GREGOIRE DUBOIS

ANNEX 1: SPATIAL ANALYSES OF LINEAR INFRASTRUCTURE THREATS TO BIODIVERSITY IN ASIA

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ACRONYMS

ADB	Asian Development Bank
ADCI	Altyn Dala Conservation Initiative
ASEAN	Association of Southeast Asian Nations
BRI	Belt and Road Initiative
CAREC	Central Asia Subregional Economic Cooperation Program
CBI	Composite biodiversity index
CEPF	Critical Ecosystem Partnership Fund
CLLC	Center for Large Landscape Conservation
DNPWC	Department of National Parks and Wildlife Conservation
GMS	Greater Mekong Subregion
GPS	Global positioning system
HoB	Heart of Borneo Initiative
IBA	Important Bird and Biodiversity Area
IFC	International Finance Corporation
IFCPS	International Finance Corporation Performance Standard
IIC	Integral Index of Connectivity
IUCN	International Union for the Conservation of Nature
KBA	Key Biodiversity Area
KDE	Kernel density estimate
LI	Linear infrastructure
NGO	Nongovernmental organization
NHAI	National Highway Authority of India
NH-37	Indian National Highway 37
N-S	North-South

PA	Protected area
PEZ	Potential effect zone
ROaDS	Roadkill Observation and Data System
SASEC	South Asia Subregional Economic Cooperation Program
TAL	Terai Arc Landscape
TSH	Trans-Sumatran Highway
USAID	United States Agency for International Development
WCS	Wildlife Conservation Society
WTI	Western Transportation Institute
WWF	World Wide Fund for Nature (formerly World Wildlife Fund)

INTRODUCTION

The impacts of linear infrastructure (LI) development on biodiversity are inherently spatial. Without knowing the locations of LI routes and the biologically important features they influence (such as protected areas, critical habitat patches, and wildlife corridors), our understanding of LI impacts will remain limited. Spatial analyses allow us to characterize the magnitude and type of impacts, identify the locations where impacts are (or will be) most severe, and prioritize efforts objectively to avoid or mitigate impacts.

Many spatial analyses have been conducted in recent years to document the observed impacts of existing roads, rails, and power lines on biodiversity in Asia; we have reviewed these retrospective studies in Annex 4 of this report. However, there is an urgent need for prospective studies that use spatial analyses to forecast the impacts to biodiversity of proposed LI early in the planning stage and before it has been constructed. Prospective spatial analyses of potential LI impacts are relatively rare in the literature. However, they are especially valuable because they provide guidance on how and where to prevent or minimize biodiversity loss from LI before it occurs, which is much easier than trying to reverse biodiversity loss following LI development.

This annex examines how spatial analyses can be used to assess potential threats to biodiversity from proposed LI development for a variety of spatial scales, geographies, LI modes, and taxa of interest. It combines original analyses conducted specifically for this report for the United States Agency for International Development with reviews of exemplary analyses conducted earlier by other researchers. We present examples that illustrate the diversity of spatial analysis approaches and their strengths and limitations. The annex is divided into three parts.

In Part I, we describe an original spatial analysis of threats to biodiversity across Asia from major LI development projects. Several recent prospective spatial analyses have explored potential impacts of LI development on biodiversity at a very coarse scale, covering all or most of Asia and considering only high-profile road and railway projects associated with China's Belt and Road Initiative (Hughes, 2019; Ng et al., 2020). Our analysis expands on this earlier work by considering a larger set of LI projects, including power line projects and projects associated with international economic development initiatives other than BRI. It also develops a single metric for quantifying biodiversity value across Asia and maps areas of exceptional biodiversity where LI development should be avoided altogether.

Coarse-scale analyses, including our own and those conducted previously, do not capture the potential impacts of LI projects planned and funded at the national and subnational levels. In addition, they rely on biodiversity data with continental or global coverage that are necessarily of coarse spatial resolution. While they are useful for broadly characterizing threats from LI development to Asian biodiversity, these coarse-scale analyses lack the detail needed to accurately describe threats to biodiversity within individual landscapes or for individual species; these require finer-scale spatial analyses. Thus, Part II of this annex describes six original, fine-scale, rapid assessments of the potential impacts of LI on species of conservation concern in selected landscapes within Asia. These assessments were conducted in collaboration with local partners who are active in wildlife conservation efforts in these landscapes and possess detailed knowledge of species biology and LI development plans. The assessments provide examples of how relatively simple spatial analyses can characterize threats to biodiversity from LI and suggest strategies for minimizing harm.

The fine-scale spatial analyses we conducted were limited in number, detail, and scientific rigor by the short timeline of this project. To provide a more complete picture of the variety and sophistication of prospective, fine-scale spatial analyses of LI development impacts in Asia, Part III of this annex summarizes a selection of recently published studies from scientific journals and the gray literature. Each study explores the potential impacts of proposed road, railway, or power line projects within a single country or a smaller landscape within a country. We describe each study and synthesize information across studies to describe the state of the science and the potential for advances.

We conclude this annex with a distillation of our key findings from across all three of its parts, and a set of recommendations based on these key findings that could lead to better and more influential spatial analyses of LI threats to biodiversity.

PART I: A COARSE-SCALE SPATIAL ANALYSIS OF LINEAR INFRASTRUCTURE THREATS TO BIODIVERSITY IN ASIA

Asia is home to some of the world's most diverse and complex ecosystems, which provide natural capital, underpin economic vitality, and increase resilience to environmental change. However, much of Asia's rich natural heritage is threatened by the rapid expansion of linear infrastructure (LI), including roads, railways, and power lines. Without proper safeguards, ongoing and anticipated expansion of LI will further fragment habitat, increase wildlife mortality, and threaten biodiversity.

The United States Agency for International Development (USAID) seeks to understand the challenges and barriers that slow the adoption and implementation of LI safeguards, and to enumerate and review ongoing and proposed infrastructure projects in Asia that will have the greatest impact to biodiversity and critical habitats. This requires an understanding of the spatial intersection of areas of high biodiversity value and sites of existing, ongoing, and future LI development.

This report describes an assessment of the threats to biodiversity in Asia from proposed LI using data sets with relatively coarse spatial resolution and broad spatial extent. The assessment consists of three components: (1) quantifying and mapping biodiversity value across Asia, (2) compiling spatial data on routes of proposed LI projects, and (3) determining where proposed LI is most likely to harm biodiversity. This coarse-scale assessment is intended to serve several purposes: provide a consistent baseline map of biodiversity value covering all of Asia; delineate "avoidance areas" with exceptional biodiversity value where future LI development could lead to unacceptable harm to species and habitats and should be permitted only as a last resort; compile a comprehensive spatial database of proposed LI projects for use in future evaluations of LI impacts; estimate the magnitude and geographic distribution of LI threats to biodiversity; and guide the selection of smaller priority regions of Asia with high biodiversity, within which USAID may desire to conduct finer-scale analyses using more local information on biodiversity and LI projects.

METHODS

PRIORITIZING BIODIVERSITY CONSERVATION

Biodiversity—the variation among living organisms—may be measured in a variety of ways, including at different levels of biological organization (e.g., genes, species, ecosystems) and for different taxonomic groups (e.g., birds, mammals, invertebrates). The number of species present at a location, known as species richness, is one of the simplest and most common ways of measuring biodiversity. More nuanced approaches may also account for additional characteristics that affect a location's relative value for biodiversity conservation, such as the presence of species restricted to a single geographic area (endemism); the abundance of individuals; the occurrence of species threatened with extinction; the degree to which the landscape has been modified by human activities (ecological condition); the fraction of originally present species remaining (intactness); and the occurrence of biomes or habitat types found in relatively few locations worldwide (rarity).

Our approach to mapping biodiversity conservation priorities is to overlay information from a diverse set of sources that represent different elements of biodiversity, taxa, and levels of organization, and to identify areas of consensus among these sources. We focus on geographic areas where many data sources suggest that biodiversity conservation value is high, which increases our confidence that these areas represent meaningful conservation priorities that are not driven by the idiosyncrasies of any particular data source.

We rely primarily on data sets that characterize irreplaceability, which refers to how important a site is for achieving conservation objectives because it cannot be easily substituted by other sites (e.g., because of high endemism, threatened species, or rarity). Some biodiversity conservation prioritizations also incorporate information on vulnerability, which refers to the risk of a site being transformed by damage to biodiversity features from threatening processes (Kukkala & Moilanen, 2013). Although vulnerability is an important consideration when prioritizing conservation, we generally exclude vulnerability information from our analysis of biodiversity because our intent is to identify areas that retain high levels of biodiversity (i.e., avoidance areas). We consider vulnerability, specifically as it relates to LI development, in another component of this assessment—the analysis of overlap between areas of high biodiversity and routes of proposed LI.

BIODIVERSITY INPUT LAYERS

We acquired spatial data for 14 biodiversity input layers (Figure 1, Table 1). These layers were recently developed (or updated) indices that represented one or more biodiversity elements as continuous (raster format) data consisting of grids of cells covering the entire study area. Biodiversity elements represented in the layers included species richness, endemism, population abundance, biodiversity intactness, ecological condition, rarity, and complementarity. Most layers focused on biodiversity of terrestrial wildlife, including the condition of their habitats, because impacts of LI on wildlife are the focus of the broader USAID report.

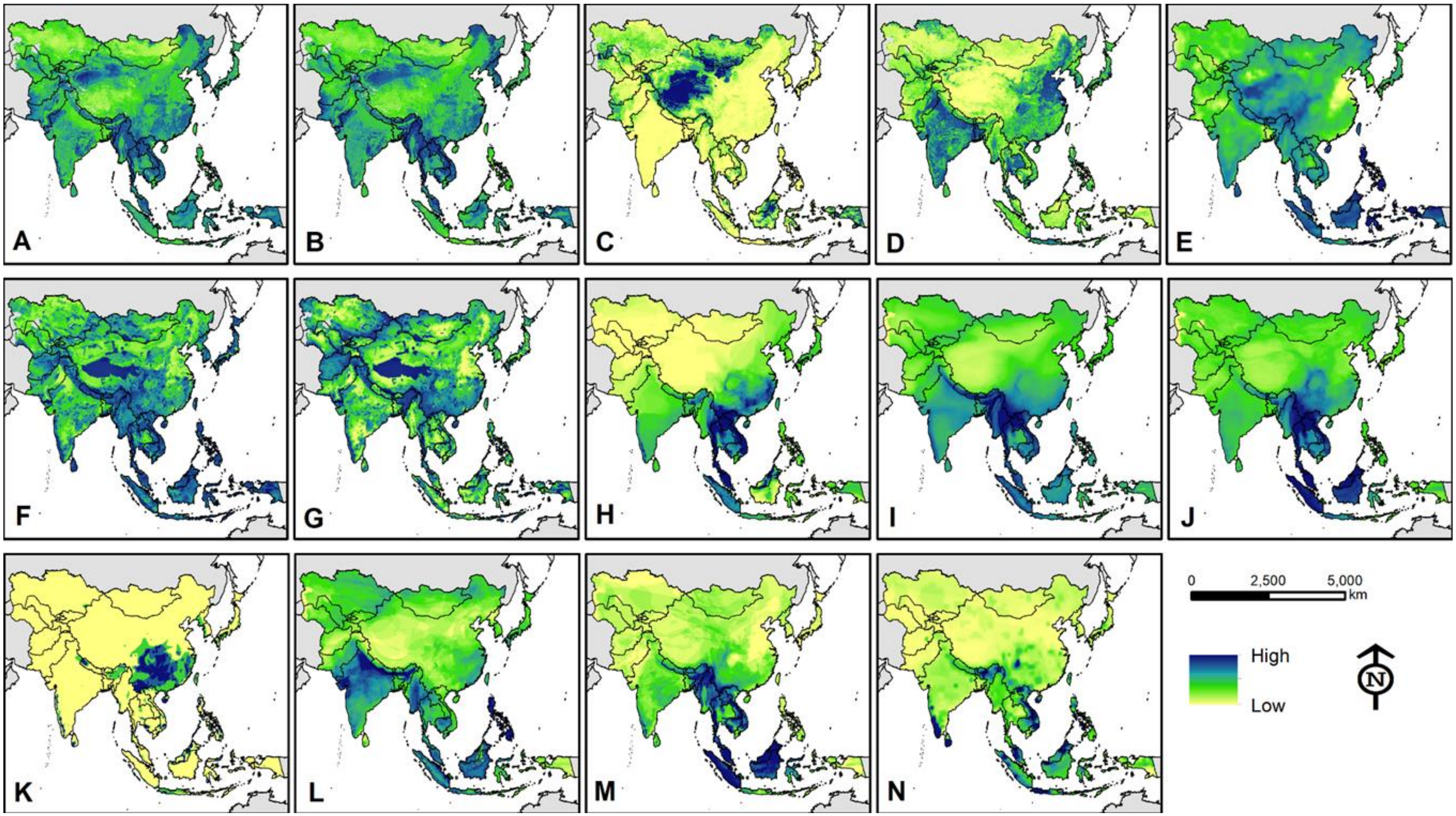

Figure 1: Biodiversity layers considered in analysis. (A) Abundance-based biodiversity intactness. (B) Richness-based biodiversity intactness. (C) Ecoregion intactness. (D) Human modification. (E) Mammal community intactness. (F) Global priority areas for protected area expansion. (G) National priority areas for protected area expansion. (H) Amphibian species richness. (I) Bird species richness. (J) Mammal species richness. (K) Threatened amphibian species richness. (L) Threatened bird species richness. (M) Threatened mammal species richness. (N) Weighted endemism including global endangerment. Layers B, D, H, I, and J were eventually removed from analysis to reduce redundancy among layers.

Table 1: Description of biodiversity data sets

TABLE 1: DESCRIPTION OF DATA SETS CONSIDERED IN COARSE-SCALE BIODIVERSITY ANALYSIS

DATA SET	DESCRIPTION	YEAR OF RELEASE/ UPDATE	SPATIAL RESOLUTION	SOURCE/ PUBLICATION
Biodiversity intactness (abundance-based)	The average abundance of originally present species across a broad range of species, relative to abundance in undisturbed habitat	2019	1 km	Newbold et al. (2016); Sanchez-Ortiz et al. (2019)
Biodiversity intactness (richness-based)	The average richness of originally present species across a broad range of species, relative to richness in undisturbed habitat	2019	1 km	Newbold et al. (2016); Sanchez-Ortiz et al. (2019)
Ecoregion intactness	A measure of habitat intactness that accounts for the combined impact of habitat loss, fragmentation, and degradation arising from anthropogenic disturbance	2020	1 km	Beyer et al. (2020)
Global human modification	A cumulative measure of human modification of terrestrial lands that reflects the proportion of a landscape modified based on modeling the physical extents of 13 anthropogenic stressors and their estimated impacts	2019	1 km	Kennedy et al. (2019)
Mammal community intactness	The ratio of current to historic mammal species richness based on contemporary and reconstructed historical ranges	2020	96.5 km	Belote et al. (2020)
Global priority areas for protected area expansion	Spatial priorities for expanding the global protected areas network to maximize representation of terrestrial vertebrate species and ecoregions	2014	0.2 degrees (~20 km at equator)	Pouzols et al. (2014)
National priority areas for protected area expansion	Spatial priorities for expanding national protected areas networks to maximize representation of terrestrial vertebrate species and ecoregions	2014	0.2 degrees (~20 km at equator)	Pouzols et al. (2014)

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DATA SET	DESCRIPTION	YEAR OF RELEASE/ UPDATE	SPATIAL RESOLUTION	SOURCE/ PUBLICATION
Amphibian species richness	The number of amphibian species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Bird species richness	The number of bird species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Mammal species Richness	The number of mammal species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Threatened amphibian species richness	The number of threatened amphibian species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Threatened bird species richness	The number of threatened bird species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Threatened mammal species richness	The number of threatened mammal species occurring in 10-km grid cells according to IUCN species range maps	2017	10 km	Jenkins & Pimm (2013)
Weighted endemism including global endangerment	A biodiversity index based on the richness of terrestrial vertebrate species, their degree of endemism, and their extinction risk	2020	100 km	Farooq et al. (2020)

LAYER PROCESSING

We reprojected all spatial layers to have a common coordinate system (Albers Conic Equal Area), resolution (1 km^2), extent (28 Asian countries; Figure 1), and grid cell alignment. We then transformed the raw values in each layer to quantiles, such that values ranged from 0 to 1, with 0 representing the lowest biodiversity conservation value and 1 the highest. Quantile transformation allowed for valid comparisons among layers with vastly different value ranges and increased robustness to variations in individual data sets.

Some of the biodiversity layers were derived from similar underlying data (e.g., species range maps from the International Union of the Conservation of Nature [IUCN]) or used similar approaches to measure biodiversity, and thus could be redundant. Because our objective was to identify areas of consensus among independent sources of biodiversity information, we performed an initial filtering step to remove redundant layers and avoid "group think" when assessing overall biodiversity value. We calculated the cell-wise Pearson correlation coefficient for each pair of quantile-transformed layers, then removed one layer of each pair with $|r| > 0.7$ from all further analyses (Dormann et al., 2013). This filtering step resulted in the removal of five redundant biodiversity layers. Richness-based and abundance-based biodiversity intactness indices were highly correlated, so we removed the richness-based layer and retained the abundance-based layer because species richness information was incorporated in several other layers. Global human modification and ecoregion intactness were highly correlated, so we removed the global human modification layer and retained the ecoregion intactness layer because the latter incorporated additional information on habitat fragmentation. Amphibian, bird, and mammal species richness were highly correlated among themselves and with weighted endemism; we removed all three of these species richness layers, while retaining the richness layers based only on threatened species for these same taxa, because threatened species richness may be more relevant for setting biodiversity conservation priorities (Brooks et al., 2006).

COMPOSITE BIODIVERSITY INDEX

We created a composite biodiversity index (CBI) to reflect the average biodiversity value across all remaining layers for each grid cell included in the analysis. The CBI was calculated as the median of the quantile-transformed layer values for each grid cell. The output was a continuous map covering the full study area at 1-km^2 resolution, with CBI values close to 1 indicating strong consensus among layers that a particular location was a high priority for biodiversity conservation, and values close to 0 indicating strong consensus that a particular location was a low priority. Moderate CBI values could indicate consensus among layers that a location was a moderate priority, or a mix of layers indicating high and low priority; thus, to better understand the variation among layers, we also calculated summary measures for each grid cell: minimum, maximum, standard deviation, and number of layers with quantile >0.9 (i.e., top decile).

IDENTIFYING BIODIVERSITY CORES

To highlight potential avoidance areas and regions for fine-scale analysis, we converted our continuous map of CBI values to a categorical map that showed aggregations of high-CBI grid cells, which we refer to as "large biodiversity cores." We first removed some of the fine-scale variation in CBI values by applying a smoothing function that averaged CBI values within a Gaussian kernel with a standard deviation of 10 km. This step also filtered out high-value cells that may be less feasible conservation targets because they are isolated from larger aggregations of high-value cells. We quantile-transformed this smoothed CBI layer, and then categorized each grid cell as either high or low biodiversity value based on a quantile threshold calculated from the distribution of values across the entire study area. We used three different thresholds (90th, 80th, and 70th percentiles, representing the top 10, 20, and 30 percent of grid cells, respectively) for defining high value, which allows USAID flexibility in determining avoidance areas and reflects the wide variation in percentage-based conservation targets among existing international agreements and conservation initiatives. Finally, we identified patches of connected high-value cells ("cores") using the 8-neighbor adjacency rule, and filtered out cores smaller than 500 km^2, which corresponds roughly to the home range size of several large mammal species of conservation concern (e.g., tiger, snow leopard, Asian elephant). Although areas smaller than 500 km^2 may have high conservation value as habitat for species with smaller home ranges or as "stepping stones" for dispersing larger wildlife, our intent was to highlight large cores representing consensus locations of exceptional biodiversity conservation value that could potentially support all local wildlife species.

Many of our biodiversity layers were at least partially based on species richness, which exhibits a clear latitudinal gradient, with richness highest near the equator and lowest near the poles (Hillebrand, 2004). Consequently, areas of high biodiversity conservation value at the continental scale were likely to be heavily skewed toward the southernmost portions of Asia. However, USAID may also wish to consider biodiversity priorities elsewhere in Asia that are nationally or regionally important, even if they may have less conservation significance at a continental or global scale. We therefore conducted separate analyses of biodiversity cores at the national scale (i.e., within each of the 28 study area countries) and at the regional scale (i.e., within each of four Asian subregions defined by the United Nations geoscheme for Asia) with CBI quantile thresholds calculated within each country or region, respectively, instead of the entire continental study area.

To better understand the ecological characteristics of the core biodiversity areas identified in our analysis, we calculated the proportion of total area of cores within each of 13 terrestrial biomes (Olson et al., 2001) present in our study area. Calculations were performed for each combination of quantile threshold (70th, 80th, and 90th percentiles) and geographic scale (continental, regional, and national).

COMPARISON TO GLOBAL PRIORITIZATION SCHEMES

There have been many previous efforts to establish spatial priorities for biodiversity conservation at large scales (Brooks et al., 2006). We compared the large core biodiversity areas identified in our analysis to biodiversity priority areas identified by five well-known global conservation prioritization schemes (Figure 2, Table 2) to get a better sense of how well our Asia-specific priorities align with previous established global priorities. These global prioritization schemes included Critical Ecosystem Partnership Fund (CEPF) Biodiversity Hotspots (Myers et al., 2000); Global 200 Ecoregions (Olson & Dinerstein, 2002); International Finance Corporation Performance Standard 6 (IFCPS6) Critical Habitats (Brauneder et al., 2018); Intact Forest Landscapes (Potapov et al., 2017); and Key Biodiversity Areas ([KBAs], IUCN, 2016). Geospatial layers for global prioritization schemes were categorical (vector format) data containing polygons representing biodiversity features (e.g., hotspots, intact forest patches), which we converted to 1-km raster data to match the biodiversity layers used in our analysis. We quantified spatial overlap between biodiversity features from global prioritization schemes and continental-scale large biodiversity cores from our own analysis in two ways: (1) the proportion of total biodiversity feature area from each prioritization scheme that overlapped with cores, and (2) the proportion of total core area that overlapped with biodiversity features from each prioritization scheme. We calculated these proportions separately for the three quantile thresholds used to establish large biodiversity cores (70th, 80th, and 90th percentiles) and the three geographic scales (continental, regional, and national).

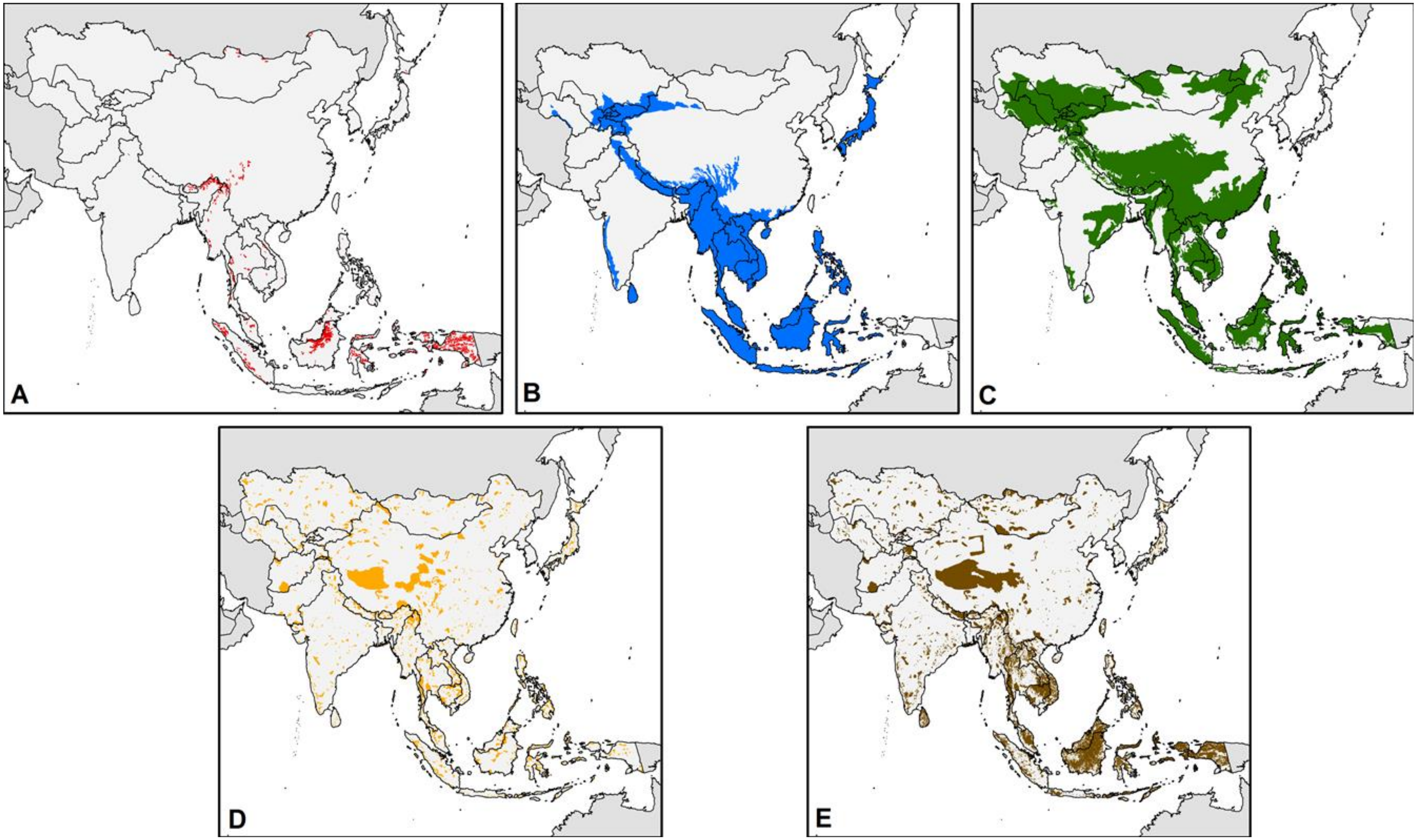

Figure 2: Existing global biodiversity conservation prioritization schemes. (A) Intact Forest Landscapes. (B) Critical Ecosystem Partnership Fund Biodiversity Hotspots. (C) Global 200 Ecoregions. (D) Key Biodiversity Areas. (E) International Finance Corporation Performance Standard 6 Critical Habitat.

