and the elasticity formula implied as a result percentage changes in GDP would be significant even if the absolute change in the stock in terms of additional kilometres was not large on a global scale.

To reduce the impact of this effect, for those countries outside Western Europe, North America and Australasia, the elasticity formula was applied to changes in the stock of infrastructure and GDP aggregated across income groups (as classified by the World Bank). The GDP benefits were then attributed back to the country level based on the absolute changes in the stock of infrastructure.

Results

Based on the method above, the best estimate result on the economic benefits of the planned change in road and rail infrastructure are presented in the Table 6 below. The total benefits ($418bn) equate to a 0.53% increase in global GDP.

Table 6. ***New and upgraded infrastructure benefits by country group for road and rail***

Country Group	New Infrastructure benefits (GDP increase $bn)		Upgraded Infrastructure benefits (GDP increase $bn)		Total
	Road	Rail	Road	Rail	
Europe	1.03	24.38	1.82	19.87	47.09
USA, Canada, New Zealand, Australia	0.28	15.22	0.22	1.42	17.14
Rest of the World - Lower Income	0.60	2.84	0.10	0.84	4.37
Rest of the World - Lower Middle Income	4.02	27.29	1.80	22.65	55.76
Rest of the World - Upper Middle Income	3.60	52.61	12.11	143.85	212.16
Rest of the World - Higher Income	1.08	72.11	0.41	7.72	81.31
Total	**10.61**	**194.44**	**16.45**	**196.33**	**417.83**

This is based on a best estimate of the split between new and upgraded infrastructure, however there is some uncertainty around the elements of planned infrastructure which will completely new routes. As such, an alternative more conservative estimate was calculated to provide a lower bound estimate of the benefits. This assumed all infrastructure effectively represented upgrades. This gave a total increase in GDP of $302bn or 0.39% of global GDP.

Approach to quantify jobs from transport infrastructure based on GDP

The approach to estimate the changes in employment in a country associated with derived GDP increases from transport infrastructure development was based on using the elasticity of employment to GDP for non-OECD countries estimated by Anderson & Braunstein (2013). The estimates by Anderson & Braunstein (2013) are relevant to the working age population of countries. This is 0.155 (based on average of female and male elasticities), implying that a 1% increase in GDP leads to a 0.155% increase in employment in the working age population.

The results of applying this elasticity to the relative changes in GDP estimated for the 82 low–low to middle income countries is presented in Table 6. Table 7 suggests that investments in rail infrastructure will yield substantially more jobs than roads. However, it is stressed this implies that investments in rail yield substantially more GDP than road on a per km basis. Although, it should also be noted that the costs of investing in rail are also substantially higher than in roads. de Soyres *et al.* (2020) suggest over USD 10 million per Km for new railway and Vilela *et al.* (2020) over USD 1million per km for road. These order of magnitude differences are reflected by the results in Table 7.

Table 7. ***Impact of increased GDP on Jobs from planned transport infrastructure.***

	Change in Jobs due to new road	Change in Jobs due to new rail	Change in Jobs due to upgraded road	Change in Jobs due to upgraded rail	Overall changes
Total new / upgrade Kms	50,092	15,723	38,722	20,678	125,216
Total jobs (No.)	330,650	2,603,811	70,252	3,480,109	6,484,822
Jobs / km	6.60	165.60	1.81	168.30	51.79

Following the evidence from Gálvez Nogales (2014), the approach to quantify jobs from transport infrastructure based on GDP focuses solely on the low and low to middle income countries (as per the World Bank Income levels). To achieve this, we implemented the following steps:

1. We estimated the aggregate GDP change in absolute terms across all low and low to middle income countries using the results of the GDP analysis
2. This was then divided by the additional planned transport infrastructure in total km across all low and low to middle income countries to get absolute GDP change per km of infrastructure for the different country income levels (see Table 8).
3. We then used the general coefficients in Table 8 to estimate absolute GDP changes for different countries based on the different planned infrastructure for road and rail in km. The reason to use coefficients estimated by income level, rather than individual countries, was to mitigate the very large GDP responses where rail infrastructure was planned, and a very low stock of rail infrastructure existed in a country (Ethiopia, Lao and Afghanistan being prime examples)
4. From the absolute changes the relative change was then calculated (i.e., % change GDP) for each different type of planned infrastructure.
5. We then applied the elasticity between jobs and GDP proposed Anderson & Braunstein (2013) of 0.155 to estimate the job response in each country from the planned infrastructure for each country. The percentage change was applied to the working age populations for each country obtained from the CIA World Fact Book.

Table 8. ***Change in GDP per km of additional infrastructure.***

Value of GDP Increase $Bn / km				
	Rail		Road	
	New	Upgrade	New	Upgrade
Low income	0.000817	0.000385	0.000047	0.000018
Lower middle Income	0.002197	0.001034	0.00011	0.000042

Based on the analysis, the total GDP change for the planned infrastructure across all the low and low to middle income countries was +USD 59.14 billion. Based on a total GDP of USD 8,289.1 Billion (2020), this implies an overall change in GDP across these.

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