Table 2: Description of existing global biodiversity prioritization schemes

TABLE 2: DESCRIPTION OF EXISTING GLOBAL BIODIVERSITY PRIORITIZATION SCHEMES			
DATA SET	DESCRIPTION	YEAR OF RELEASE/ UPDATE	SOURCE/ PUBLICATION
Critical Ecosystem Partnership Fund Biodiversity Hotspots	36 global hotspots based on endemic vascular plant species richness and original natural vegetation loss	2016	Myers et al. (2000)
Global 200 Ecoregions	Ecoregions with high irreplaceability or distinctiveness, as indicated by species richness, endemism, unusual higher taxa, unusual ecological or evolutionary phenomena, and global rarity of habitats	2002	Olson & Dinerstein (2002)
International Finance Corporation Performance Standard 6 Critical Habitat	Screening layer of critical habitat based on five criteria that address habitat of significant importance to threatened, endemic, congregatory and migratory species, threatened or unique ecosystems, and key evolutionary processes	2018	Brauneder et al. (2018)
Intact Forest Landscapes	Unbroken expanses of natural ecosystems within the zone of forest extent that show no signs of significant human activity and are large enough that all native biodiversity, including viable populations of wide-ranging species, could be maintained	2016	Potapov et al. (2017)
Key Biodiversity Areas	Sites that are globally important for conservation based on threatened biodiversity, geographically restricted biodiversity, ecological integrity, biological processes, or irreplaceability	2020	IUCN (2016)

MAPPING PROPOSED LI

We compiled a geospatial database of the routes of proposed roads, railways, and power lines associated with global and regional economic development initiatives in Asia (Table 3). These initiatives are associated with many of the largest proposed LI developments in Asia and are often funded by multilateral development banks. Although LI development associated with national, state, and local initiatives is also occurring throughout Asia, compiling information on these projects across the continent was not feasible for this study. Routes of some LI projects were available in geospatial data formats for several initiatives, but in most cases, we relied on maps found in reports and planning documents to determine the route locations, which we digitized using ArcGIS 10.8. Some LI routes were included in multiple initiatives, and we screened our database for these duplicates and retained the feature that was sourced from the more recent or more detailed map. We also filtered out any LI routes that source maps or databases indicated were already operational. Although we used the most recent information that we could find on the status of LI projects, we acknowledge that some of the projects included in our final data set may have been recently completed. The projects in our database included entirely new LI routes and improvements to existing routes (e.g., widening a road from two to four lanes).

Table 3: Linear infrastructure data sources

TABLE 3: LINEAR INFRASTRUCTURE DATA SOURCES			
INITIATIVE	LI MODE	REGION	DATA SOURCE
Belt and Road Initiative (BRI)	Road, railway	Asia-wide	Reed & Trubetskoy (2019)
Asian Development Bank (ADB) Regional Transport Infrastructure	Road, railway	South and Southeast	Morgan et al. (2015)
Asian Highway Network	Road	Asia-wide	UNESCAP (2019a)
Great Mekong Subregion Economic Cooperation Program (GMS)	Road, railway, power line	Southeast	ADB (2018c); GMS, (2018, 2020)
Association of Southeast Asian Nations (ASEAN) Infrastructure Projects Initial Pipeline	Road, railway, power line	Southeast	ASEAN (2019)
Central Asia Regional Economic Cooperation Program (CAREC)	Road, railway	Central	ADB (2017, 2020a)
South Asia Subregional Economic Cooperation Program (SASEC)	Road, railway, power line	South	(ADB, 2020b)
Trans-Asian Railway Network	Railway	Asia-wide	UNESCAP (2019b)
CASA-1000	Power line	Central	CASA-1000 (2018)
North-East Asian Super Grid/Gobitec	Power line	East	Mano et al. (2014)
ASEAN Power Grid	Power line	Southeast	IEA (2019)

ASSESSING POTENTIAL IMPACTS

We calculated the total length of proposed routes for each LI mode, and further distinguished between proposed new routes and proposed improvements to existing routes (e.g., paving or widening existing roads). We were unable to distinguish between new routes and improvements for a small number of proposed road projects. We ranked countries by the length of proposed LI and density of proposed LI within their borders for each mode.

We mapped potential areas of conflict between biodiversity and LI development by intersecting biodiversity cores with digitized LI routes. We buffered routes by 25 km on either side to account for uncertainty in the exact location of routes due to poor spatial precision of LI features digitized from coarse-scale source maps and possible changes in route design between initial planning and construction. This buffer encompasses the likely spatial extent of most LI impacts to wildlife, including direct effects (e.g., disturbance from noise, artificial light, or vehicle exhaust fumes; edge effects; mortality from vehicle collision or electrocution) that typically occur within 5 km of LI (Benítez-López et al., 2010) and secondary effects (e.g., hunting and poaching; habitat loss from illegal logging) that occur over greater distances from LI (Ng et al., 2020). We henceforth refer to these areas within 25 km of the estimated routes of proposed LI features as "potential effect zones," or PEZs. For each LI mode and each biodiversity core definition, we calculated the proportion of total core area in Asia within PEZs. We also ranked countries by their total area of cores intersecting PEZs and by the percentage of their core area intersecting PEZs.

We explored the overlap between PEZs and PAs in Asia. We focused specifically on PAs in IUCN categories 1a (strict nature reserve) and 1b (wilderness area) because these areas have minimal human impact and stringent protections for biodiversity, so impacts of proposed LI could compromise the biodiversity protection mandate in these areas. We calculated the number and total area of category 1a and 1b PAs within PEZs for each LI mode, as well the proportion of total PA area within PEZs and vice versa.

RESULTS

BIODIVERSITY MAPPING

The CBI (i.e., median quantile value across nine biodiversity layers) is highly variable across Asia, but the lowest values are primarily in Central and East Asia, while the highest values are primarily in South and Southeast Asia (Figure 3). This observation of increasing biodiversity nearer the equator is consistent with the well-documented latitudinal biodiversity gradient mentioned previously. Areas with especially high CBI values include the Malay Peninsula, Borneo, Sumatra, southwestern India, northeastern India, the Himalayan foothills, the northern Tibetan Plateau, and eastern Cambodia.

An examination of other summary measures derived from quantile-transformed biodiversity layers suggests that there is strong agreement among layers regarding areas of highest biodiversity value. Areas with high CBI (median quantile value) also tend to have the highest maximum and minimum values, and they score in the top decile for all or nearly all the biodiversity layers (Figure 4). There is lower agreement among biodiversity layers regarding moderate- and low-value areas. For instance, the standard deviation of quantile values (an indicator of agreement among layers) is particularly high in western China, a region that has low species richness but is ecologically intact, and in north central India, which is rich in species but has been ecologically degraded. Many other areas of Asia exhibit inconsistencies among values assessed for different elements of biodiversity, although to a lesser degree.

Continental-scale large biodiversity cores derived from the CBI align closely with the high-CBI regions described above and are again concentrated primarily in South Asia—especially Southeast Asia (Figure 5). At lower thresholds for high-value biodiversity areas (80th and 70th percentile of CBI values), cores expand to include nearly all of Southeast Asia, and additional cores occur in central India, southern China, and scattered areas of northern China and Mongolia (Figure 5). Cores identified at the regional scale include many of the same areas of South and Southeast Asia as identified in the continental-scale analysis, but with many additional cores in Central and East Asia (Figure 6). Regional cores in South Asia are primarily in far northeast and southwest India, the Terai Arc (including parts of India, Nepal, and Bhutan), and interior Sri Lanka. In Southeast Asia, regional cores are primarily in interior peninsular Malaysia, central Borneo, interior Sumatra, and northern Myanmar. Regional cores in Central Asia are located primarily in southern and eastern Kazakhstan. In East Asia, regional cores are located primarily in the northern Tibetan plateau and southern China near the border with Myanmar, Laos, and Vietnam. Cores identified at the national scale are very similar to the regional cores (Figure 7).

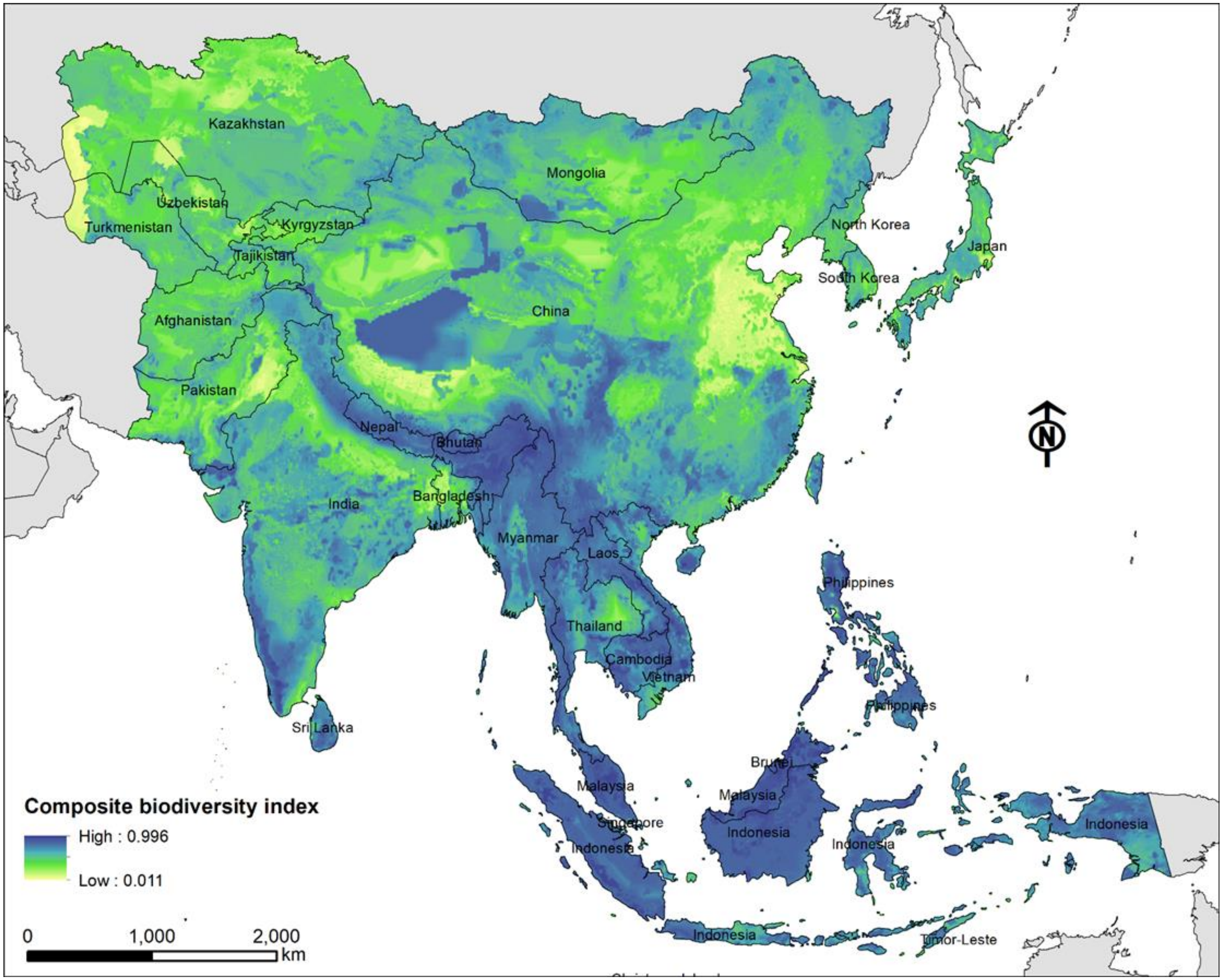

Figure 3: Composite biodiversity index (CBI) at 1-km resolution across Asian study area. CBI was calculated as the median of quantile-transformed values across all biodiversity input layers.

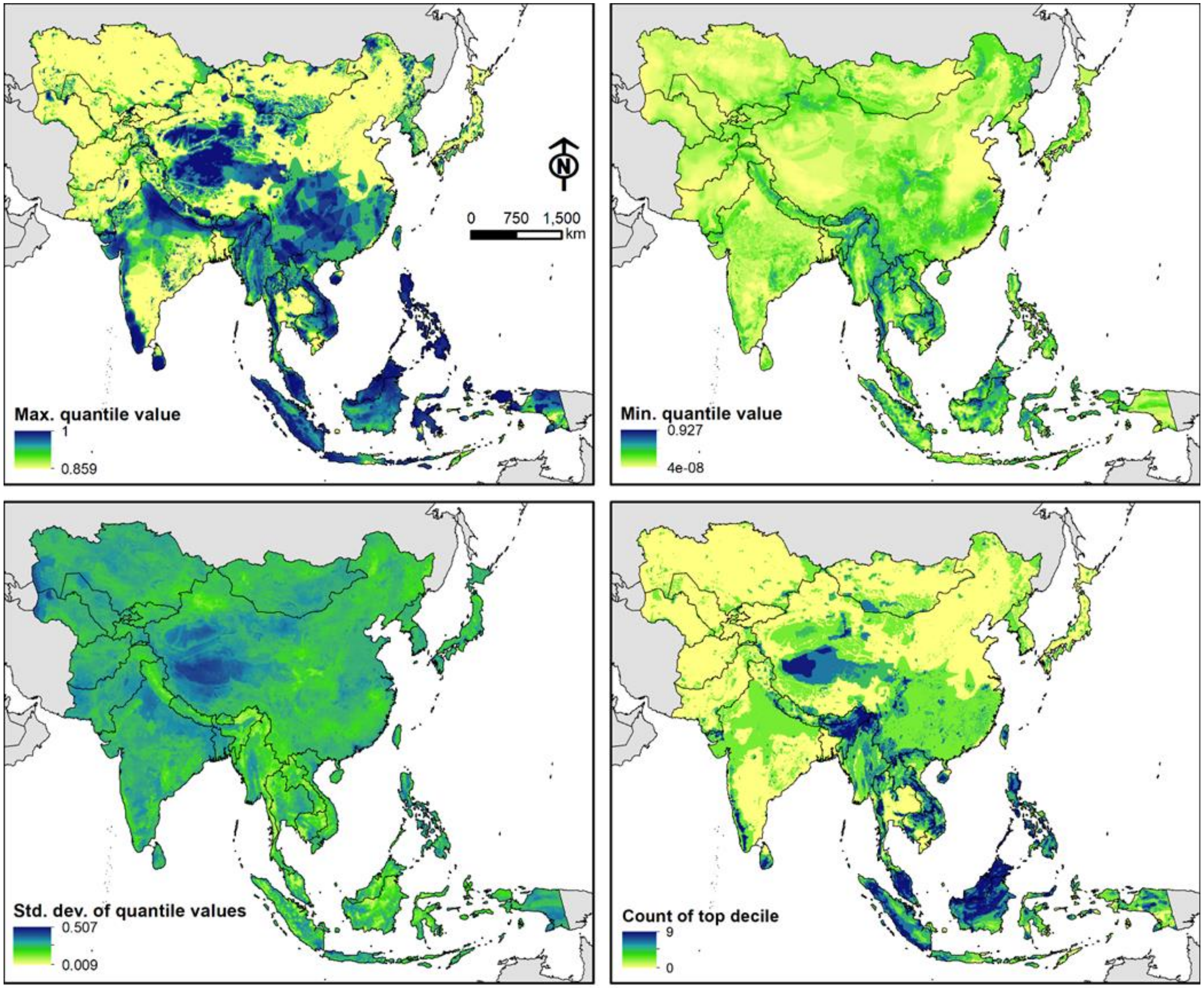

Figure 4: Variability in biodiversity value across input layers. Each panel shows a different summary statistic calculated from the set of nine quantile-transformed values (one per biodiversity layer) for each grid cell: maximum quantile (top left), minimum quantile (top right), standard deviation of quantiles (bottom left), and count of layers with quantile >0.9 (bottom right).

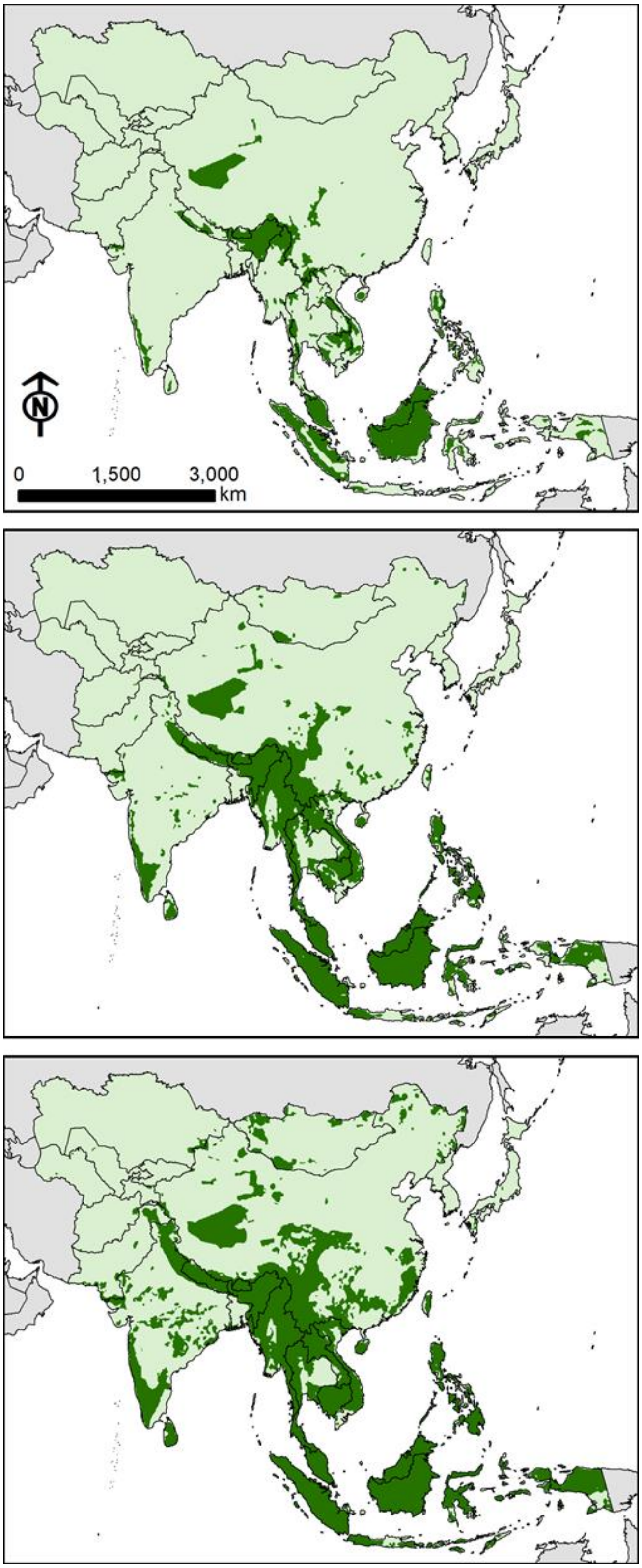

Figure 5: Continental-scale large biodiversity cores (dark green patches), assuming a quantile threshold of 0.9 (top panel), 0.8 (middle panel), or 0.7 (bottom panel) for defining high biodiversity value.

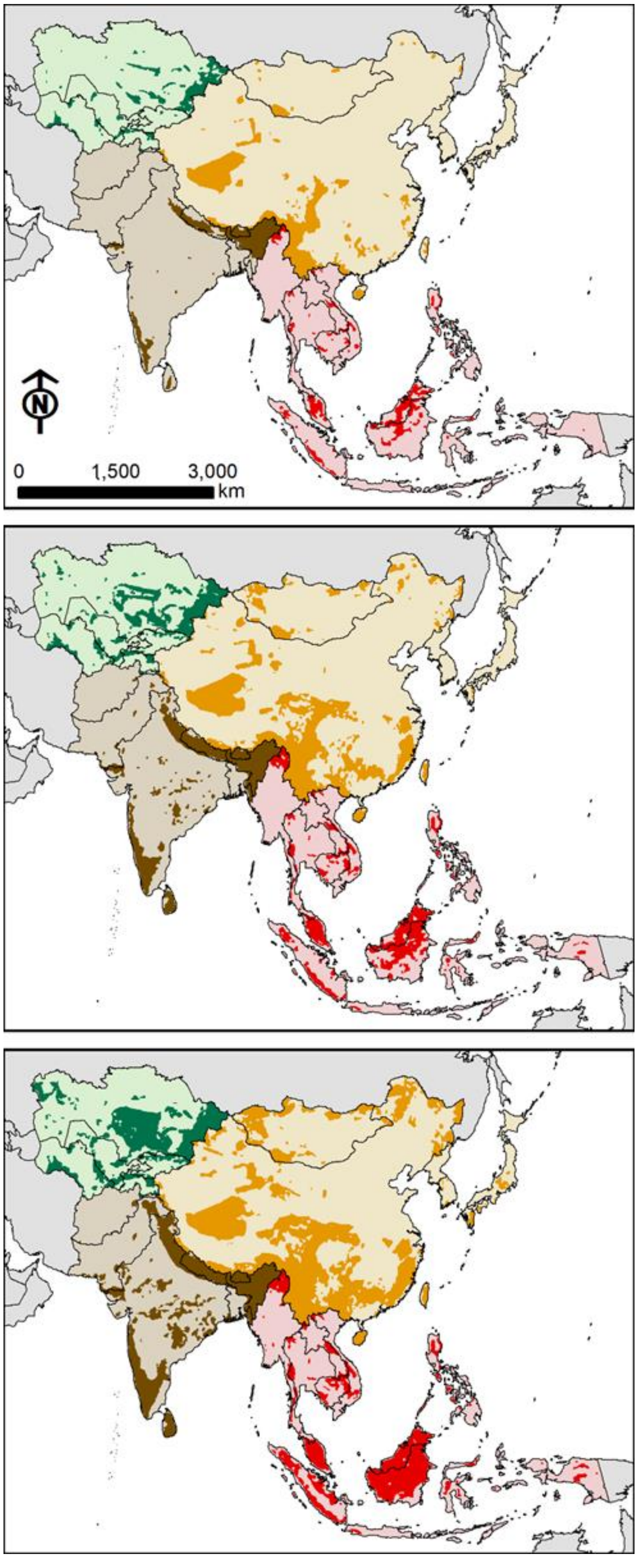

Figure 6: Regional-scale large biodiversity cores, assuming a quantile threshold of 0.9 (top panel), 0.8 (middle panel), or 0.7 (bottom panel) for defining high biodiversity value. Dark-shaded patches indicate cores and light-colored background shading distinguishes regions (green = Central Asia, orange= East Asia, brown = South Asia, red = Southeast Asia).

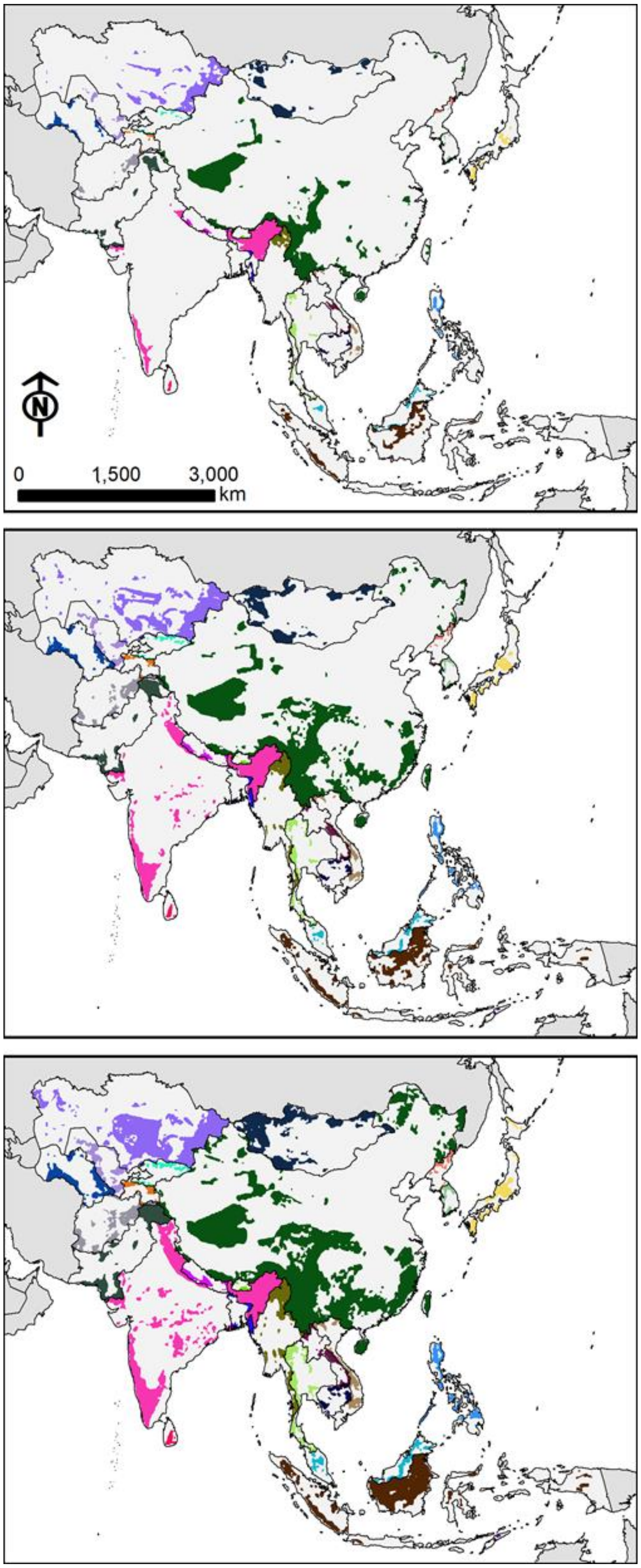

Figure 7: National-scale large biodiversity cores, assuming a quantile threshold of 0.9 (top panel), 0.8 (middle panel), or 0.7 (bottom panel) for defining high biodiversity value. Different colors are used to distinguish among cores in different countries.

Most continental cores (59-72 percent of total core area, depending on quantile threshold) are within the tropical and subtropical moist broadleaf forests biome, which covers much of Southeast Asia (Table 4). The montane grasslands and shrublands biome are the next most common biome for continental cores (10-13 percent). All other biomes account for less than nine percent of total core area for all quantile thresholds at the continental scale. At the regional scale, cores are less dominated by tropical forests (36-38 percent), and other more northerly biomes that comprise a substantial fraction of regional cores include montane grasslands and shrublands (18-21 percent), desert and xeric shrublands (11-16 percent), temperate conifer forests (7-10 percent), temperate broadleaf and mixed forests (7-8 percent), and temperate grasslands, savannas, and shrublands (7 percent). Biome representation of cores at the national scale is nearly identical to representation at the regional scale. Cores identified using a lower quantile threshold (i.e., incorporating more total area within Asia) tend to include a more balanced representation of biomes at the continental scale, but not at the regional or national scales.

Continental-scale cores exhibit considerable overlap with biodiversity features from existing global biodiversity prioritization schemes, and the degree of overlap is partly dependent on the relative area included in the cores versus the prioritization scheme features (Table 5). For instance, Intact Forest Landscapes cover only a tiny fraction of Asia and fall almost entirely within the continental-scale cores identified using the 70th percentile threshold. In contrast, Global 200 Ecoregions cover considerably more area than even the 70th percentile cores, and thus it is impossible for the cores to achieve full coverage of Global 200 Ecoregions. For most global prioritization schemes, overlap with continental cores is higher than overlap with regional or national cores. This is especially true for Intact Forest Landscapes, and to a lesser degree for CEPF Biodiversity Hotspots, Global 200 Ecoregions, and IFCPS6 Critical Habitats. Interestingly, overlap between KBAs and biodiversity cores is similar for all geographic scales. At all geographic scales and quantile thresholds, at least 78 percent of cores fall within the combined footprint of all the global prioritization schemes, including 99 percent of continental cores at the 90th percentile threshold.

Table 4: Proportion of continental-scale large biodiversity cores within each biome

TABLE 4: PROPORTION OF CONTINENTAL-SCALE LARGE BIODIVERSITY CORES WITHIN EACH BIOME, FOR THREE DIFFERENT QUANTILE THRESHOLDS AND THREE DIFFERENT GEOGRAPHIC SCALES USED TO DEFINE HIGH BIODIVERSITY VALUE

	CONTINENTAL			REGIONAL			NATIONAL		
BIOME	TOP 10	TOP 20	TOP 30	TOP 10	TOP 20	TOP 30	TOP 10	TOP 20	TOP 30
Boreal Forests/Taiga	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Deserts & Xeric Shrublands	0.01	0.03	0.05	0.11	0.14	0.16	0.15	0.17	0.19
Flooded Grasslands & Savannas	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mangroves	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Montane Grasslands & Shrublands	0.11	0.10	0.12	0.21	0.19	0.18	0.21	0.19	0.18
Rock & Ice	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Temperate Broadleaf & Mixed Forests	0.04	0.04	0.05	0.07	0.07	0.08	0.07	0.08	0.08
Temperate Conifer Forests	0.05	0.05	0.05	0.10	0.07	0.07	0.10	0.07	0.07
Temperate Grasslands, Savannas & Shrublands	0.00	0.00	0.01	0.07	0.07	0.07	0.08	0.07	0.07
Tropical & Subtropical Coniferous Forests	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
Tropical & Subtropical Dry Broadleaf Forests	0.04	0.07	0.09	0.02	0.04	0.05	0.01	0.03	0.04
Tropical & Subtropical Grasslands, Savannas & Shrublands	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.00
Tropical & Subtropical Moist Broadleaf Forests	0.72	0.68	0.59	0.38	0.38	0.36	0.34	0.36	0.35

Table 5: Overlap between biodiversity features identified in previous global prioritization schemes and large biodiversity cores from this analysis

TABLE 5: OVERLAP BETWEEN BIODIVERSITY FEATURES IDENTIFIED IN PREVIOUS GLOBAL PRIORITIZATION SCHEMES AND LARGE BIODIVERSITY CORES FROM THIS ANALYSIS. RESULTS ARE SHOWN FOR THREE DIFFERENT QUANTILE THRESHOLDS USED TO ESTABLISH LARGE BIODIVERSITY CORES. NUMBERS TO THE LEFT OF THE SLASH ARE THE PROPORTION OF TOTAL BIODIVERSITY FEATURE AREA OVERLAPPING LARGE BIODIVERSITY CORES; NUMBERS TO THE RIGHT OF THE SLASH ARE THE PROPORTION OF TOTAL CORE AREA OVERLAPPING BIODIVERSITY FEATURES

	CONTINENTAL CORES			REGIONAL CORES			NATIONAL CORES		
GLOBAL PRIORITIZATION SCHEME FEATURE	TOP 10	TOP 20	TOP 30	TOP 10	TOP 20	TOP 30	TOP 10	TOP 20	TOP 30
CEPF Biodiversity Hotspots	0.31 / 0.85	0.56 / 0.76	0.67 / 0.61	0.21 / 0.58	0.34 / 0.47	0.44 / 0.41	0.20 / 0.54	0.32 / 0.44	0.43 / 0.39
Intact Forest Landscapes	0.59 / 0.11	0.83 / 0.08	0.91 / 0.06	0.36 / 0.07	0.52 / 0.05	0.59 / 0.04	0.38 / 0.07	0.52 / 0.05	0.57 / 0.04
IFCPS6 Critical Habitat	0.32 / 0.63	0.52 / 0.50	0.65 / 0.42	0.25 / 0.48	0.41 / 0.40	0.52 / 0.34	0.24 / 0.47	0.40 / 0.39	0.51 / 0.33
Global 200 Ecoregions	0.17 / 0.76	0.31 / 0.71	0.44 / 0.66	0.15 / 0.71	0.30 / 0.67	0.41 / 0.63	0.15 / 0.68	0.28 / 0.65	0.40 / 0.61
KBAs	0.29 / 0.31	0.44 / 0.24	0.58 / 0.21	0.29 / 0.32	0.47 / 0.25	0.56 / 0.20	0.30 / 0.32	0.47 / 0.25	0.57 / 0.20
All schemes combined	0.17 / 0.99	0.33 / 0.96	0.45 / 0.90	0.16 / 0.92	0.29 / 0.85	0.40 / 0.79	0.15 / 0.90	0.28 / 0.83	0.40 / 0.78

EXTENT OF PROPOSED LI

We identified more than 81,000 km of proposed LI associated with major international economic development initiatives in Asia (Table 6, Figure 8). Roughly 36,000 km (44 percent) of this is proposed railways, followed by roads (~28,000 km; 34 percent) and power lines (~18,000 km; 22 percent). Sixty-two percent of proposed LI length would be new routes and 36 percent would be improvements to existing routes. The greatest length of proposed railways is in South and East Asia (especially Pakistan, Mongolia, and Afghanistan), but countries with the highest density of proposed railways are mostly in Southeast Asia (including Singapore, Vietnam, and Laos). The greatest length of proposed roads is in South and Southeast Asia, particularly Myanmar, India, Pakistan, and Bangladesh. Countries in these regions also have the highest density of proposed roads, with additional Southeast Asian countries such as Cambodia and Laos near the top of the list. Countries in East Asia (China and Mongolia) and Southeast Asia (Cambodia and Laos) have the greatest length of proposed power lines, and Southeast Asian countries have the highest density of proposed power lines (Cambodia, Laos, Brunei, and Malaysia). Across all LI modes, the greatest length of proposed LI is primarily in South and East Asian countries (Pakistan, Mongolia, and China), but the greatest density is primarily in Southeast Asian countries (Cambodia, Laos, and Vietnam).

Table 6: Length of proposed LI projects in Asia

TABLE 6: LENGTH OF PROPOSED LI PROJECTS IN ASIA BY LINEAR INFRASTRUCTURE MODE (RAILWAY, ROAD, OR POWER LINE) AND PROJECT TYPE (NEW ROUTE OR IMPROVEMENT OF EXISTING ROUTE)

LI MODE	PROJECT TYPE	COMBINED LENGTH (KM)	TOP 5 COUNTRIES BY PROPOSED LI LENGTH	TOP 5 COUNTRIES BY PROPOSED LI DENSITY
Railway	Improvement	8,648	Pakistan, Mongolia, Afghanistan, Thailand, China	Singapore, Vietnam, Afghanistan, Bangladesh, Laos
	New	27,051		
	Unclear	0		
	All project types	35,698		
Road	Improvement	20,402	Myanmar, India, Pakistan, Bangladesh, Afghanistan	Bangladesh, Cambodia, Myanmar, Laos, Tajikistan
	New	5,560		
	Unclear	1,957		
	All project types	27,919		
Power line	Improvement	0	China, Cambodia, Laos, Mongolia, Japan	Cambodia, Laos, Brunei Darussalam, Japan, Malaysia
	New	17,991		
	Unclear	0		
	All project types	17,991		
All LI modes	Improvement	29,050	Pakistan, Mongolia, China, Afghanistan, Myanmar	Cambodia, Singapore, Bangladesh, Laos, Vietnam
	New	50,602		
	Unclear	1,957		
	All project types	81,608		

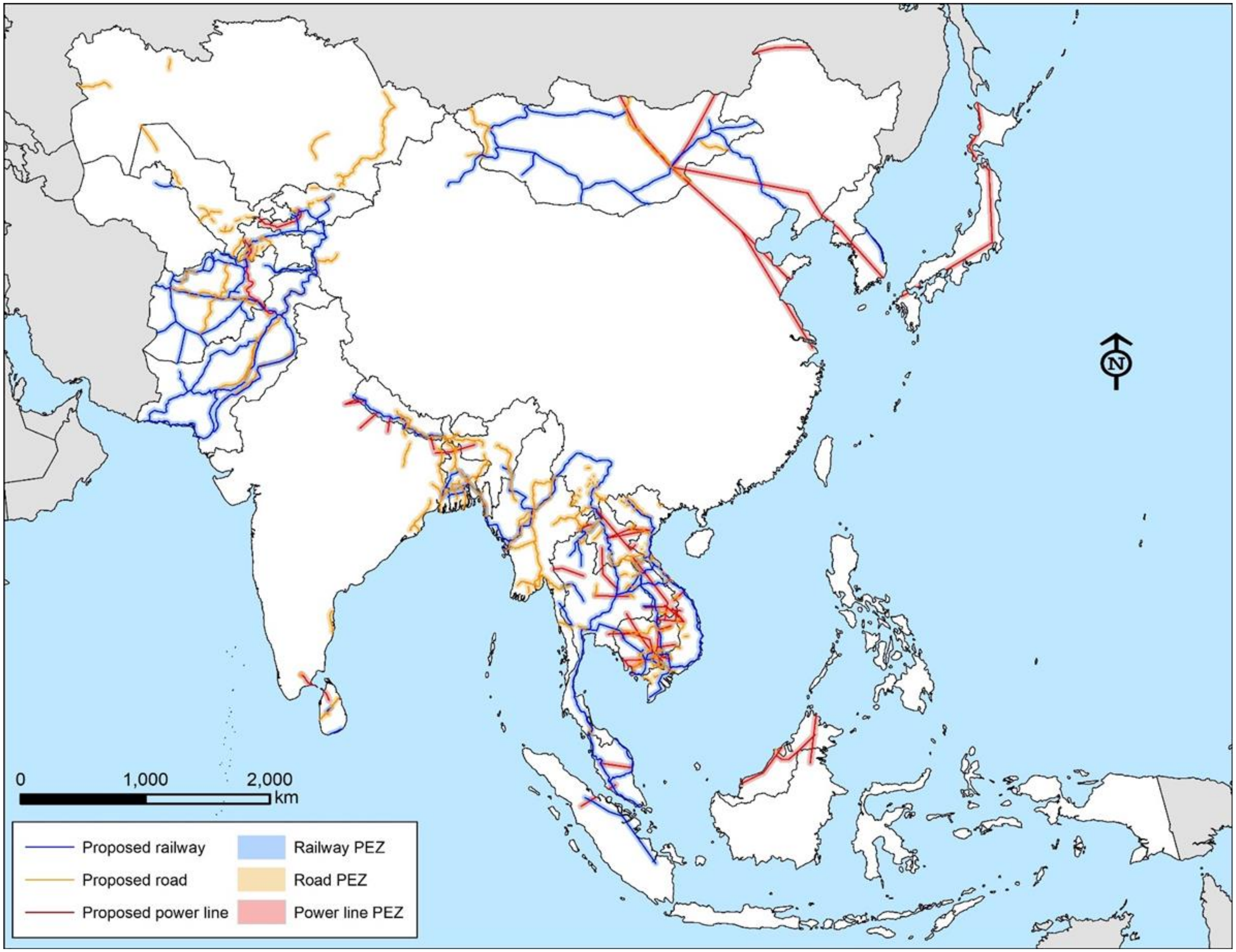

Figure 8: Routes and potential effect zones (PEZs) of proposed linear infrastructure projects across Asia.

POTENTIAL LI IMPACTS TO BIODIVERSITY

The degree of overlap between biodiversity cores and PEZs varies by LI mode and by core definition (i.e., geographic scale and CBI percentile threshold) as shown in Table 7. PEZs for all LI modes intersect 12-20 percent of cores, depending on how the cores are defined (Figure 9, Figure 10). Railway PEZs intersect 7-12 percent of cores, while road PEZs intersect 4-9 percent of cores and power line PEZs intersect 2-6 percent of cores. For all core definitions, railway PEZs have the greatest total overlap with core areas, followed by road PEZs, and then power line PEZs. The largest areas of national and regional biodiversity cores overlapping with PEZs are within East Asian and South Asian countries, particularly China, India, Pakistan, and Afghanistan. The largest areas of overlap for continental cores are in Southeast Asian countries, especially Laos, Myanmar, Cambodia, and Malaysia. However, when considering the proportion of biodiversity cores within a country that overlap PEZs (as opposed to the total area of overlap), the greatest potential impacts are in smaller countries in South and Southeast Asia, such as Nepal, Bangladesh, Laos, Cambodia, and Vietnam.

PEZs intersect 363 PAs categorized as strict nature reserves (1a) or wilderness areas (1b) by the IUCN (
Table 8). More than 25,000 km^2 of 1a and 1b PAs fall within PEZs, which is approximately 8 percent of the combined area of these PAs. Road PEZs intersect the largest number of PAs of the three LI modes, but power line PEZs intersect the greatest total area of PAs.

Table 7: Proportion of total area of biodiversity cores within potential effect zone (PEZ) of proposed linear infrastructure routes.

TABLE 7: PROPORTION OF TOTAL AREA OF BIODIVERSITY CORES WITHIN POTENTIAL EFFECT ZONE (PEZ) OF PROPOSED LINEAR INFRASTRUCTURE ROUTES. RESULTS ARE SHOWN FOR EACH BIODIVERSITY CORE DEFINITION AND FOR EACH LI MODE

BIODIVERSITY CORES	RAILWAY	ROAD	POWER LINE	ALL LI MODES	TOP 5 COUNTRIES BY AREA (ALL MODES)	TOP 5 COUNTRIES BY PROPORTION (ALL MODES)
National, top 10%.	0.10	0.06	0.02	0.16	China, India, Pakistan, Kazakhstan, Afghanistan	Nepal, Laos, Bangladesh, Vietnam, Pakistan
National, top 20%	0.10	0.05	0.02	0.15	China, India, Mongolia, Pakistan, Afghanistan	Nepal, Laos, Bangladesh, Cambodia, Vietnam
National, top 30%	0.09	0.05	0.02	0.15	China, Mongolia, India, Pakistan, Afghanistan	Nepal, Laos, Bangladesh, Cambodia, Vietnam
Regional, top 10%.	0.07	0.06	0.03	0.13	China, India, Nepal, Malaysia, Kazakhstan	Bangladesh, Laos, Nepal, Cambodia, Kyrgyzstan
Regional, top 20%	0.07	0.05	0.03	0.12	China, India, Malaysia, Nepal, Kazakhstan	Laos, Cambodia, Bangladesh, Nepal, Sri Lanka
Regional, top 30%	0.07	0.04	0.02	0.12	China, India, Malaysia, Mongolia, Nepal	Laos, Cambodia, Bangladesh, Nepal, Sri Lanka
Continental, top 10%	0.12	0.07	0.06	0.20	Malaysia, Cambodia, India, Laos, Indonesia	Bangladesh, Nepal, Laos, Cambodia, Vietnam
Continental, top 20%	0.12	0.09	0.06	0.20	Laos, Myanmar, Malaysia, Cambodia, China	Laos, Cambodia, Vietnam, Bangladesh, Nepal
Continental, top 30%	0.11	0.08	0.05	0.18	Myanmar, Laos, Cambodia, Thailand, Malaysia	Cambodia, Laos, Bangladesh, Vietnam, Brunei Darussalam

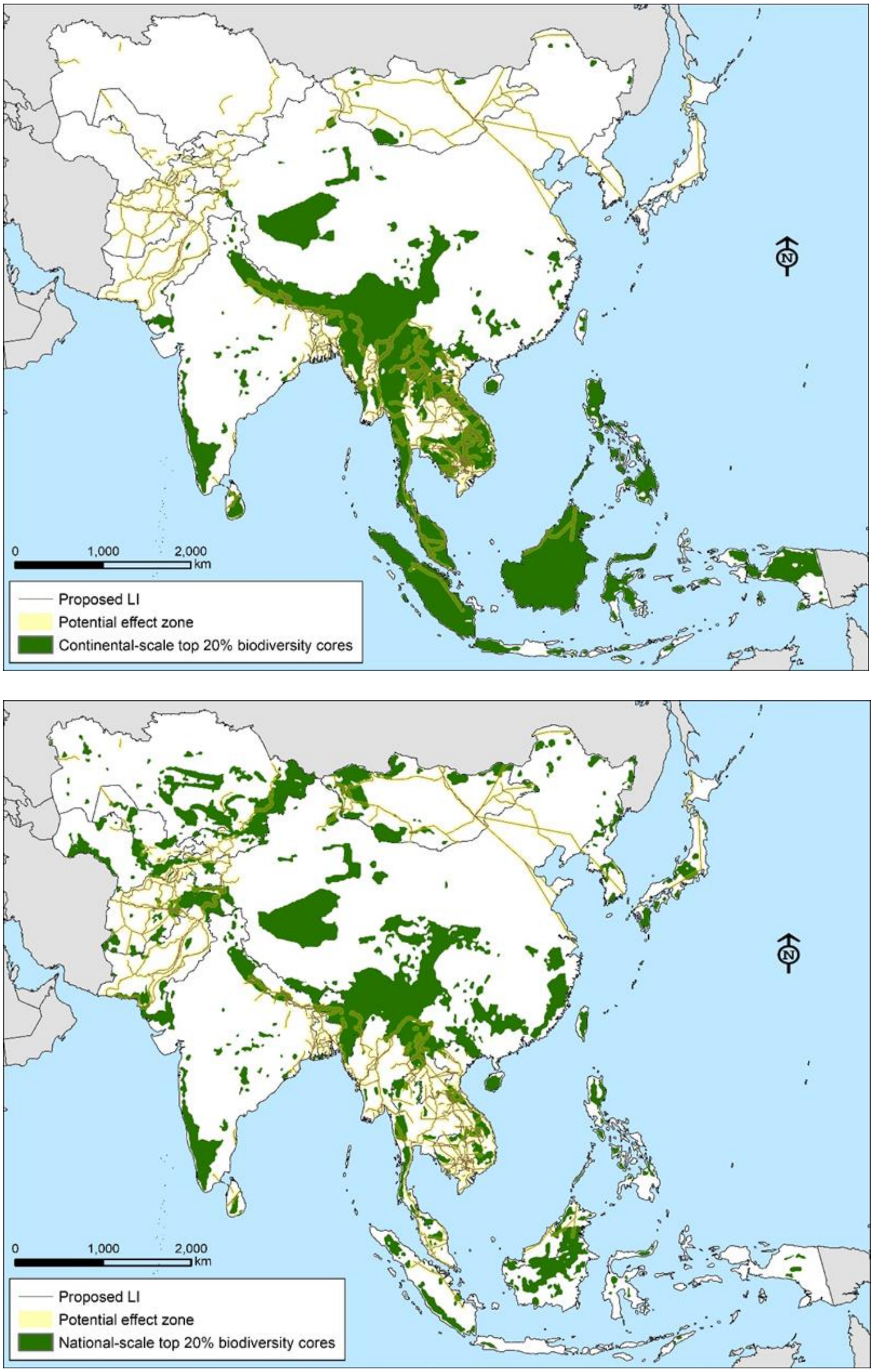

Figure 9: Overlap between potential effect zones (PEZs) of proposed LI routes (all modes) and top 20% biodiversity cores at the continental scale (top panel) and national scale (bottom panel).

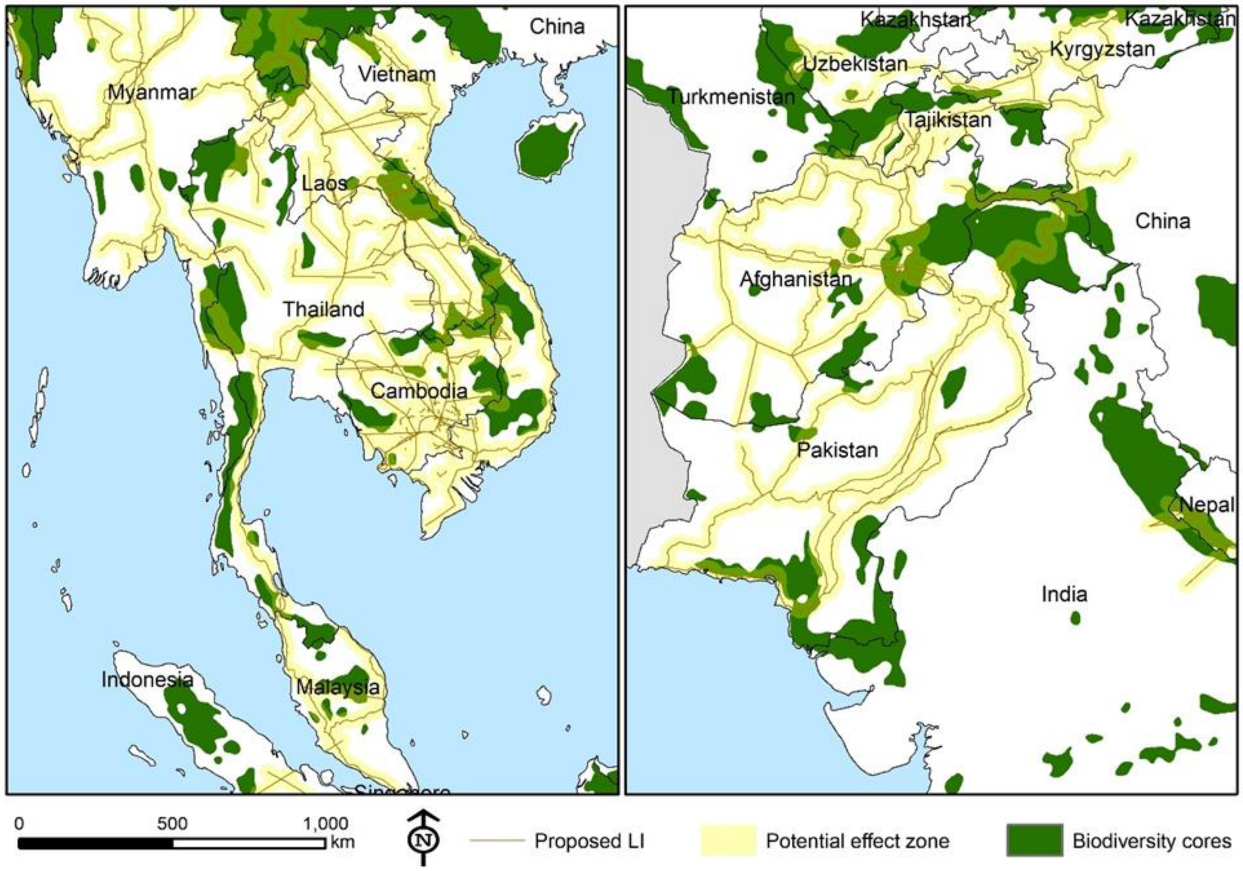

Figure 10: Overlap between potential effect zones (PEZs) of proposed LI routes and biodiversity core areas within selected regions of Asia. Biodiversity cores shown are based on top 20% of CBI values at the national scale. LI routes shown include all three modes (roads, railways, power lines).

Table 8: Overlap between potential effect zones (PEZs) of proposed LI routes and protected areas

TABLE 8: OVERLAP BETWEEN POTENTIAL EFFECT ZONES (PEZS) OF PROPOSED LI ROUTES AND PROTECTED AREAS (IUCN CATEGORIES 1A AND 1B)

LI MODE	NO. OF PAS WITHIN PEZ	AREA OF OVERLAP (KM^2)	PROP. OR PA AREA WITHIN TOTAL PEZ
Railway	156	9,119	0.028
Road	184	6,254	0.019
Power line	132	13,014	0.041
All LI models	363	25,295	0.079

DISCUSSION

We mapped biodiversity conservation values across Asia and identified large biodiversity cores that can inform USAID strategies for wildlife-friendly LI development and mitigation. By overlaying biodiversity cores with routes of proposed roads, railways, and power lines, we have identified areas where future LI development presents the greatest risk to biodiversity. Our results reflect a range of possible conservation priorities for avoiding, minimizing, or mitigating impacts of future LI development at three geographic scales: Asia-wide, regionally, and nationally.

One of the uses of the core maps in this analysis is as an avoidance layer for siting future LI projects in a manner that protects the most biodiverse locations of the 28 Asian countries in the study area. We delineated large biodiversity cores using three thresholds for what constitutes high biodiversity value—cores covering approximately 10, 20, or 30 percent of the continent. This approach provides USAID with flexibility when determining the scope of efforts to reduce conflicts between LI and biodiversity. The most stringent definition of biodiversity cores from this analysis (e.g., the 90th percentile threshold) may be appropriate when conservation resources are limited and must be used to address potential LI conflicts in a small set of exceptionally biodiverse locations. However, there is increasing consensus that a large fraction of the Earth, perhaps as much as 30 to 50 percent, will need to be protected to halt the extinction crisis and avoid the worst impacts of climate change. The Convention on Biological Diversity's Strategic Plan for Biodiversity 2011-2020 called for each signatory nation to conserve at least 17 percent of terrestrial and inland waters and 10 percent of coastal and marine areas in well-connected systems of PAs. More recently, the Half Earth (Wilson, 2016), Nature Needs Half (Locke, 2014), and Thirty by Thirty (Dinerstein et al., 2019) movements have called for more ambitious biodiversity conservation targets and have gained traction among scientists and practitioners. Thus, a more liberal definition of biodiversity cores (e.g., the 80th or 70th percentile thresholds from our analysis) may be more in line with current thinking, or at least serve as an aspirational target.

Our results highlight the influence of geographic scale when assessing conservation priorities. The latitudinal biodiversity gradient means that global priorities are often heavily skewed toward low-latitude, tropical biomes where species richness is highest. The continental-scale CBI mapping produced by this study also suggests that areas of highest biodiversity value are concentrated in Southeast and South Asia. However, regional- and national-scale priorities are considerably different and encompass a wider variety of biomes and much more area in Central and East Asia. Results for different geographic scales may be applied differently to LI planning and mitigation; for instance, local or national conservation programs could be informed by maps of national cores, while maps of continental cores could inform and guide USAID's conservation strategies across the whole of Asia. Core areas common to all three geographic scales are excellent places in which to focus initial conservation efforts.

The approach we used to develop the CBI and identify large biodiversity cores is based on the idea of consensus among many independent biodiversity data sources. We recognize that some redundancy exists among the data sets we used to calculate the CBI (e.g., many rely on species richness as the basis for estimates of biodiversity value), but we tried to minimize this redundancy by removing highly correlated layers. The divergent estimates of biodiversity value among layers for some areas of Asia (Figure 4, bottom left) suggest that the remaining layers incorporate independent and complementary information. Moreover, the fact that agreement among these layers was so strong for the highest-CBI areas (Figure 4, bottom right) strengthens the case that these are meaningful priority areas for biodiversity conservation and are not overly influenced by how biodiversity is measured.

We treated all biodiversity layers as having equal importance when calculating the CBI, primarily because we had no objective means of assessing the relative importance of layers. However, future investigation could assign different weights to individual layers when calculating average biodiversity value, with weights reflecting the degree to which layers reflect users' specific biodiversity conservation objectives, or perhaps reflecting data reliability as indicated by spatial resolution or recency of data collection.

Spatial overlap between core areas and the biodiversity features from existing global prioritization schemes is highly variable, and there are several possible explanations why this overlap is low in some cases. First, differences in spatial scale (global versus continental, regional, or national) likely lead to some differences in priorities. Second, the elements of biodiversity captured in global prioritization schemes are not identical to those in the biodiversity layers we used; for instance, plant species richness and unusual ecological or evolutionary phenomena are both components of global prioritization schemes but not incorporated in the layers we used, which are largely oriented toward terrestrial wildlife. Third, the total area of biodiversity features and of the cores identified in this analysis are sometimes very different, meaning that a high degree of overlap is not possible. Despite this, the spatial distribution of biodiversity features and cores is roughly similar, and virtually all cores overlap with a biodiversity feature identified in at least one global prioritization scheme.

THREATS TO BIODIVERSITY

Our analysis revealed several important characteristics of proposed LI development in Asia. Proposed roads are a major component of the threat posed by LI development to biodiversity, but threats from other LI modes may be just as important. The total length of proposed roads that we identified in Asia is smaller than the length of proposed railways, which have received less attention than roads from conservationists and researchers in most regions, and whose impacts on biodiversity are not as well understood (Popp & Boyle, 2017). Power lines have been omitted entirely from most assessments of LI impacts to biodiversity, yet our analysis suggests that their impact could be substantial. Power lines account for more than a fifth of the total length of proposed LI identified in our analysis and are concentrated mainly in Southeast Asia, where biodiversity value is relatively high. Proposed routes for power lines may also have greater potential for impacting PAs based on our analysis. These findings suggest that a greater focus on railways and power lines is merited when considering threats to biodiversity from LI, particularly in regions where proposed roads constitute a minority of LI development pressure.

The magnitude of LI development will be especially large in Southeast Asia, which accounts for 18 percent of Asia's total area, but includes 37 percent of its total length of proposed LI. This is particularly concerning given that the continental-scale biodiversity core areas identified in our analysis are also largely concentrated in Southeast Asia. Threats from LI development to some areas within this region have received considerable media coverage and attention from researchers because they affect ecosystems or species that have been widely recognized as conservation priorities, such as the Heart of Borneo and Sumatra's Leuser ecosystem. However, many less iconic areas within Southeast Asia also have high biodiversity value and plans for LI development, and the threat to these areas has attracted much less attention. For instance, Cambodia, Laos, and Vietnam have some of the highest overlap between biodiversity cores and proposed LI but are mentioned much less frequently in discussions of LI development threats, although efforts such as the Mekong Infrastructure Tracker (Stimson Center, 2021) are helping to change this.

More recent analyses of LI development impacts in Asia have focused on LI projects associated with China's Belt and Road Initiative, or BRI (Foggin et al., 2021; Hughes, 2019; Hughes et al., 2020; Lechner et al., 2018; Ng et al., 2020). BRI projects are geographically widespread, receive considerable media coverage, have important geopolitical ramifications, and are captured well in existing spatial databases, all of which contribute to the attention they receive. However, our analysis suggests that the threat to biodiversity from LI development in Asia extends well beyond the BRI. Only 34 percent of the total length of proposed LI routes in our analysis was associated with BRI. The remaining two-thirds of the proposed LI development we documented is part of regional initiatives such as the South Asia Subregional Economic Cooperation Program (SASEC), Central Asia Subregional Economic Cooperation Program (CAREC), Greater Mekong Subregion Program (GMS), and Association of Southeast Asian Nations (ASEAN). A small number of projects was associated with both BRI and another international initiative (e.g., CAREC, ASEAN). In addition, some Asian countries have ambitious plans for LI development that will be nationally funded, and thus were not included in our assessment that focused on international economic development initiatives. For instance, India and China appear as relatively blank areas on our map of proposed LI (Figure 8), but both countries are expanding their LI networks rapidly and unilaterally. India is expected to account for 40 percent of the total global share of rail activity by 2050 and invest US $715 billion in rail infrastructure by 2030 (IBEF, 2021a). The Indian government's 2021-22 budget includes US $42 billion for a revamped power distribution sector scheme (IBEF, 2021b), as well as funding for 19,500 km of road and high construction projects (Chakravarty, 2021). In China, a blueprint recently released by the Central Committee of the ruling Communist Party and the State Council calls for expanding the nation's railway network by 200,000 km and its highway network by 460,000 km over the next 15 years (Wang, 2021). Tracking LI development plans from national and subnational initiatives will be necessary to fully characterize the threat to biodiversity posed by LI development in Asia.

TOWARD A BETTER UNDERSTANDING OF LI THREATS

Our analysis provides a basis for understanding the general magnitude and geographic distribution of potential LI impacts to biodiversity in Asia. It builds on existing analyses of LI impacts in Asia by including LI projects beyond those associated with the BRI, considering impacts of power lines, and synthesizing biodiversity information across many data sources to produce a composite biodiversity index useful for LI planning. Yet our analysis was significantly limited by three aspects of LI spatial data for Asia:

1. Availability. Acquiring spatial data on proposed LI was the most time-consuming and challenging aspect of this study. We initially expected that multilateral development banks would be able to provide data in a geospatial format on proposed LI projects that they are funding, but soon discovered that these data are not systematically organized in any way. Because compiling data on all proposed LI projects across Asia from scratch was not feasible, we focused our analysis on projects associated with international economic development initiatives for which we could find maps in reports and websites we could use to manually digitize routes. This lack of available spatial data on proposed LI routes means that our analysis only considers a sample of the LI projects likely to impact biodiversity in Asia and may be biased toward projects for which we were most easily able to find information. Comprehensive and regularly updated geospatial databases of LI projects that are maintained by LI project funders or planners would vastly improve the completeness of future analyses of potential LI impacts.

2. Project detail. The data sources used to construct our database of proposed LI projects varied greatly with respect to the amount of detail they provided on LI characteristics. For some projects, we were unable to determine much more than the LI mode. Additional information on LI characteristics, such as number of lanes and anticipated traffic volume of roads, track gauge of railways, or voltage of power lines, would allow for more nuanced assessments of potential impacts. For instance, we had to treat all proposed roads as having equal potential to harm biodiversity in a given area, but an analysis that distinguished between two-lane undivided highways and four-lane divided highways (which may have quite different impacts on species and ecosystems) would provide more useful information for LI planning and conservation.
3. Spatial precision. We used a wide buffer around proposed LI routes to define areas that could be affected by these routes (PEZs), which was necessary because of the potentially large spatial error associated with routes that were manually digitized from coarse-scale maps. Accordingly, it is not clear whether some proposed LI routes will directly intersect areas of importance for biodiversity conservation, such as PAs or the biodiversity core areas we identified in this analysis. The influences of LI development extend well beyond the physical footprint of LI features—for instance, poaching and illegal logging facilitated by LI development can occur many kilometers away from a road or railway—and our buffer-based analysis has the advantage of capturing potential impacts to biodiversity of these diffuse secondary effects of LI. However, more precise spatial data on proposed LI routes would allow identification of areas likely to be directly influenced by more localized LI impacts (e.g., wildlife-vehicle collisions, electrocution, noise disturbance, loss of wildlife movement corridors).

Until these limitations can be reduced by improvements in the availability, level of detail, and spatial precision of LI data for Asia, we suggest that the best use of our coarse-scale analysis is as an initial screening tool for identifying areas that warrant a finer-scale analyses because they have high potential for conflict between biodiversity and proposed LI. A fine-scale analysis should (1) seek out project-level planning documents that describe the characteristics of the proposed LI as specifically as possible; (2) acquire spatial data that represents the proposed route in as much detail as planners can provide at present; and (3) compile biodiversity data that was collected as locally and with as fine spatial resolution as possible, and focused on species of conservation concern in the project area. These tasks require a level of effort that was not possible for us to apply across all of Asia, but which is necessary for adequately assessing the potential impacts of individual LI projects. We present six fine-scale analyses in Part II of this annex that illustrate how impacts of proposed LI projects can be assessed for species of conservation concern in selected landscapes within Asia.

CONTRIBUTIONS

Tyler Creech (Center for Large Landscape Conservation [CLLC]) conducted spatial analyses and drafted the report. Grace Stonecipher (CLLC) and Mat Bell (Western Transportation Institute–Montana State University [WTI]) compiled and digitized data on proposed LI routes. Rob Ament (CLLC/WTI) and Tony Clevenger (WTI) helped design and review the report.

DATA AVAILABILITY

Spatial data products of this analysis biodiversity core areas with this analysis, including biodiversity cores, proposed LI routes, and PEZs, are archived in USAID's Development Data Library.

PART II: FINE-SCALE ANALYSES OF POTENTIAL LI IMPACTS IN SELECTED ASIAN LANDSCAPES

Coarse-scale analyses such as the one presented in Part I of this annex are useful for identifying general areas where impacts to biodiversity from proposed LI may be significant. Yet these analyses typically lack the level of detail and spatial resolution needed to adequately assess the potential impacts of individual LI projects on species or ecosystems of conservation concern. Part II provides six examples of original fine-scale analyses of vulnerable species or taxa that were conducted for this report and highlight the potential effects of proposed LI development projects. These analyses are rapid assessments that were completed over a short time frame using available biological and LI data. They were conducted in collaboration with local non-governmental organization (NGO) partners who are active in wildlife research and conservation efforts and have expertise regarding LI influences on wildlife populations.

Our six analyses are taxonomically diverse, focusing on large carnivores, ungulates, birds, herptiles, and other species. They consider LI projects of all three modes (roads, railways, and power lines) and both new routes and improvements to existing routes. The analyses are also geographically diverse, including study areas within South, Southeast, East, and Central Asia. They rely on several types of biological data (e.g., wildlife telemetry, roadkill surveys, population density estimates, and wildlife corridor maps) and a variety of spatial analysis methods. In addition to characterizing potential impacts of several high-profile LI projects on vulnerable species, these fine-scale analyses provide examples of how rapid, prospective spatial assessments can inform efforts to safeguard biodiversity.

Each of the six analyses is presented below as a stand-alone study, but we present a short synthesis of key findings across all analyses at the conclusion of Part II.

ANALYSIS 1: POTENTIAL IMPACTS OF PROPOSED PAVED ROADS AND RAILWAYS IN MONGOLIA ON SNOW LEOPARDS

The snow leopard is a top predator and an indicator of the health of Central and South Asia's high mountain ecosystems. Snow leopard populations have decreased from historical levels across much of their range due to habitat loss, poaching, and climate change impacts. Mongolia has the second largest snow leopard population—approximately 1,000 individuals of the 12 Asian countries within the species' range, and three priority landscapes identified by the Global Snow Leopard Ecosystem Protection Program are within Mongolia (WWF, 2015). Newly published survey data for Mongolia indicate that the country's snow leopard population is now stable (Bayandonoi et al., 2021), likely due to conservation efforts such as anti-poaching patrols, livestock compensation programs, and public education campaigns.

Despite this conservation success, Mongolia's snow leopards still face many threats, and LI development is one of the most significant. Mongolia is rich in minerals and other extractive resources, and a major road and railway network is being developed to transport these resources to the neighboring countries of China and Russia. Only 13 percent of Mongolia's ~50,000-km road network is currently paved, and further upgrades to the road network have been proposed to increase access to markets and improve connectivity and safety for residents (ADB, 2018a). Mongolia's Sustainable Development Vision 2030 calls for extending asphalt roads by nearly 3,000 km and constructing several new railways to support international and domestic travel and serve the agricultural, industrial, and mining sectors (Government of Mongolia, 2016).

LI may harm snow leopard populations via three mechanisms. First, LI can cause degradation and fragmentation of snow leopard habitat. Snow leopards avoid areas of human activity (Wolf & Ale, 2009), and new roads and railways often lead to increased local human population density. Conversion of natural habitat to agricultural land may occur as farmers procure lands near roads or railways for ease of transport (Diener & Batjav, 2019). Expanded and improved linear infrastructure may also facilitate natural resource extraction in new areas, which may then be less suitable as snow leopard habitat. Paved roads and railways could also act as barriers to movement for snow leopards, preventing movement among habitat patches that is needed for gene flow and adaption to climate change (Snow Leopard Network, 2014).

Second, new LI and the increased human access and land use change associated with it can result in direct killing of snow leopards by humans. Snow leopards are poached for their pelts and for bones and other body parts used in traditional medicine (Wingard & Zahler, 2006). They are also killed in retaliation for livestock depredation (Jackson & Wangchuk, 2001).

Third, expanding human presence and land use along new roads and railways may reduce the availability of prey for snow leopards. Snow leopards occupy areas with dense populations of ungulate prey, and these prey populations may be reduced near transport corridors because of poaching, competition with livestock, or habitat degradation associated with agricultural development (WWF, 2015).

Here, we present a rapid assessment of potential areas of conflict between snow leopards and proposed LI in Mongolia. Our objective is to characterize the magnitude and geographic distribution of the threat posed to the country's snow leopard population by proposed paved roads and railways, and to highlight areas where action is needed to avoid the most severe impacts.

METHODS

We spatially overlaid routes of proposed LI with habitat patches occupied by snow leopards and with predicted dispersal routes for snow leopards moving between habitat patches. We obtained spatial data on proposed paved roads and proposed railways (including one currently under construction) from the Wildlife Conservation Society's Mongolia Program. We obtained spatial data on occupied snow leopard habitat patches and dispersal corridors from the World Wide Fund for Nature's Mongolian Programme Office. These snow leopard data were generated during a recent multi-year, nationwide population assessment that estimated the spatial distribution and density of snow leopards across Mongolia (Bayandonoi et al., 2021). The assessment used sign-based occupancy surveys and camera-based capture-recapture methods to create a stratified map of snow leopard density that classifies habitat into high-, medium-, and low-density categories. It also used least-cost path models to predict optimal dispersal corridors among isolated snow leopard territories based on landscape characteristics such as topography and human presence. Corridors were classified into five categories based on their cost-effectiveness for snow leopard dispersal (i.e., amount of energy required for dispersal).

We quantified the potential for proposed LI to impact snow leopard populations in two ways: (1) we calculated the total length of proposed paved roads and railways that would intersect occupied snow leopard habitat of each density category as an estimate of potential habitat degradation; and (2) we calculated the number of intersection points between proposed paved roads or railways and least-cost dispersal corridors as an estimate of potential connectivity loss. We created maps of both types of intersections to help visualize these locations of potential conservation concern. Because PAs may afford greater assurance of safeguards in LI projects, we also determined whether or not intersections between proposed LI and occupied snow leopard habitat occurred within PAs, as defined by the World Database on Protected Areas (UNEP-WCMC & IUCN, 2021).

RESULTS

More than 1,900 km of proposed LI would intersect occupied snow leopard habitat in Mongolia, with paved roads and railways each accounting for approximately half of the total (Table 9). Most of these areas of intersection are located within medium-density occupied habitat, but nearly 370 km are within high-density habitat, where impacts to snow leopards could be especially severe. Although many intersection areas occur along the margins of occupied habitat patches (e.g., near valley bottoms), proposed LI would cut through the middle of occupied habitat in several locations (Figure 11). A long swath of nearly continuous occupied habitat spanning the Altai Mountains between northwestern and southern Mongolia would be bisected by two proposed paved roads (Dayan-Ulgii city road and Altai city-Bugat-Burgastai road) and two proposed railways (Altai city-Burgastai railway and Altai city-Bulgan railway). These developments could fragment this continuous habitat patch into many smaller patches.

Approximately 200 km (10 percent) of proposed LI within occupied snow leopard habitat would occur within PAs, including: 56 km of proposed paved road within medium-density occupied habitat in Altai Tavan Bogd National Park; 37 km of proposed railway within medium- and low-density habitat in Mayangan Ugalzat National Park; 28 km of proposed paved road within high- and medium-density habitat in Ikh Bogd Uul National Park; and 16 km of proposed road in high- and medium-density habitat in Khar-Us Nuur National Park.

Proposed LI would intersect predicted dispersal corridors in 59 locations (Table 9), many of which lie along corridors in the highest cost-effectiveness category, those most likely to be used for dispersal. If snow leopards perceive new paved roads and railways along these corridors as movement barriers, many smaller occupied habitat patches could become isolated from the larger snow leopard metapopulation. The proposed LI features with greatest potential for causing habitat degradation are not necessarily the same as those features with the greatest potential for causing connectivity loss; for instance, the proposed Altai city-Gurvantes-Dalanzadgad city railway in southern Mongolia would intersect relatively little occupied habitat but would bisect 11 dispersal corridors.

Table 9: Extent of overlap between proposed linear infrastructure (paved roads and railways) and snow leopard occupied areas and potential dispersal corridors

TABLE 9: EXTENT OF OVERLAP BETWEEN PROPOSED LINEAR INFRASTRUCTURE (PAVED ROADS AND RAILWAYS) AND SNOW LEOPARD OCCUPIED AREAS AND POTENTIAL DISPERSAL CORRIDORS

		INTERSECTION LENGTH (KM) WITH OCCUPIED AREA			
PROPOSED LI TYPE	INTERSECTIONS WITH DISPERSAL CORRIDORS	LOW-DENSITY PATCHES	MEDIUM-DENSITY PATCHES	HIGH-DENSITY PATCHES	ALL PATCHES
Paved road	25	284.3	488.4	204.5	977.2
Railway	34	208.0	561.5	164.0	933.5

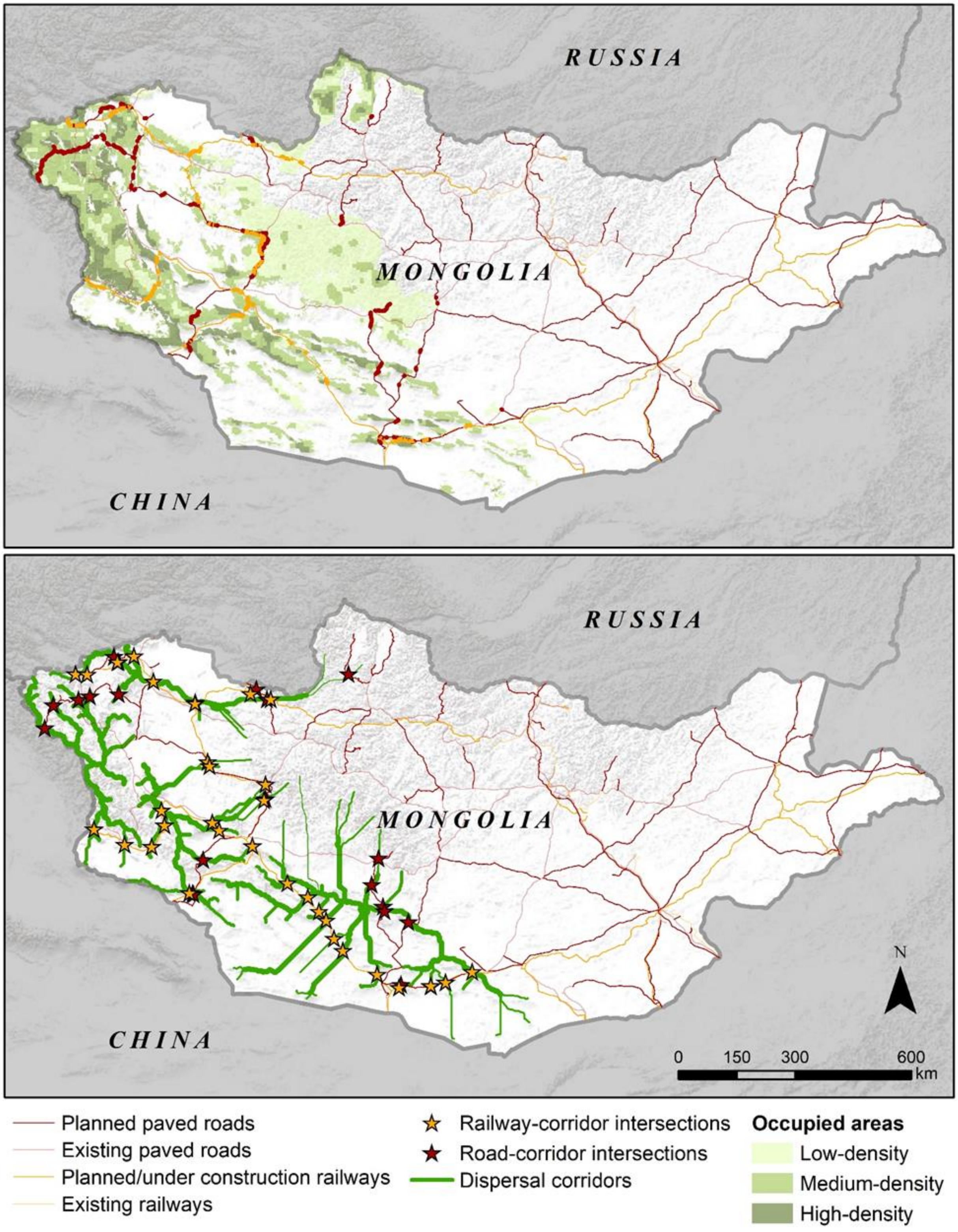

Figure 11: Areas of potential conflict between snow leopards and proposed paved roads and railways. *Top panel:* overlap between proposed LI and areas occupied by snow leopards. Sections of proposed LI features that overlap occupied areas are shown with thicker lines. *Bottom panel:* points of intersection between proposed LI and potential dispersal corridors for snow leopards. Thicker green lines represent corridors that are more efficient for snow leopard movement.

DISCUSSION

Our analysis suggests that proposed LI has the potential to impact snow leopards negatively across much of their range within Mongolia. New paved roads and railways, if completed as proposed, would cut through several remote areas that currently support relatively high densities of snow leopards, and many areas of moderate or low density. The effect of LI development on snow leopards and their habitat will depend on the extent to which improved and expanded LI results in increased human pressures, such as new mining development, settled agriculture, poaching, and prey depletion. It is difficult to predict how intense these pressures will be, but past road improvements in Mongolia have been followed by human migration toward and subsequent settlement along paved roads (Diener & Batjav, 2019), and it seems reasonable to expect this trend to continue. Opportunities to enact LI safeguards for snow leopards and other wildlife may be greatest for sections of proposed paved roads and railways that pass through national parks and other PAs that are managed specifically to conserve wildlife populations.

Effects of proposed LI on connectivity of Mongolia's snow leopard metapopulation could also be considerable, with our analysis indicating that many of the predicted dispersal corridors among habitat patches could be bisected by a newly paved road or a new railway. The potential for connectivity loss is high if these LI features are barriers to snow leopard movement, but this may depend on specific characteristics of roads and railways and how snow leopards respond to them. For instance, road width and traffic volume are important determinants of road-crossing behavior for many wildlife species (Jacobson et al., 2016), but how these factors influence snow leopard road-crossing behavior is not well understood. Similarly, fencing along roads and railways presents a strong barrier to movement for many species (McInturff et al., 2020). Current standards require barbed wire fencing along railways in Mongolia, and these fences have reduced the mobility and increased the mortality (via entanglement) of nomadic ungulates such as khulan, goitered gazelle, and Mongolian gazelle (Batsaikhan et al., 2014). These negative impacts to ungulate populations could influence Mongolia's snow leopards by reducing their prey base. However, it is unclear whether railway fencing presents a movement barrier or direct mortality risk to snow leopards themselves.

Our rapid assessment used available spatial data to highlight locations where impacts to snow leopards are most likely, but more detailed follow-up studies in these locations will be needed to fully understand the risk to snow leopards. Finer-scale information on snow leopard occurrence and density, anthropogenic pressures, and characteristics of proposed roads and railways would allow for more comprehensive and localized assessments, which will be critical for designing effective strategies for minimizing impacts of LI development on snow leopards.

Mongolia has yet to include mitigation measures such as wildlife crossings in any of the road or railway projects in their emerging Sustainable Development Vision 2030 program. A fine-scale assessment and mitigation recommendations for a new road from the Oyu-Tolgoi mine to the Chinese border was prepared to mitigate impacts on khulan, argali, goitered gazelle, and Mongolian gazelle; however, to our knowledge, these measures have not been implemented (Huijser et al., 2013). Snow leopards present a unique challenge for mitigating LI impacts because of the rugged terrain and climatic conditions of the areas they occupy. In mountainous environments many LI projects utilize tunnels and large viaducts to obtain necessary grade of two percent or less for freight railways. These features are the most effective means of mitigating LI impacts to wildlife because they do not modify habitat (Clevenger & Huijser, 2011). It will be important to ensure that these features are located correctly to keep snow leopard populations connected and impacts minimized.

CONTRIBUTIONS

Chimeddorj Buyanaa and Gantulga Bayandonoi (WWF Mongolia) provided spatial data on snow leopard density and dispersal corridors and contributed to the preparation of this report. Buuveibaatar Bayarbaatar and Narangua Batdorj (WCS Mongolia) provided spatial data on proposed roads and railways. Tyler Creech (CLLC) conducted spatial analyses and drafted the report. Rob Ament (CLLC/WTI) and Tony Clevenger (WTI) also contributed to the report.

ANALYSIS 2: POTENTIAL IMPACTS OF ROAD AND RAIL DEVELOPMENT ON TIGERS IN NEPAL'S TERAI ARC LANDSCAPE

The Terai Arc Landscape (TAL) is a ~50,000-km^2 area of forests, grasslands, and wetlands along the India-Nepal border that is a global conservation priority because of its high biodiversity and presence of charismatic and endangered megafauna such as elephant, rhinoceros, and tiger. The natural habitats of the TAL historically supported contiguous, high-density populations of tigers and their prey, but much of the landscape has been converted to human land uses, and tigers now occur in relatively isolated sub-populations within PAs (Thapa et al., 2017). Tigers and other wide-ranging species cannot be preserved through PAs alone; dispersal and seasonal movements among sub-populations are necessary for maintaining tiger genetic diversity and population health (Thatte et al., 2018). In recognition of this need, Nepal and India adopted a landscape-scale conservation approach for the TAL in 2004 to preserve habitat linkages among PAs in both countries. However, rapid LI development in the region, particularly in Nepal, is now threatening to harm tiger populations through habitat degradation, landscape fragmentation, and increased mortality from collisions with vehicles (Carter et al., 2020).

Three major LI projects that span the Nepal portion of the TAL in an east-west orientation may be particularly damaging for tigers. The East-West Railway is a proposed new 945-km electrified railway, of which only a small section at the eastern extent of the TAL has been completed thus far. The 1,028-km Mahendra Highway is Nepal's longest existing highway and is being upgraded from a two-lane undivided highway to a four-lane divided highway in various sections. A roughly 200-km section of this route that bisects Parsa National Park and borders Chitwan National Park is partly under construction and will fragment one of the most important tiger habitats in the TAL of Nepal (DNPWC, 2016). The Chitwan-Parsa complex holds a staggering 111 tigers according to the most recent survey (DNPWC & DoFSC, 2018). The 1,792-km Postal Highway is a paved two-lane road being constructed along the route of an existing dirt road built in the 1930s, and construction has been completed along approximately 60 percent of its length so far. Here, we conduct a simple spatial analysis of the potential impacts of construction and upgrades of these LI features on the TAL tiger population.

METHODS

We spatially overlaid LI routes with four types of priority areas for tiger conservation in the TAL: PAs, buffer zones around PAs, forested corridors among PAs, and areas of high tiger density. We obtained spatial data on PAs and buffer zones from the World Database on Protected Areas (UNEP-WCMC & IUCN, 2021), which included five PAs (Banke, Bardia, Chitwan, Parsa, and Shuklaphanta National Parks) and a buffer zone established around each PA. We obtained spatial data from WWF-Nepal on nine forested corridors within Nepal that connect tiger sub-populations in the TAL, including corridors that connect sub-populations in Nepal with those just across the border in India. We obtained spatial data from the Department of National Parks and Wildlife Conservation (DNPWC) on tiger density from a 2018 nationwide tiger survey that used camera trapping to estimate tiger density within 2×2 km grid cells encompassing all tiger-bearing PAs and adjoining forests in Nepal (DNPWC & DoFSC, 2018). We converted estimates of continuous tiger density to a categorical map of areas with high tiger density, which we defined as all grid cells with densities in the top quartile of values among all surveyed cells with non-zero density.

We focused on the three LI features described above as major threats to the tiger population: the East-West Railway, Mahendra Highway, and Postal Highway. We obtained spatial data for the routes of these

LI features from WWF-Nepal. Routes were based on the best information available at the time of writing, but route alignments are still being finalized for some sections of proposed new construction (i.e., a section of proposed East-West Railway rerouted north of Chitwan National Park), and thus proposed new routes should be considered approximate. Some sections of LI routes have already been constructed or upgraded, but we lacked reliable information for identifying these sections, so we opted to include the full length of all routes in our analysis to ensure that all possible threats were considered. We calculated the length of each LI feature intersecting each type of tiger conservation priority area (PA, buffer zone, corridor, or high tiger density area) as an estimate of the threat posed by that feature. We mapped these areas of intersection to highlight locations where impacts to tigers are expected to be most severe if new construction and upgrades to LI proceed as planned and without adequate mitigation measures.

RESULTS

More than 800 km of proposed LI routes intersect priority areas for tiger conservation and could impact the tiger population negatively if new construction or upgrades occur in these locations (Table 10, Figure 12). The Mahendra Highway is the LI feature with the greatest length of intersection with priority areas for tiger conservation (319 km), although large sections of the Postal Highway (270 km) and the East-West Railway (215 km) also intersect priority areas.

LI features have generally been routed to avoid PAs, but there are several areas where they nonetheless intersect PAs: the Postal Highway cuts through western Chitwan National Park; the Mahendra Highway cuts through western Bardia National Park and Parsa National Park; and the Postal Highway, Mahendra Highway, and East-West Railway all cut through Shuklaphanta National Park.

Most of the potential impact areas from proposed LI development occur outside of PAs and high tiger density areas, within buffer zones and forested corridors. LI features generally avoid areas of highest estimated tiger density, but there are two notable exceptions: the Mahendra Highway cuts through a high-density area in northwest Bardia National Park, and the Postal Highway intersects several high-density areas in southern Chitwan National Park.

Buffer zones surrounding PAs are intersected by at least one LI feature, and in many cases multiple features. The buffer zone around Shuklaphanta National Park is intersected by the Mahendra Highway, East-West Railway, and Postal Highway. The Banke-Bardia complex buffer zone is intersected by the Mahendra Highway and to a lesser extent by the East-West Railway and Postal Highway along its outer margins. The Chitwan-Parsa complex buffer zone is intersected by the Postal Highway and to a lesser extent by the East-West Railway and Mahendra Highway along its outer margins.

Perhaps the most severe potential impacts from proposed LI are to the nine forested corridors linking PAs in Nepal and India. The Karnali, Basanta, and Laljhadi corridors are each intersected by all three LI features. The Khata, Lamahi, Barandabhar, and Kamdi corridors are each intersected by two LI features, with the Kamdi corridors having a third LI feature running along its border. Only the Brahmadev and Dovan corridors are not intersected by any of the LI features.

Table 10: Length (km) of proposed/under-construction road and rail routes intersecting important areas for tiger conservation in the Terai Arc

TABLE 10: LENGTH (KM) OF PROPOSED/UNDER-CONSTRUCTION ROAD AND RAIL ROUTES INTERSECTING IMPORTANT AREAS FOR TIGER CONSERVATION IN THE TERAI ARC						
		PRIORITY AREAS FOR TIGER CONSERVATION				
		PROTECTED AREAS	BUFFER ZONES	FOREST CORRIDORS	HIGH TIGER DENSITY AREAS	ALL PRIORITY AREAS[1]
Linear infrastructure feature	East-West Railway	4.5	106.3	83.0	21.6	215.4
	Mahendra Highway	58.2	119.6	93.0	48.3	319.1
	Postal Highway	67.3	100.1	64.5	37.7	269.5
	All features	130.0	326.0	240.5	107.6	804.1

[1] Length for all priority areas combined is less than sum of lengths for individual priority areas because areas overlap in some locations (e.g., protected areas and high tiger density areas)

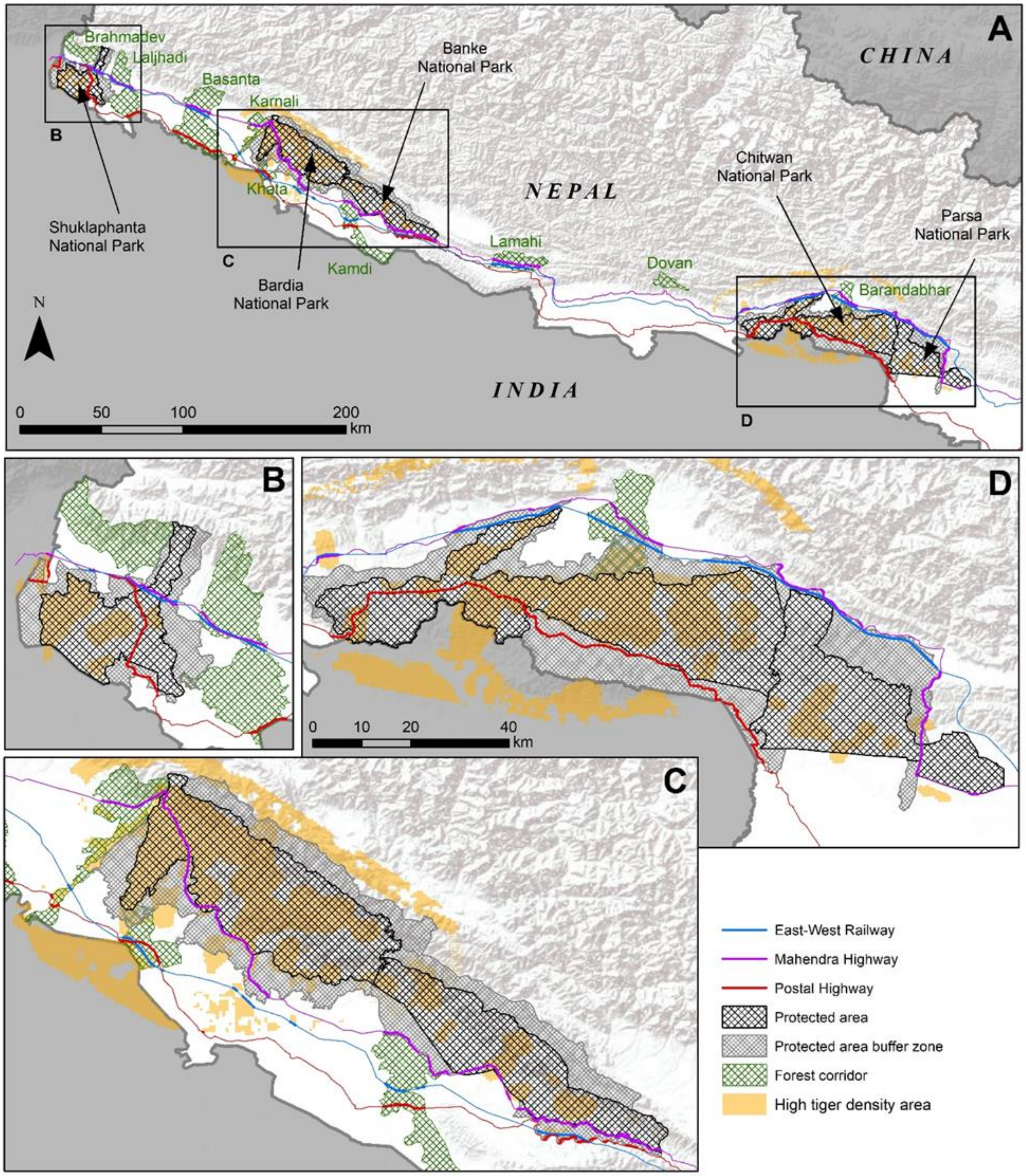

Figure 12: Intersection between proposed LI routes and priority areas for tiger conservation. Sections of LI routes that intersect areas of conservation significance are shown with thicker line width. (A) Full study area including all protected areas, buffer zones, forest corridors, and high tiger density areas; (B) area around Shuklaphanta National Park; (C) area around Banke-Bardia complex; and (D) area around Chitwan-Parsa complex.

DISCUSSION

Our analysis suggests that road and rail construction or upgrades could pose threats to Nepal's tiger sub-populations and the transboundary metapopulation in the TAL. Impacts within PAs may be relatively minor, but LI development in buffer zones and forested corridors is expected to be substantial. These less protected areas serve as crucial habitat links among subpopulations, and metapopulation connectivity could decline if they are severed by construction of new LI routes or by upgrades to existing LI routes that lead to increased traffic volume and a stronger barrier effect for tigers. Loss of connectivity in other parts of the tiger range has contributed to reduced genetic diversity and increased extinction risk, and insufficiently mitigated LI development in the TAL could lead to similar outcomes, reversing the tiger conservation successes that have been achieved there in recent decades (Carter et al., 2020; DNPWC, 2016).

Cumulative impacts are also a concern in Nepal, where human populations are expanding and so are LI projects to improve local economies (ADB, 2018b; NEFEJ, 2020). Several of the forested corridors that would be bisected by new or upgraded LI have already been fragmented by human development. The growth of settlements in and around the Basanta and Laljhadi corridors between Shuklaphanta National Park and Bardia National Park has eroded their connectivity value for tigers (Chanchani et al., 2014; Thapa et al., 2017), and the proposed Mahendra Highway and East-West Railway routes through these corridors could render them completely non-functional for tiger movement unless well mitigated. Nepal will need to consider cumulative impacts of multiple LI projects and human development when planning mitigation measures, using an integrated approach rather than treating projects as singular and isolated. An example of overlapping infrastructure-development pressures is in eastern Parsa National Park, where the Mahendra Highway, East-West Railway, India-Nepal oil pipeline, a high-voltage power line, and a new airport (Simara) are currently proposed or constructed. These projects will effectively sever regional-scale landscape connectivity for key wildlife populations in the eastern TAL.

We considered only locations of direct intersection between proposed LI routes and tiger conservation priority areas, but the impacts of roads and rails can expand well beyond their physical footprints. Improved access provided by new and upgraded LI routes may increase human settlement, natural resource use, poaching pressure, and development of additional roads along these routes. We also limited our analyses to LI developments on the Nepalese side of the TAL, but development on the Indian side poses a significant threat as well (Biswas et al., 2020). For instance, the Sashastra Sema Bal Road being constructed by India will follow the Indo-Nepal border for 558 km and bisect several corridors linking protected areas on either side.

A fourth major LI project in Nepal, the Kathmandu-Terai Fast Track, was excluded from our analysis because it will not intersect any of the tiger conservation priority areas that we considered, but it has the potential to impact tiger and elephant populations. This 74-km highway will run in a north-south orientation near the eastern border of Parsa National Park and could restrict movement between the Chitwan-Parsa complex and habitats further east in the TAL. Track opening, or initial construction, has occurred along approximately 40 percent of the Fast Track route, but none of the route has been paved yet.

Nepal's Strategy and Action Plan 2015-2025 for the TAL calls for avoiding new LI in PAs and corridors; ensuring conservation-friendly design and operation of any LI within PAs, buffer zones, and corridors; and ensuring that environmental analyses are of high quality and identify mitigation measures. Some of these actions are already being taken. For instance, a portion of the proposed East-West Railway was rerouted north of the Chitwan-Parsa complex to bypass PAs and avoid impacts to areas with high tiger density. The realigned railway, however, also presents a threat to tigers because it now bisects the Barandabhar forested corridor, which provides an important link between lowland habitat in the Chitwan-Parsa complex and higher-elevation habitat in the foothills of the Mahabharat Range to the north (Aryal et al., 2012). Thus, while avoiding PAs is commendable, appropriate mitigation planning will need to be coordinated among road and railway projects to minimize cumulative impacts and ensure that tiger corridors remain functional.

Nepal has recently begun incorporating wildlife crossing structures in highway projects and developing a best practices manual for wildlife-friendly LI, including irrigation canals and power lines as well as transportation infrastructure (Ministry of Forest and Environment, in preparation). Nepal's first wildlife underpasses were built within the Barandabhar habitat linkage on the Narayanghat-Muglin Highway to facilitate north-south movements of tigers from Chitwan National Park. Camera trapping studies have documented 15 mammal species (primarily wild boar and common leopard) and four bird species using the crossings (Poudel et al., 2020; WWF, 2019). Tigers and ungulates (sambar, barking deer) have been found using the underpasses outside the sampling period of these studies.

New Asian Development Bank (ADB) guidelines require environmental safeguards, including wildlife crossing structures, on all Category A projects, which include the Mahendra Highway and East-West Railway. These two LI features will run parallel and in close proximity along the northern border of the Chitwan-Parsa complex. The 115-km Narayanghat-Butwal section of the Mahendra Highway is currently being upgraded from two to four lanes and has a mitigation strategy consisting of 112 wildlife underpasses and two 50-m-wide wildlife overpasses (Karki, 2020). Continuing east of Narayanghat and connecting Hetauda and Pathlaiya (a 108-km section), the ADB-financed upgrade will have a similar wildlife crossing strategy implemented in 2022 (Clevenger et al., 2020). This new safeguard strategy reflects a joint commitment by the Nepalese government and ADB to develop a more comprehensive approach to preserving biodiversity. Wildlife crossing structures are also being planned for the East-West Railway where it will run adjacent to the Chitwan-Parsa complex (Karma Yanzom, ADB Manila, Philippines, personal communication) and for the Mahendra Highway in Bardia and Banke National Parks.

Nepal's PAs are critical for conservation of tigers and other wildlife because they support source populations that can disperse and repopulate larger within-country and transborder landscapes (Carter et al., 2020). However, Nepal is currently marching toward massive LI developments, and striking a fine balance between its development models and conservation commitment is a challenge. Rigorous monitoring of wildlife crossings in Nepal will provide important information on species use and help us understand specific designs that facilitate movement by tigers and other species impacted by LI projects. Understanding tiger movement and source and sink areas at local and regional scales will be needed to properly plan safeguards for ongoing and future LI developments. Transboundary coordination between India and Nepal will be needed to ensure habitat and genetic connectivity and long-term sustainability of tigers in this globally important landscape.

CONTRIBUTIONS

WWF-Nepal provided spatial data and contributed to the development of this report. Tyler Creech (CLLC) conducted spatial analyses and drafted the report. Rob Ament (CLLC/WTI), Tony Clevenger (WTI), and Grace Stonecipher (CLLC) also contributed to the report.

ANALYSIS 3: MITIGATING IMPACTS TO WILDLIFE DURING THE EXPANSION OF NATIONAL HIGHWAY 37 IN ASSAM, INDIA

National Highway 37 (NH-37) connects northeastern Assam to the rest of India, providing passage for an average of 5,500 vehicles per day (Menon et al., 2017). For 60 km, NH-37 stretches along the southern border of Kaziranga National Park, one of India's most biodiverse and important PAs. Kaziranga National Park provides habitat for Bengal tigers, Asian elephants, and two-thirds of the world's one-horned rhinoceroses, as well as a diverse array of smaller mammals, reptiles, amphibians, and birds. Kaziranga National Park is bordered to the north by the Brahmaputra River, which floods the park every monsoon season (June–September). As the rains begin, many animals are forced to cross NH-37 to access the higher elevation hills in the Karbi-Anglong district to the south, becoming vulnerable to collisions with vehicles. Several wildlife corridors connect these two areas, including four elephant corridors (Menon et al., 2017) and at least one used by felid species such as tigers, leopards, and Asiatic golden cats (Lalthanpuia et al., 2014). Many of these corridors are situated between the tea plantations, villages, paddy fields, and teak plantations that also border NH-37, leaving only narrow strips of natural forest for animals to use as corridors (Das et al., 2007); in some cases, cultivated areas make up part of the corridor (Menon et al., 2017). Roadkill data from NH-37 along Kaziranga National Park has not been systematically collected until recently, but anecdotal reports indicate more than 200 animals are killed annually, and perhaps many more. Some mitigation measures have been put in place to prevent wildlife mortalities, including signage, striping, and rumble strips to slow vehicles down near elephant corridors.

Creating additional pressure on wildlife is the planned expansion of the Kaziranga National Park section of NH-37 from two to four lanes, proposed by the National Highway Authority of India (NHAI) under the Special Accelerated Road Development Programme for North-East. This portion of NH-37, also called Asian Highway 1, is part of the international Asian Highway Network, a coordinated effort to develop 140,000 km of highways across the continent. While the development of this network will facilitate the movement of freight and people, this upgrade to NH-37 has the potential to affect wildlife adversely in three ways. First, a larger road will likely lead to increased traffic volume and speed as drivers travel from eastern Assam to the rest of India, increasing the likelihood of wildlife-vehicle collisions. Second, higher traffic volumes may prevent certain species from attempting to cross the road, trapping them in less suitable or perhaps even inhospitable habitat, especially during the monsoon season. Finally, the increased road width may render some of the current mitigation measures, such as the at-grade crossings at key elephant corridors, less effective.

As the road is expanded, there is an opportunity to introduce additional mitigation measures to lessen the impact to wildlife. For these measures to be effective, however, pre-construction data on both wildlife-vehicle collision hotspots and current wildlife crossing locations is required to understand what type of mitigation to implement and where. Fortunately, data were collected on both wildlife roadkills and live crossings along the Kaziranga National Park section of NH-37 from 2018 to 2020 by Aaranyak, a wildlife NGO based in Guwahati, Assam. This work was funded by the U.S Fish and Wildlife Service and conducted in partnership with WTI. Here, we use these data to conduct a spatial hotspot analysis of roadkill and live crossings to understand the potential impacts of widening NH-37 on wildlife near Kaziranga National Park.

METHODS

Data on the occurrence of wildlife roadkills and live crossings were collected by driving the Kaziranga National Park section of NH-37 approximately every two to four days between November 2018 and March 2020. Surveys consisted of an individual on a motorbike driving the length of Kaziranga National Park in both directions collecting data using a mobile device application called ROaDS ([Roadkill Observation and Data Systems], Ament et al., 2021), which allows the user to record the species, number of animals, status (dead, alive crossing road, alive near road), relative confidence in the species identified, a geo-synched photograph, and other information, all attached to a precise global positioning system (GPS) location, date, and time.

We separated each ROaDS entry into individual animal observations, and then classified every observation within three main categories: (1) monsoon (June–September) vs. dry season (October–May), (2) taxonomic type (meso-carnivore, herptile, primate, bird, ungulate, other mammal), and (3) observation status (dead, live near road, live crossing road). We then conducted a series of optimized hotspot analyses to identify statistically significant spatial clusters of observations ("hotspots") along a 60-km section of NH-37 for observations belonging to each of the above sub-categories. We also looked for hotspots for observations belonging to multiple categories (e.g., live crossing ungulates). Finally, we overlaid elephant corridors mapped by the Wildlife Trust of India (Menon et al., 2017) on the live crossing or near road hotspot maps to examine if the elephant corridor locations aligned with observed ROaDS hotspots.

RESULTS

Aaranyak personnel collected wildlife data along the Kaziranga National Park section of NH-37 an average of 10 days per month from November 2018 through March 2020, for a total of 162 study days, of which 41 days were during monsoon and 121 were in the dry season. A total of 1,423 individual animals were observed during the 17-month period from November 2018 to March 2020, representing 75 species. Of these, 582 animals were dead, 685 were near the road, and 156 were actively crossing the road (Table 11). Ungulates (708 individuals) were observed most often, including 157 Asian elephants and 79 one-horned rhinoceroses. Herptiles were the next most common (303 individuals) and represented the greatest diversity with 15 species observed. No large carnivores, such as the Bengal tiger, were observed during the entire study period. The highest monthly total of animals (179) was observed in October 2019 over 13 study days; the largest daily average (17) occurred in November 2018, with 34 observations over 2 study days. The greatest number of dead animals was recorded during the summer and fall of 2019, from July through November, ranging from 6.4 to 8 animals on average per study day. The most observations of animals crossing the road occurred in November 2018, and the greatest number of animals near the road was seen in winter of 2018-2019, with an average between 5.3 and 9.7 animals per study day.

Table 11: The number of animals observed in each taxonomic category

TABLE 11: THE NUMBER OF ANIMALS OBSERVED IN EACH TAXONOMIC CATEGORY BY STATUS (DEAD, ALIVE CROSSING ROAD, ALIVE NEAR ROAD) ALONG A 60-KM SECTION OF NH-37 BORDERING KAZIRANGA NATIONAL PARK FROM NOVEMBER 2018 THROUGH MARCH 2020

	DEAD	ALIVE CROSSING ROAD	ALIVE NEAR ROAD	TOTAL
Herptile	330	0	0	330
Bird	195	1	0	196
Meso-carnivore	27	0	37	64
Primate	3	40	57	100
Ungulate	2	115	591	708
Other Mammal	25	0	0	25
Total	582	156	685	1423

Animal status was often related directly to species group; 100 percent of the herptiles observed were dead, as were 99 percent of the birds and animals classified as other mammals. Dead primates, however, were rarely observed, with 97 percent either alive crossing the road or near the road. Similarly, 83 percent of ungulates were observed alive near the road, 16 percent alive crossing the road, and only one percent were dead. Meso-carnivores were split, with 42 percent dead and 58 percent alive near the road. No primates were observed during the monsoon, while herptiles were disproportionately observed during the monsoon, with 3.5 herptiles observed on average per monsoon study day as compared to 1.5 per non-monsoon study day. In general, more dead animals were observed during the monsoon—5.3 on average per monsoon study day as opposed to 3, while more live animals (crossing or near the road) were observed outside of the monsoon—5.6 animals per non-monsoon study day versus 3.9.

The optimized hotspot analysis revealed spatial patterns regarding wildlife status along NH-37. Across all observations, the greatest number of animals was recorded along a stretch of NH-37 around the western end of Kaziranga National Park, encompassing both the Kanchanjuri and Deochur elephant corridors. Hotspots of live animals both near and crossing the road also aligned with these corridors and the area between them, with an additional live crossing hotspot to the east of the Panbari corridor near eastern Kaziranga National Park. Mortality hotspots were in different locations: there was high mortality along a 4-km stretch to the east of the Kanchanjuri corridor, and another stretch between the Haldibari and Panbari corridors (Figure 13). Hotspots also changed seasonally for wildlife mortality; while the west end of Kaziranga National Park was a high-mortality area throughout the year, more dead animals were observed just east of the Haldibari corridor during the monsoon, and just west of the Panbari corridor during the non-monsoon months.

Species groups also exhibited different spatial and temporal patterns of road crossing and/or mortality (Figure 14). Smaller animals, including birds and herptiles, were observed (almost always dead) in similar locations, but in different seasons. Both were observed just east of the Kanchanjuri corridor year-round, along with meso-carnivores. Herptiles were found west of the Panbari corridor outside of the monsoon, and birds in the same location during the monsoon. Herptiles were also observed on both sides of the Haldibari corridor during the monsoon. Ungulates were observed alive either crossing or near the road along the Kanchanjuri and Deochur corridors, while live primates were observed further west. Ungulates crossed the road most often near the Kanchanjuri and Haldibari corridors outside of the monsoon season, and near the Deochur and Panbari corridors during the monsoon months. There were not enough observations of meso-carnivores or other mammals to separate them seasonally.

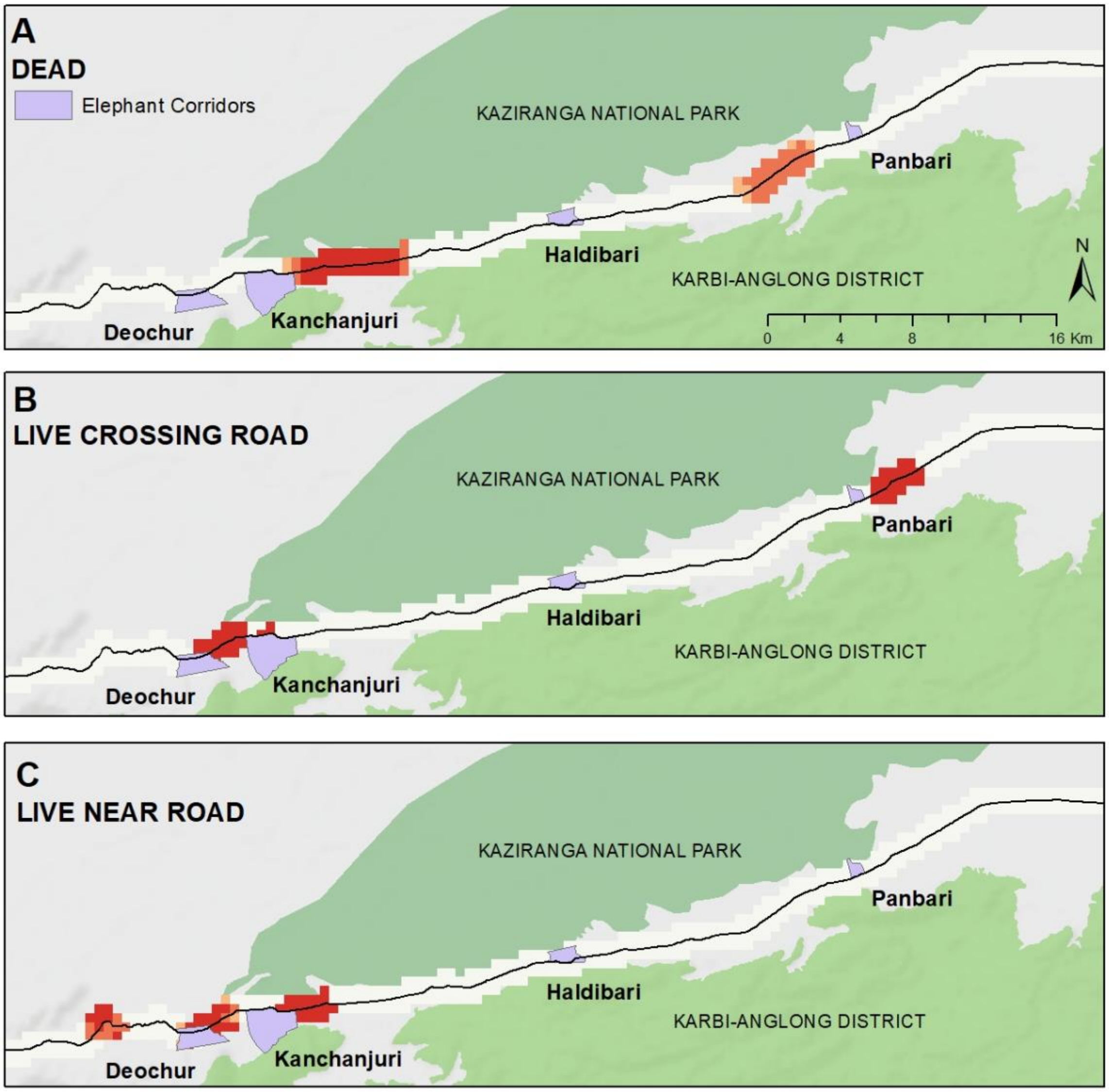

Figure 13: The results of four optimized hotspot analyses where darker red indicates a greater density of observations and white indicates areas that were not statistically significant hotspots. A) Hotspots of dead animals. B) Hotspots of live animals crossing the road. C) Hotspots of live animals near the road. Purple polygons are elephant corridors identified by Menon et al. (2017).

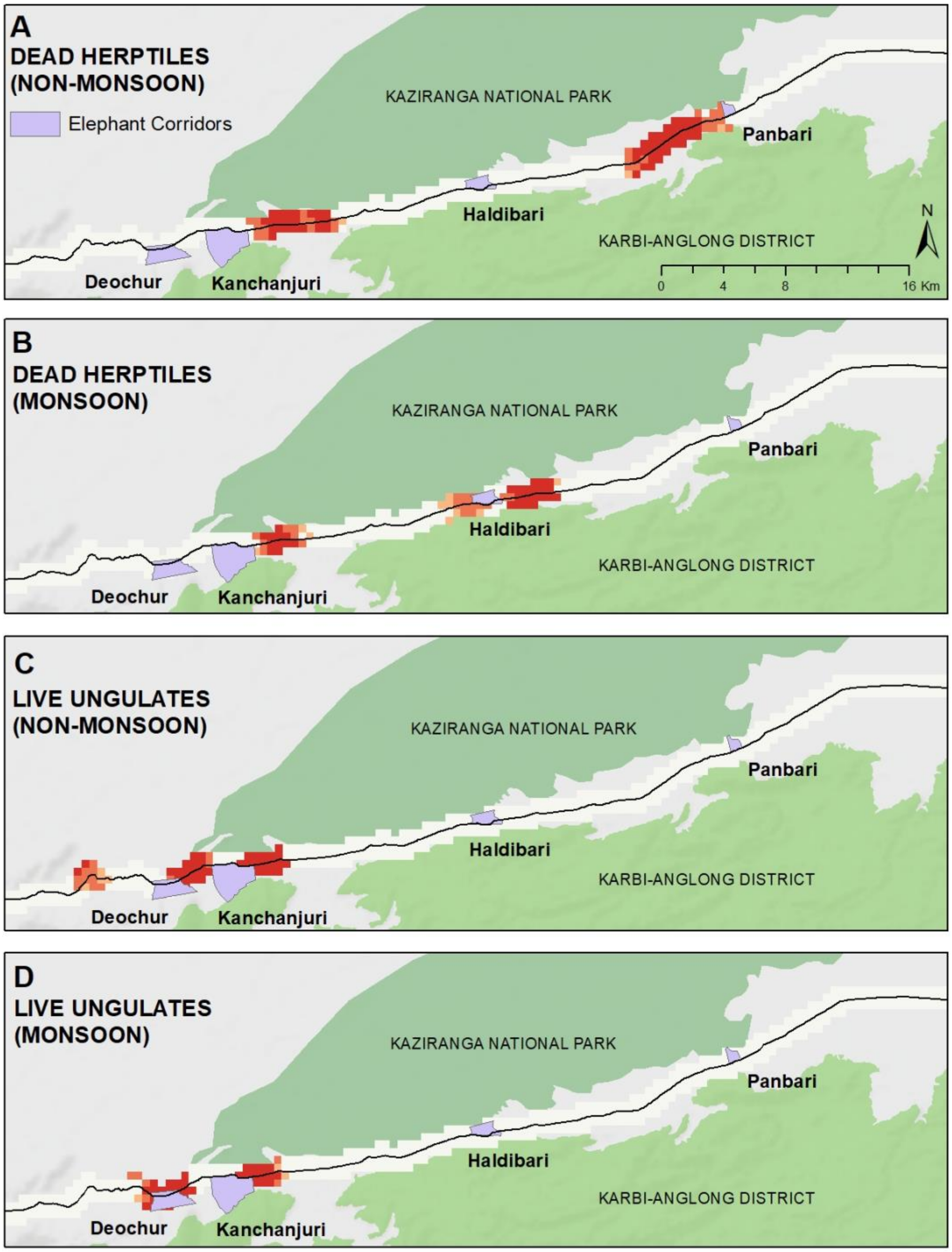

Figure 14: The results of four optimized hotspot analyses where darker red indicates a greater density of observations and white indicates areas that were not statistically significant hotspots. A) Hotspots of dead herptiles outside of the monsoon. B) Hotspots of dead herptiles during the monsoon. C) Hotspots of live ungulates (near or crossing road) outside of the monsoon. D) Hotspots of live ungulates (near or crossing road) during the monsoon. Purple polygons are elephant corridors identified by Menon et al. (2017).

DISCUSSION

Since the original proposal to widen the existing footprint of the road, it has been reported that a series of three flyovers, or elevated sections of highway, will be constructed (Parashar, 2019). These flyovers will stretch 18, 11, and 6 km, coming back down to ground level at each of the Kaziranga National Park entrance villages. Collectively, these flyovers will account for more than half of our 60-km study area. The flyover highway means that vehicles will be able to travel more quickly through the Kaziranga National Park section of NH-37 with few concerns regarding collisions with wildlife. Flyovers (along with tunnels) are some of the most effective and optimal wildlife crossing designs given that they leave habitat intact below them (Clevenger & Huijser, 2011). However, it has been reported that vehicles, primarily local community traffic and vehicles accessing Kaziranga National Park entrances, will continue to use the current two-lane footprint of NH 37, meaning that additional mitigation measures may be needed to reduce wildlife mortality and promote habitat connectivity.

Our analysis shows that wildlife mortality is already a significant problem along NH-37 near Kaziranga National Park and suggests that expanding the road to four lanes likely would have resulted in more wildlife death as successful crossing areas were made more dangerous. Collecting data on both wildlife mortality and living animals near, and crossing, the road provides crucial information for planners as various mitigation options are considered in the context of road expansion. The mortality data indicate problem locations on the existing road, which would likely have worsened with more lanes and their associated traffic. A four-lane highway with increased traffic volume also would have the potential to increase the barrier effect, reducing or stopping wildlife movement across the highway. Thus, identifying locations where animals successfully cross the road is equally important, as these locations must also be considered when planning the location of mitigation measures (Zeller et al., 2020). While the newly planned flyover will help facilitate continued safe crossing for some species, our analysis can help planners identify additional mitigation needs for mortality hotspots on the current road footprint. The analysis shows that while wildlife observations were generally clustered around the western end of Kaziranga National Park, mortality hotspots were located further east than the successful crossing hotspots, indicating that those sections of the road may require different types of mitigation.

Analysis of the data also shows that time of year, location, and species category may be important drivers for how animals interact with the road. Currently, it appears that only smaller species (herptiles, birds, other mammals) are being killed, while larger animals that are more visible to motorists may be crossing more successfully. However, due to the small size of these species, it is likely that herptiles or birds near the road were not spotted as readily during data collection, meaning that living animals in these categories are under-represented in the dataset. Nevertheless, given that small and medium-sized terrestrial vertebrates made up over 95 percent of all observed mortalities in this study, the needs of these species will have to be part of the mitigation scheme. While the flyover, as opposed to road widening, may prevent additional mortalities for larger species, small wildlife passages, culverts, and arboreal crossing for canopy-dwelling species are also needed to reduce the current levels of mortality. Design for mitigation measures, such as underpasses or culverts, also should account for the monsoon and associated flooding, especially given the higher proportion of herptiles, and dead animals overall, observed during the monsoon. Overall, the monsoon showed less of an effect than expected; while there were proportionally more dead animals observed during the monsoon, this effect was largely limited to birds and herptiles. Other species—ungulates, primates, and meso-carnivores—were spotted more often during the rest of the year.

The hotspot analysis also reveals that the elephant corridors identified by Menon et al. (2017), especially the Deochur and Kanchanjuri corridors, are being used by other ungulate species for successful crossing. This indicates that existing mitigation measures, such as rumble strips that force vehicles to slow down, are working as intended. Even with the planned flyovers, it remains important to revisit these areas to ensure that the most appropriate mitigation measures are designed and implemented at these critical habitat linkages, especially for focal species such as Asian elephants and one-horned rhinoceroses. The high use of these corridors also shows the importance of protecting these areas from the pressures of additional human development over the long term. Further research on the land use surrounding NH-37 could also be helpful for identifying additional potential crossing areas by relating landcover to wildlife observation hotspots.

CONTRIBUTIONS

Bibhuti Lahkar, Jyoti Das, and Arup Kumar Das (Aaranyak) collected and provided data on wildlife observations along NH-37 and contributed to the preparation of this report. Animekh Hazarika, Ankur Nahok, and Jyotish Ranjan Deka (Aaranyak) also assisted with data collection and preparation. Upasana Ganguly (Wildlife Trust of India) provided spatial data on elephant corridors. Grace Stonecipher (CLLC) conducted spatial analyses and drafted the report. Tyler Creech (CLLC), Rob Ament (CLLC/WTI), and Tony Clevenger (WTI) also contributed to the report.

ANALYSIS 4: POTENTIAL IMPACTS OF THE CENTER-WEST ROAD ON KAZAKHSTAN'S BETPAK-DALA SAIGA ANTELOPE POPULATION

The saiga antelope is a nomadic herding species that occupies the semiarid deserts and steppe grasslands of Central Asia. It is categorized as Critically Endangered by the IUCN and has experienced dramatic population declines since the late 1990s due to severe poaching pressure, climatic variability, and disease (Milner-Gulland et al., 2001). Saiga migrate seasonally between northern summer ranges and southern winter ranges in response to forage availability and snow depth, and these seasonal ranges may be separated by up to 1,200 km. Local migrations within seasonal ranges are also common and allow saiga to find better forage or watering places and avoid fires, floods, and extreme weather conditions (Bekenov et al., 1998).

Kazakhstan contains more than 97 percent of the world's saiga, including central Kazakhstan's Betpak-Dala population, historically the largest. In 2015, a disease outbreak killed over 200,000 individuals (88 percent of this region's herds), but since then a rapid recovery has occurred and the population now numbers approximately 285,000 individuals (Altyn Dala Conservation Initiative, 2021). However, LI development within the range of the Betpak-Dala population now threatens to halt or reverse its recovery. The Government of Kazakhstan plans to construct a 2,000-km paved road between the cities of Nur-Sultan and Aktau, known as the Center-West Road, as part of its US $9 billion Nurly Zhol economic stimulus plan to develop and modernize roads, railways, and other infrastructure. A significant portion of the proposed route of the Center-West Road exists as dirt roads, and paving has occurred or is underway in some sections. Of particular concern for saiga conservation is a 612-km stretch between Nur-Sultan and Irgiz that bisects the range of the Betpak-Dala population. Much of this stretch consists of natural steppe with no existing roads along the proposed route, although dirt or paved roads do exist in places.

Construction of the paved Center-West Road between Nur-Sultan and Irgiz would likely harm saiga in several ways. Foremost, a paved road would act as a barrier to saiga movement among seasonal ranges. Previous telemetry studies and anecdotal evidence indicate that saiga are highly sensitive to LI and other human disturbances and will avoid crossing roads and railways that have high traffic volume (Association for the Conservation of Biodiversity of Kazakhstan, 2021, unpublished data). The barrier effect of a paved road could limit or eliminate access to a significant portion of the population's summer range north of the road, which could result in insufficient availability of forage and other resources, increased risk of disease due to concentration of animals in a smaller area, and decreased mating opportunities (Wingard et al., 2014b). Increased human access facilitated by the Center-West Road could also make saiga more vulnerable to poaching. Finally, road improvement would increase traffic volume, which could increase the rate at which saiga are killed in collisions with vehicles while attempting road crossings.

Here, we present a spatial analysis that uses saiga location data to illustrate how and where the Center-West Road project could harm the Betpak-Dala population.

METHODS

We used telemetry data from GPS-collared saiga to explore how movement and space use patterns are shaped by the presence and surface type of existing roads along the proposed route of the Center-West Road, and to infer how additional road construction and improvement could affect these patterns. We obtained spatial data on the proposed route and existing surface type (paved road, dirt road, or no road) of the Center-West Road from planning documents produced by the Ministry of Industry and Infrastructure Development of Kazakhstan. We obtained telemetry data for 81 saiga individuals outfitted with GPS collars between 2009 and 2017 as part of a research study conducted in the framework of the Altyn Dala Conservation Initiative (ADCI). Individuals were collared from two groups, Tengiz and Torgai, that occupy different subranges within the broader range of the Betpak-Dala population. Each group currently occupies habitat both north and south of the Center-West Road during different seasons. Individuals were tracked for up to 2.5 years, at which point collars dropped off the animals.

We examined the impact of road paving in two ways. First, we used dynamic Brownian bridge movement models (Horne et al., 2007; Kranstauber et al., 2012) to map the home range of each collared individual. These models estimate the probability of use by saiga across the landscape based on recorded GPS locations of individuals and the elapsed time between consecutive locations. We calculated home ranges as the 99 percent (Tengiz group) or 99.5 percent (Torgai group) utilization distribution for each individual, then combined these distributions across all individuals within each group into a single cumulative home range reflecting overall space use of the group. We then overlaid the proposed route of the Center-West Road on the home range of each group and determined the length of each surface type (paved road, dirt road, or no road) along the route that intersected the home range.

Second, we examined the observed movement paths of 43 collared individuals that crossed the proposed route of the Center-West Road at least once during the study period. We determined how many times each individual crossed the route during the study period and the existing surface type (paved road, dirt road, or no road) of each crossing location. Crossing locations were inferred by assuming a straight-line movement path between consecutive GPS collar locations on opposite sides of the proposed route. We combined these crossing statistics across all individuals to summarize population-level route crossing behavior.

RESULTS

The home ranges of the Tengiz and Torgai group both include areas on either side of the Center-West Road proposed route. Approximately 19 percent of the Tengiz home range and 26 percent of the Torgai home range lies to the north of the route and could potentially be cut off from the larger home range areas south of the route once construction is completed (Figure 15).

Home range maps suggest that space use around and movement across the proposed route are highly constrained by existing roads (

Table 12). The home range of the Tengiz group overlaps 53 km of the route, all of which currently lacks a road. The Torgai group's home range overlaps 125 km of the route, all but 4.8 km of which is dirt road or lacks a road. Home ranges of both groups exclude nearly all areas within approximately 5 km of already paved portions of the route (Figure 15).

Thirty collared saiga from the Tengiz group and 13 from the Torgai group crossed the proposed route of the Center-West Road during the study period. Individuals crossed the route an average of 5.8 times each during the study period, with some individuals crossing as many as 20 times. Collectively, the collared saiga made 249 movements across the proposed route, of which only 2 percent occurred along sections with paved road (

Table 13). Because far more than 2 percent of the proposed route is paved in the general area occupied by the Torgai and Tengiz populations (Figure 15), this suggests that saiga exhibit a strong pattern of avoidance of paved road sections; instead, saiga prefer crossing the proposed route in areas where there is a dirt road or where no road exists yet.

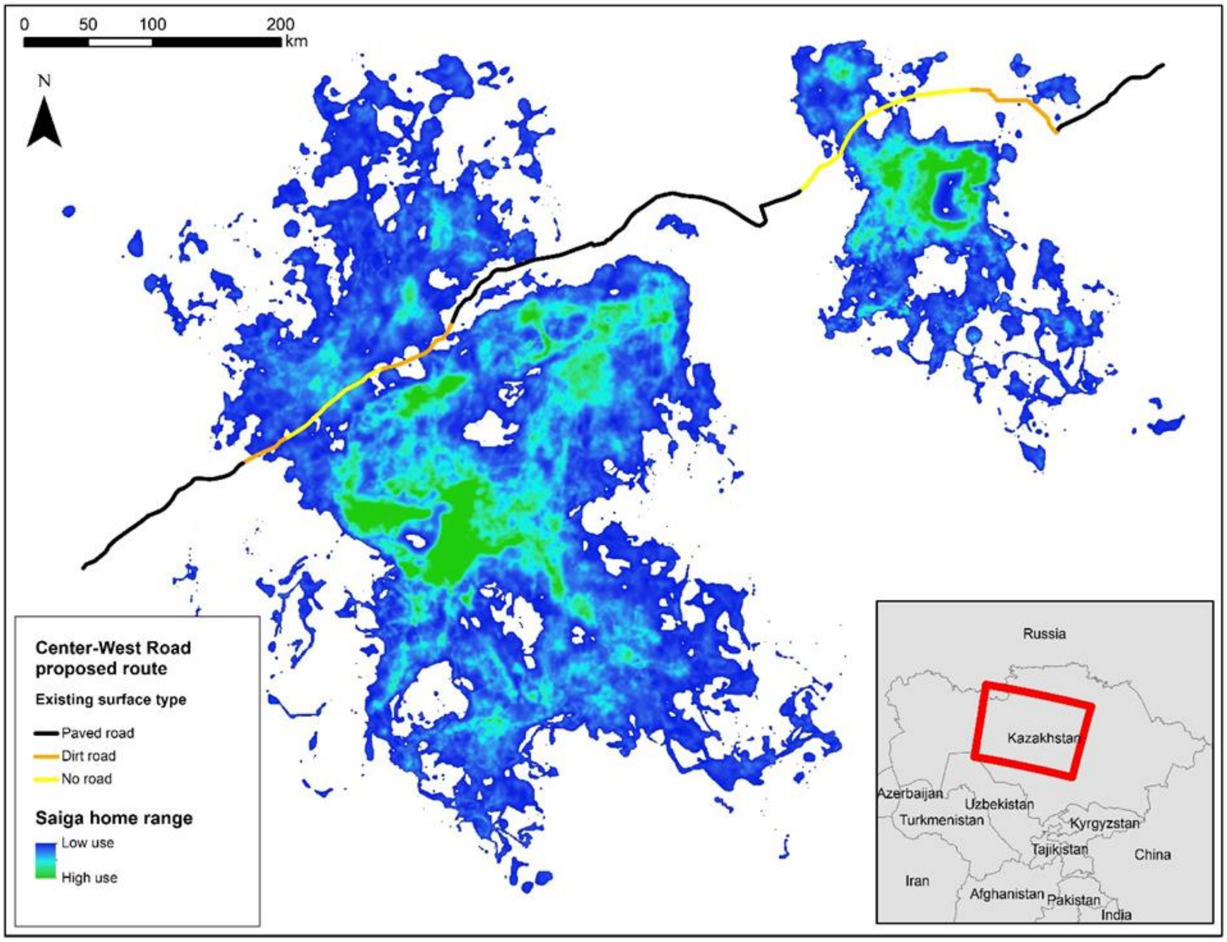

Figure 15: Home ranges of the Torgai group (center left) and Tengiz group (upper right) of the Betpak-Dala saiga antelope population in central Kazakhstan. The proposed route of the Center-West Road bisects the home range of both groups.

Table 12: Overlap of home ranges of the Tengiz and Torgai groups of the Betpak-Dala saiga population with the Center-West Road proposed route

TABLE 12: OVERLAP OF HOME RANGES OF THE TENGIZ AND TORGAI GROUPS OF THE BETPAK-DALA SAIGA POPULATION WITH THE CENTER-WEST ROAD PROPOSED ROUTE

	LENGTH OF OVERLAP WITH HOME RANGE (KM)	
EXISTING SURFACE TYPE	TENGIZ GROUP	TORGAI GROUP
No road	53.6	75.4
Dirt road	0	44.4

Paved road	0	4.8

Table 13: Number of observed crossings of the Center-West Road proposed route by 43 collared saiga antelope from the Betpak-Dala population during the study period

TABLE 13: NUMBER OF OBSERVED CROSSINGS OF THE CENTER-WEST ROAD PROPOSED ROUTE BY 43 COLLARED SAIGA ANTELOPE FROM THE BETPAK-DALA POPULATION DURING THE STUDY PERIOD		
EXISTING SURFACE TYPE	NUMBER OF CROSSINGS	PERCENTAGE OF CROSSINGS
No road	203	81
Dirt road	40	16
Paved road	6	2

DISCUSSION

Results of our spatial analysis provide strong evidence that movement and space use of the Betpak-Dala saiga population is limited by paved roads. The home ranges of the Tengiz and Torgai groups span large sections of the Center-West Road proposed route but almost entirely avoid paved road sections and the areas immediately surrounding them. Movement data indicate that saiga are regularly crossing the Center-West Road proposed route during seasonal migrations, but these crossings occur nearly exclusively in areas with dirt roads or no roads. Thus, complete paving of the Center-West Road proposed route is likely to reduce habitat quality along the road, and more significantly, prevent saiga movement across the road to access important seasonal habitats.

It is reasonable to expect that complete paving would subdivide the home ranges of both groups into northern and southern fragments with limited movement between them. The extent to which movement does occur across paved roads may depend on vehicle traffic volume. If traffic volume is high enough that the road acts as a total barrier, then a significant portion of the saiga home range will become inaccessible, and saiga will experience higher population density and poorer forage quality during the summer and will be unable to move away from harsh weather conditions in the winter. If traffic volume is lower and presents only a partial barrier to movement, saiga will still likely be hesitant to cross and may therefore be delayed in reaching their summer range and the higher-quality forage available there. Over the long term, the reduction in resources available to saiga due to the Center-West Road project could result in declines in genetic diversity and population size. These road effects are also likely to interact with or compound the effects of other threats to saiga, including poaching, infectious disease, climate change, and extreme weather (IUCN, 2018).

The biological impacts of paving the Center-West Road would not be limited to saiga. Unpaved road sections of the proposed route intersect natural, untouched steppe within the “Turgaiskiy state nature zakaznik” (sanctuary), which is a PA, a Ramsar site since 1976, and a Key Biodiversity Area. The route also passes between clusters of the Yrgyz-Torgai-Zhylanshyk ecological corridor, the Irgiz-Turgai state nature reserve, and the Altyn Dala state nature reserve, all of which were established to protect the migration, calving, and summer pastures of the saiga antelope, requiring good connectivity between them. Building a paved road in these sections could affect other species of conservation concern. The wetlands in the area provide a molting place for many rare bird species and a breeding ground for 25,000 pairs of waterbirds, including the Dalmatian Pelican and White-headed Duck.

Kazakhstan's Ministry of Industry and Infrastructure Development has proposed to mitigate the impacts of the Center-West Road on saiga and other wildlife by installing a series of crossing structures (e.g., overpasses and underpasses) to facilitate safe wildlife passage across the paved road. However, biologists believe that saiga are unlikely to utilize these structures and will avoid the road entirely once it is paved and experiences a high volume of vehicle traffic. It is also unclear where the crossing structures should ideally be located to maximize opportunities for saiga crossings because the migratory paths used by saiga vary considerably among individuals and years.

The mitigation challenges outlined above suggest that rerouting the Center-West Road to avoid bisecting the range of the Betpak-Dala population may be the best option for avoiding serious impacts to saiga. The ADCI has identified an alternative route that was considered by government planners during the initial feasibility study; it would minimize impacts to saiga by bypassing the saiga range while adding only 50 km to the total route length. This alternative route could lower overall construction costs because it would follow existing, already improved roads. It would also provide economic benefits by linking small human settlements with larger communities in the region.

CONTRIBUTIONS

Data on saiga movements were collected in the ADCI framework in Kazakhstan. Steffen Zuther and Albert Salemgareyev were responsible for data collection, processing, and analysis. Stephanie Ward reviewed the report on behalf of the ADCI, which is primarily implemented by the Association for the Conservation of Biodiversity of Kazakhstan and financially and technically supported by Fauna & Flora International, Frankfurt Zoological Society, and the Royal Society for the Protection of Birds in partnership with the Committee for Forestry and Wildlife of the Ministry of Ecology, Geology and Natural Resources of Kazakhstan. Tyler Creech (CLLC) prepared the report. Rob Ament (CLLC/WTI) and Tony Clevenger (WTI) also contributed to the report.

ANALYSIS 5: THREATS TO IMPORTANT BIRD AREAS FROM FUTURE POWER LINE DEVELOPMENT IN THAILAND

Power lines transport energy from power generating centers (e.g., hydroelectric dams, nuclear plants, and solar farms) to regions of energy consumption such as cities and industrial centers, as well as to substations from which energy is fed into distribution lines serving smaller centers of energy demand. The network of power lines across the landscape can impact the environment in many ways, including loss, degradation, and fragmentation of habitat; acoustic and electromagnetic disturbance; and direct mortality of wildlife via electrocution and collisions (Biasotto & Kindel, 2018; Ferrer & Janns, 1999). Mortality from power lines is a significant problem for many avian species, particularly large bird species that use energized wires as perches (Chevallier et al., 2015). Avian groups commonly killed by electrocution or collision with power lines include bustards, flamingos, cranes, waterfowl, shorebirds, gamebirds, and raptors; power line mortality has been identified as a factor in the population declines of several species from these groups (A. R. Jenkins et al., 2010).

Thailand is home to many of these vulnerable avian groups and has ambitious plans for expanding its national power grid, so the threat to its biodiversity from power line development is high. Thailand is part of the Indo-Burma Biodiversity Hotspot (Myers et al., 2000), one of the most biologically important regions of the globe. It has the 17th highest avian species richness of all countries, with 936 bird species. It also has 67 globally threatened bird species, 12th highest among countries (BLI, 2021). But habitat loss and other threats to species are increasing. Between 1961 and 2009, terrestrial forest cover declined from 53 percent of the country to 32 percent (Convention on Biological Diversity, 2021), a huge loss of habitat for forest-dwelling birds and other wildlife. Additional habitat loss and direct mortality of birds is likely to occur in the near future as a result of power line construction to meet the demand for energy in Thailand, which is predicted to increase by 78 percent between 2017 and 2036 (IRENA, 2017).

Here, we conduct a simple spatial analysis of the potential for proposed power lines to impact areas of exceptional importance for bird species in Thailand.

METHODS

We overlaid routes of proposed power lines in Thailand with Important Bird and Biodiversity Areas (IBAs). IBAs are areas deemed significant for the long-term viability of naturally occurring bird populations based on the presence of globally threatened, restricted-range, and congregatory species. We focused on IBAs rather than the more general KBAs because we were especially interested in impacts to birds, which are highly susceptible to impacts from power lines (see Annex 4). We obtained spatial data on IBAs from BirdLife International (BLI, 2020).

We were unable to obtain spatial data directly from the government for this rapid assessment, so we hand-digitized routes of proposed power lines from a map in the most recent Thailand Power Development Plan (Energy Policy and Planning Office, 2019). Using the information provided in the 2018 plan, we classified each proposed power line as a new construction project (i.e., one that does not follow an existing power line route) or an improvement (i.e., new lines added to an existing route). We also classified each project as currently under construction or a future project yet to be initiated (as of Thailand's plan publication in April 2019).

We characterized the extent of proposed power grid expansion by calculating the total length of proposed power lines by project type (new or improvement) and by project status (under construction or future project). We calculated the length of proposed power lines intersecting IBAs as a measure of potential for harm to bird populations. Because some power transmission routes have multiple, parallel lines, we calculated both the route length and the circuit length, the latter of which accounts for both the route length and number of parallel lines along the route.

RESULTS

Power lines with a total route length of 7,026 km and circuit length of 12,718 km are proposed to be added to the power grid by 2037 under Thailand's Power Development Plan (Table 14, Figure 16). Approximately 65 percent of this projected route length increase would consist of power lines constructed along new routes, while the remaining 35 percent would consist of power lines added along existing routes (i.e., improvements). As of April 2019, 73 percent of the route length and 81 percent of the circuit length of proposed power lines were already under construction.

Proposed power lines would intersect nine IBAs in Thailand: Bu Do-Sungai Padi, Chaloem Pra Kiet, Kaeng Krachan, Khao Banthad, Khao Nor Chuchi, Khao Yai, Lower Central Basin, Thaleban, and Tonpariwat (Figure 16). Approximately 468 km (6.7 percent) of the total route length of proposed power lines would intersect IBAs, and these statistics are higher when circuit length is considered (880 km, 6.9 percent). IBAs that would be intersected by proposed power lines are located mainly in southern peninsular Thailand or in the general vicinity of Bangkok. While some proposed power lines appear to cut directly through IBAs, lines running near the borders of IBAs are more common.

Table 14: Length of proposed power lines in Thailand and within Important Bird and Biodiversity Areas (IBAs)

TABLE 14: LENGTH OF PROPOSED POWER LINES IN THAILAND AND WITHIN IMPORTANT BIRD AND BIODIVERSITY AREAS (IBAS). CIRCUIT LENGTH IS THE ROUTE LENGTH MULTIPLIED BY THE NUMBER OF PARALLEL POWER LINES ALONG THE ROUTE

		ALL POWER LINES	POWER LINES WITHIN IBAS	PERCENT WITHIN IBAS
Route length (km)	New	4,579	315	6.9
	Improvement	2,448	153	6.2
	Future	1,902	53	2.8
	Under construction	5,124	415	8.1
	All categories	7,026	468	6.7
Circuit length (km)	New	9,291	660	7.1
	Improvement	3,427	221	6.4
	Future	2,443	72	2.9
	Under construction	10,275	809	7.9
	All categories	12,718	880	6.9

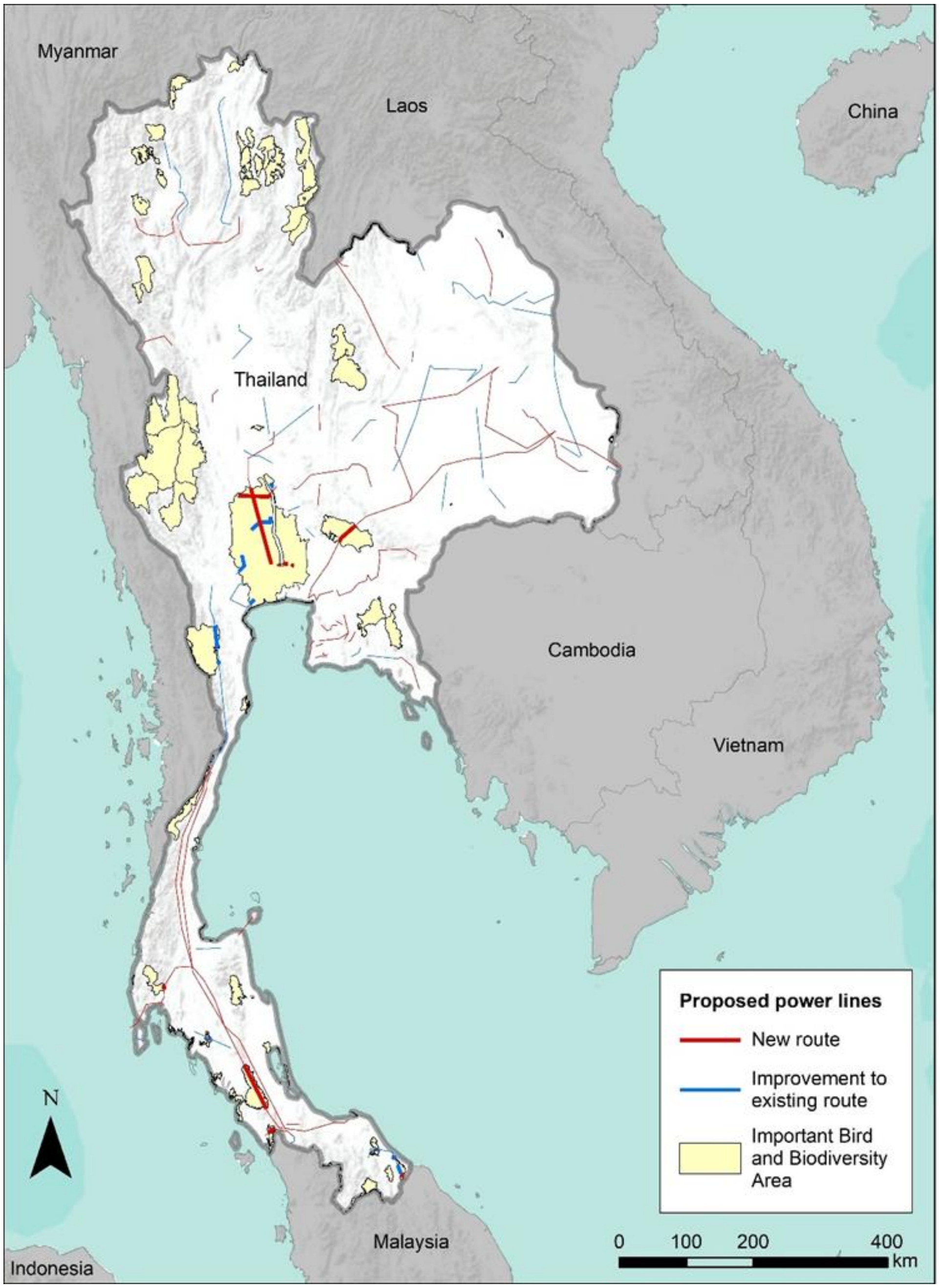

Figure 16: Proposed power lines and Important Bird and Biodiversity Areas (IBAs) in Thailand. Thicker lines indicate sections of proposed power lines that would intersect IBAs.

DISCUSSION

The Thailand Power Plan calls for a substantial expansion of the national power grid, including in areas that are critical for conservation of birds and other taxa. If all proposed power lines are constructed, this would represent a 38 percent increase over the total circuit length of the national grid as of March 2017 (IRENA, 2017). Most of the proposed expansion would involve constructing new routes (along with associated road building, vegetation clearing, earth moving, etc.) rather than improving existing routes, so the potential for disturbance to intact habitat is considerable.

Four IBAs have especially high potential for harm to bird populations because of the extent of proposed power line development in these areas. Khao Yai National Park, approximately 100 km northeast of Bangkok, is the third largest national park in Thailand and remains 80 percent forested. It is part of the Dong Phayayen-khao Yai Forest Complex, a Natural World Heritage Serial Site. Khao Yai is one of only a few known wintering sites for the globally threatened silver oriole and is home to several other bird species that are globally near-threatened or vulnerable, including brown hornbill, great hornbill, oriental darter, spot-billed pelican, pale-capped pigeon, and coral-billed ground-cuckoo (BLI, 2021a; IUCN and UNEP, 2017). Proposed new power lines with a route length of 34 km and circuit length of 68 km would bisect this national park.

Khao Banthad Wildlife Sanctuary in southern peninsular Thailand is an area of limestone hills dominated by evergreen forest. This IBA supports the globally threatened Wallace's hawk eagle and 32 globally near-threatened species, including the wrinkled hornbill and golden-throated barbet (BLI, 2021c). Proposed new power lines with a route length of 73 km and circuit length of 146 km would traverse this IBA near its eastern border.

Lower Central Basin IBA consists of the Lower Central Plain of the Chao Phraya River, including the city of Bangkok. The area was once dominated by natural swamps but has been largely converted to rice cultivation and has high human population density, although a set of small patches are protected as non-hunting areas. This IBA regularly supports more than 20,000 waterbirds and is used by globally threatened bird species including the greater spotted eagle, imperial eagle, spot-billed pelican, and greater adjutant (BLI, 2021d). New power lines with a route length of 184 km and circuit length of 398 km are proposed within Lower Central Basin IBA, along with improvements with route length of 85 km and circuit length of 113 km.

Kaeng Krachan National Park, located along the border with Myanmar to the southwest of Bangkok, is Thailand's largest national park. It is also part of the Kaeng Krachan Forest Complex, which has been nominated to become a Natural World Heritage Site. This IBA contains extensive evergreen and semi-evergreen forest habitat in the mountainous terrain of the Tenasserim Range, and it has the highest number of recorded bird species of any single site in the country. At least five globally threatened bird species (plain-pouched hornbill, blue-banded kingfisher, white-fronted scops owl, silver oriole, and grey-sided thrush) occur in Kaeng Krachan, plus at least 25 globally near-threatened species (BLI, 2021b). Proposed power line improvements with a route length of 40 km and circuit length of 80 km would run through this IBA near its eastern border.

Power line development in Thailand also has the potential to impact non-avian biodiversity. IBAs that would be intersected by proposed power lines support numerous IUCN Red-Listed mammals, such as the Asian elephant, guar, tiger, clouded leopard, Asian golden cat, dhole, Asian giant tortoise, pig-tailed macaque, pileated gibbon, and East Asian porcupine. Red-Listed reptiles and amphibians, such as the Asian giant tortoise, Chantaburi warted treefrog, and Thai slender toad, are also present in IBAs. Arboreal primates and bats are susceptible to electrocution from power lines, and ground-dwelling mammals and herptiles may experience habitat loss and fragmentation associated with vegetation clearing in power line rights-of-way (see Annex 4). Breaks in canopy cover caused by power lines also fragment the habitat of arboreal species and may be particularly damaging to species like gibbons that are strictly arboreal and never come to the ground to cross canopy breaks.

We chose to focus on power line impacts to IBAs because the value of these areas for conservation of birds and other taxa is very high and well established. However, new or improved power lines outside of IBAs will also have consequences for biodiversity. Thailand is within the East Asian-Australasian Flyway, which is used by millions of migratory birds traveling between breeding grounds in the arctic and wintering grounds in Southeast Asia and Australasia. Birds migrating through Thailand may encounter and be harmed by new power lines, including those located between stopover sites that lie outside IBAs.

A variety of options exist for reducing the impacts of power lines on birds and other species. Power lines should ideally be rerouted to avoid areas where impacts to species are unacceptable, such as PAs and critical habitat patches. Burying power lines underground may be preferable where rerouting is not an option (Silva et al., 2014), but avoiding bird mortality from electrocution and collisions is necessary, although this can be costly and still involve impacts to species during the construction phase. Where neither rerouting nor burying lines is feasible, several types of mitigation measures have been used successfully to reduce bird mortality: measures that prevent birds perching on lines (e.g., rotating mirrors, brush deflectors, and spikes), measures that prevent contact with energized wires (e.g., insulator caps and reconfiguring wires), and measures that increase visibility of wires to reduce collisions (e.g., flight diverters and wire marking). These measures vary in effectiveness, but some have been shown to reduce mortality by up to 91 percent (Barrientos et al., 2012; Dixon et al., 2018, 2019), and many are relatively low cost and technically simple to install (Mahood, 2021). Mitigation measures to reduce mortality of primates from power lines that traverse their habitats are also available, such as metal shields on powerline poles to prevent primates from reaching the top.

The power line routes used in our analysis suffer from some degree of spatial inaccuracy because they were hand-digitized from a country-scale map, which could impact our conclusions about overlap with IBAs. This problem is most acute in areas where a proposed power line route is close to the border of an IBA and a small spatial error could indicate overlap where none exists, particularly where routes have been purposely designed to run just outside borders of PAs. For this reason, our national-scale analysis is best suited as an initial screening tool, and finer-scale, project-level analyses should be considered in areas where our analysis suggests intersections with IBAs. We note, however, that power lines that are near but not within IBAs also have the potential to impact biodiversity, especially highly mobile bird species that frequently move across IBA boundaries.

CONTRIBUTIONS

This report was prepared by Mat Bell (WTI), Tyler Creech (CLLC), Rob Ament (CLLC/WTI), Grace Stonecipher (CLLC), and Tony Clevenger (WTI). Chaitanya Krishna (consulting wildlife biologist, India) and Petch Manopawitr (consulting conservation scientist, Thailand) also contributed to the report.

ANALYSIS 6: POTENTIAL IMPACTS OF PLANNED PAVED ROADS AND RAILWAYS IN MONGOLIA ON KHULAN AND GOITERED GAZELLE

The Gobi Steppe Ecosystem in southeast Mongolia serves as one of the last relatively intact ecosystems for migratory ungulates (Ito et al., 2013; Joly et al., 2019) and is home to the largest remaining populations of both khulan and goitered gazelle (Buuveibaatar et al., 2017). The population of khulan in southeastern Mongolia has one of the highest total cumulative annual distances travelled of any species—as much as 6,145 km/year (Joly et al., 2019). While both khulan and goitered gazelle are considered to be migratory, they do not necessarily follow the same pathways each season; instead, their movements are more nomadic, driven by the search for quality forage, which is in turn driven by fluctuating precipitation patterns (Batsaikhan et al., 2014). Goitered gazelle are listed as vulnerable on the IUCN Red List, while khulan are listed as near threatened, and both species are also conserved through the Convention on Migratory Species. Human impacts have dramatically reduced the populations of both species from historical levels, making the Gobi Steppe Ecosystem a particularly important landscape for their conservation (Wingard et al., 2014a).

However, the integrity of the Gobi Steppe Ecosystem is threatened by the expansion of Mongolia's LI network. Numerous railways are either planned or under construction to increase access to mineral and fossil fuel extraction areas, while new paved roads are being built to connect population centers and facilitate the movement of people and goods (Batsaikhan et al., 2014). As new infrastructure is built, it carves up the landscape, fragmenting ungulate habitat and creating barriers to movement (Ito et al., 2013). Previous studies have found that khulan are particularly impacted by railways, which are typically fenced; one study found that the Trans Mongolia Railroad in eastern Mongolia creates an absolute barrier to ungulate movement, cutting one population of khulan off from additional suitable habitat further east (Kaczensky et al., 2011). Further limiting ungulate movement in southern Mongolia is the border between Mongolia and China, which is almost entirely fenced (Linnell et al., 2016). Finally, in additional to fragmenting habitat and limiting animal movement, the increased human access facilitated by LI may lead to additional pressure from poaching (Kaczensky et al., 2006) or higher human density in general, which ungulates tend to avoid (Batsaikhan et al., 2014).

Here, we conduct a spatial analysis to demonstrate potential impacts of planned LI to the home ranges and movements of a sample of khulan and goitered gazelle in southern Mongolia.

METHODS

We obtained telemetry data for 20 khulan and 20 goitered gazelle individuals from the Wildlife Conservation Society's Mongolia Program, along with spatial data on planned and existing paved roads and planned, under construction, and existing railways. Collared animals were captured as part of research projects investigating habitat use in areas of differing land management and development intensity, and thus were not a representative sample from across the khulan or goitered gazelle population range. We removed location data points associated with gazelle collar initiation and retrieval periods.

We explored the potential impact of existing and planned LI on collared individuals in two ways. First, we looked at potential impact to ungulate habitat by examining the overlap of LI and home ranges. We mapped the home range for each individual using a 95% kernel density estimate (KDE) contour (Leonard, 2017) and calculated the home range area. For khulan, given the lack of any fix locations in

China, home ranges were limited to only areas inside Mongolia. We then spatially overlaid the LI data on the individual home range polygons and calculated the average length of each LI type in each home range for both species. We created maps for each species to show where home ranges showed the greatest overlap among individuals and where planned LI might block animals from accessing portions of their home ranges.

We then examined the potential impacts of LI to connectivity for collared individuals by counting the number of times that each animal crossed each existing and planned LI route. Crossing locations were inferred from the telemetry data by assuming a straight-line travel path between consecutive location data points, with a maximum of eight hours between fixes. Each time an individual's path intersected an LI feature, it was counted as a crossing location. We also created maps of these crossing locations to identify any areas of particularly high crossing density.

RESULTS

Goitered Gazelle

Goitered gazelle were tracked for an average of 310 days, with a median fix interval of one hour for 13 animals and half an hour for seven animals. All recordings started on either 10/14/2018 (12 animals) or 10/18/2018 (eight animals). The shortest tracking period lasted only 16 days, ending on 10/30/2018, while the longest tracking period lasted for 485 days, ending on 2/11/2020.

The 20 goitered gazelle occupied two distinct areas—one further south near the border with China and one slightly further northeast (Figure 17). On average, goitered gazelle home ranges were found to be 143,977 hectares (ha); the smallest home range was 677 ha, and the largest was 380,688 ha (Table 15). The large variation in home range size is likely due to the large variation in tracking period length, as the individual that was only tracked for 16 days had the smallest home range. An average of 21.5 km of existing road runs through each home range, with a maximum of 130.5 through one individual's home range, all in the southern area. The highest density of home range overlap occurred directly between two existing roads. An average of 6.4 km of planned road alignments overlap with each gazelle's home range, and an average of 13.43 km of rail is under construction in gazelle home ranges. No planned rails or existing rails overlap with gazelle home ranges. The home range for one gazelle extended across the border into China; due to the presence of multiple fixes in China, we retained these fixes in our analysis.

Table 15: LI Overlap of Home Ranges for 20 Goitered Gazelle by Mode

TABLE 15: LI OVERLAP OF HOME RANGES FOR 20 GOITERED GAZELLE BY MODE

		LENGTH OF OVERLAP				
	Area (ha)	Planned Road (km)	Planned Rail (km)	Under Construction Rail (km)	Existing Road (km)	Existing Rail (km)
Average	143,977	6.40	0	13.43	21.50	0
Minimum	677	0	0	0	0	0
Maximum	380,688	57.95	0	55.79	130.50	0

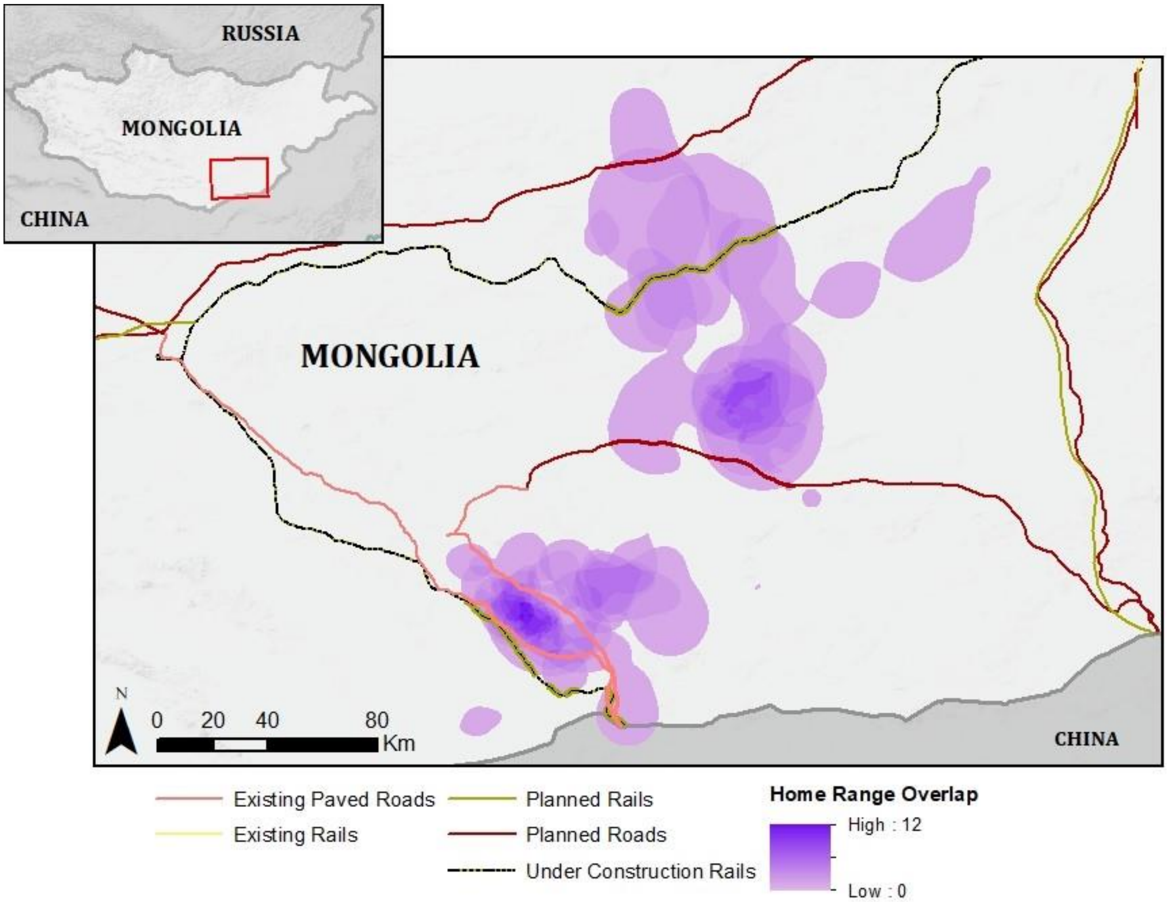

Figure 17: Linear Infrastructure overlap with 20 gazelle home ranges. Thicker lines indicate where existing or planned LI intersects with home ranges.

The goitered gazelle tracked in this study crossed planned road alignments an average of 1.82 times per year, and never crossed planned rail alignments (Table 16). They crossed railways that were under construction an average of 3.8 times per year. Gazelle never crossed existing rails but crossed existing roads an average of 3.45 times per year. Half of the gazelles crossed either planned roads or under construction rails at least once. Gazelle crossing locations were somewhat clumped along planned road alignments and were spread more evenly along the length of under-construction rails (Figure 18).

Table 16: Rate of Crossings per Year by LI Type for 20 Goitered Gazelle

TABLE 16: RATE OF CROSSINGS PER YEAR BY LI TYPE FOR 20 GOITERED GAZELLE					
	CROSSING RATE (CROSSINGS/YEAR)				
	Planned Road	Planned Rail	Under Construction Rail	Existing Road	Existing Rail
Average	1.82	0	3.80	5.79	0
Minimum	0	0	0	0	0
Maximum	24.28	0	19.73	31.00	0

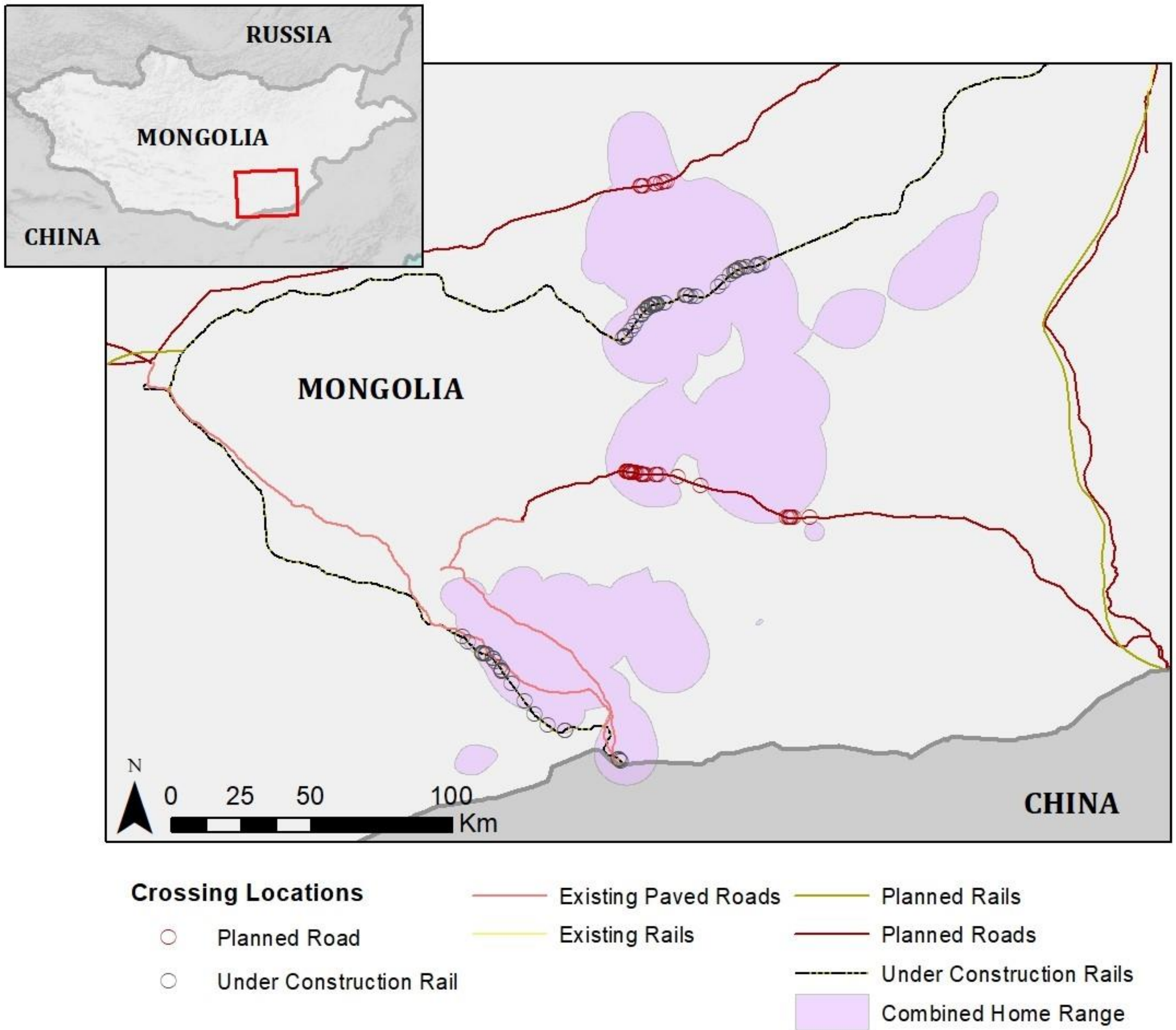

Figure 18: Locations where 20 goitered gazelle crossed planned rails, planned roads, and under construction rails.

Khulan

Khulan were tracked for an average of 623 days, with a median fix interval of one hour. All recordings started between 8/23/2013 and 8/30/2018. The shortest tracking period lasted 270 days, ending on 5/26/2014, and the longest tracking period lasted 727 days, ending on 8/21/2015.

Khulan home ranges were larger than those of goitered gazelle, with an average size of 2,643,885 ha (Table 17, Figure 19). The smallest home range was 328,492 ha, and the largest was 5,340,698 ha. An average of almost 215 km of new road and 83 km of new rail is planned to be built through the 20 khulan home ranges, and an average of 102.27 km of under construction rail overlaps with each home range. There is 101.93 km of existing road on average that already overlaps with khulan home ranges, while only 0.03 km of existing rail overlaps with a single khulan's home range. While the home ranges produced by the KDE algorithm for some khulan did extend into China, this area was not included in the totals, due to the presence of the border fence and the lack of any fix recordings within China.

Table 17: LI Overlap of Home Ranges for 20 Khulan by Mode

TABLE 17: LI OVERLAP OF HOME RANGES FOR 20 KHULAN BY MODE						
			LENGTH OF OVERLAP			
	Area (ha)	Planned Road (km)	Planned Rail (km)	Under Construction Rail (km)	Existing Road (km)	Existing Rail (km)
Average	2,643,885	214.84	82.66	102.27	101.93	0.001
Minimum	328,492	20.74	0	0	0	0
Maximum	5,340,698	606.09	231.86	317.73	243.05	0.03

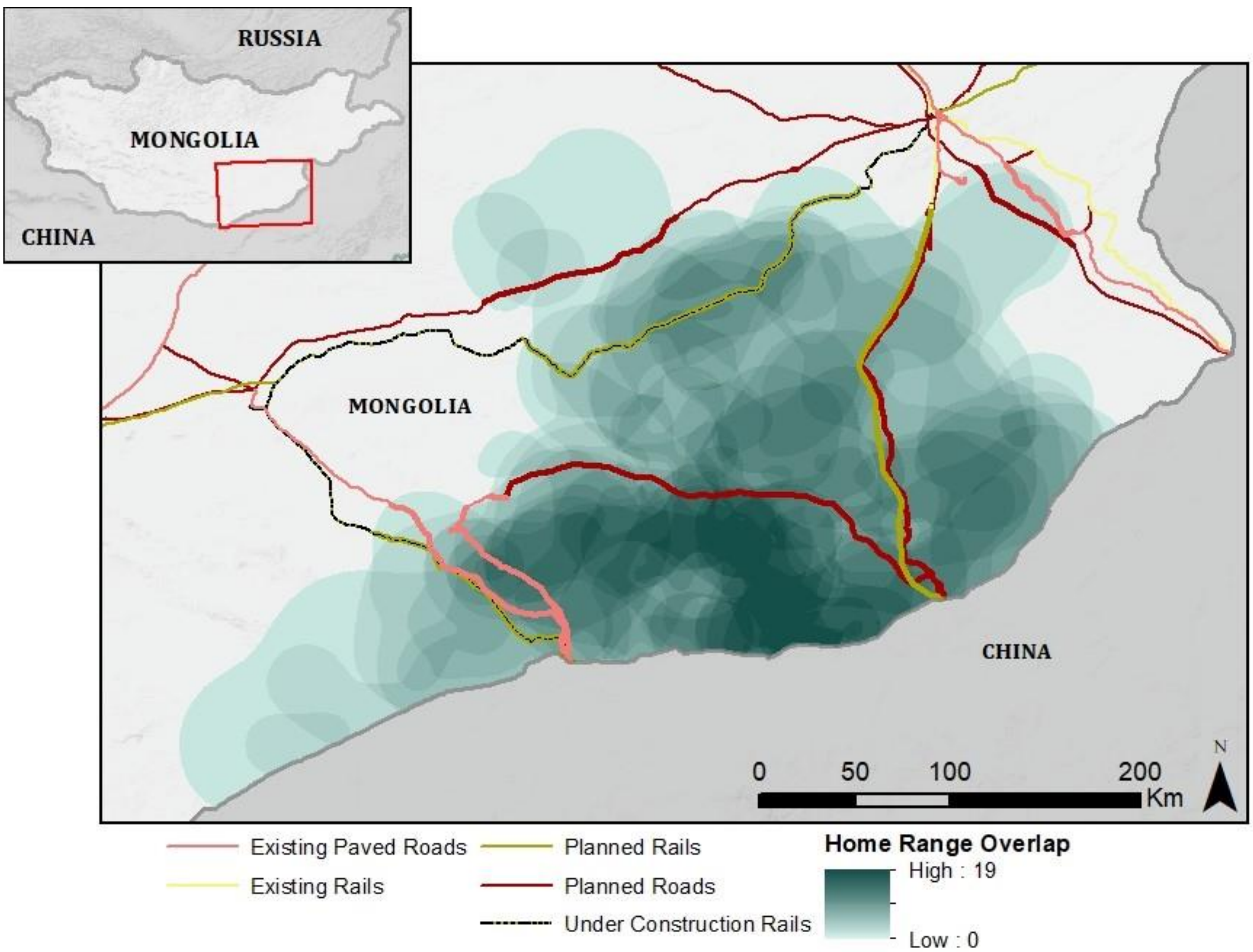

Figure 19: Linear Infrastructure overlap with 20 khulan home ranges. Thicker lines indicate where existing or planned LI intersects with home ranges.

The khulan tracked in this study crossed planned road alignments an average of 23.9 times per year, and planned rail alignments an average of 10.4 times per year (Table 18). They crossed railways that were under construction an average of 8.9 times per year. Khulan crossed existing paved roads an average of 5.0 times per year, and never crossed existing railways. Every individual khulan crossed a planned road alignment at least twice during the study period, and one individual crossed over the planned alignment 101 times, for a rate of 76.6 crossings per year. Crossing locations were generally spread out along the full length of planned LI, with some areas of higher density (Figure 20).

Table 18: Rate of Crossing per Year by LI Type for 20 Khulan

TABLE 18: RATE OF CROSSINGS PER YEAR BY LI TYPE FOR 20 KHULAN					
	CROSSING RATE (CROSSINGS/YEAR)				
	Planned Road	Planned Rail	Under Construction Rail	Existing Road	Existing Rail
Average	23.87	10.36	8.87	5.01	0
Minimum	1.29	0	0	0	0
Maximum	76.63	31.17	29.52	26.00	0

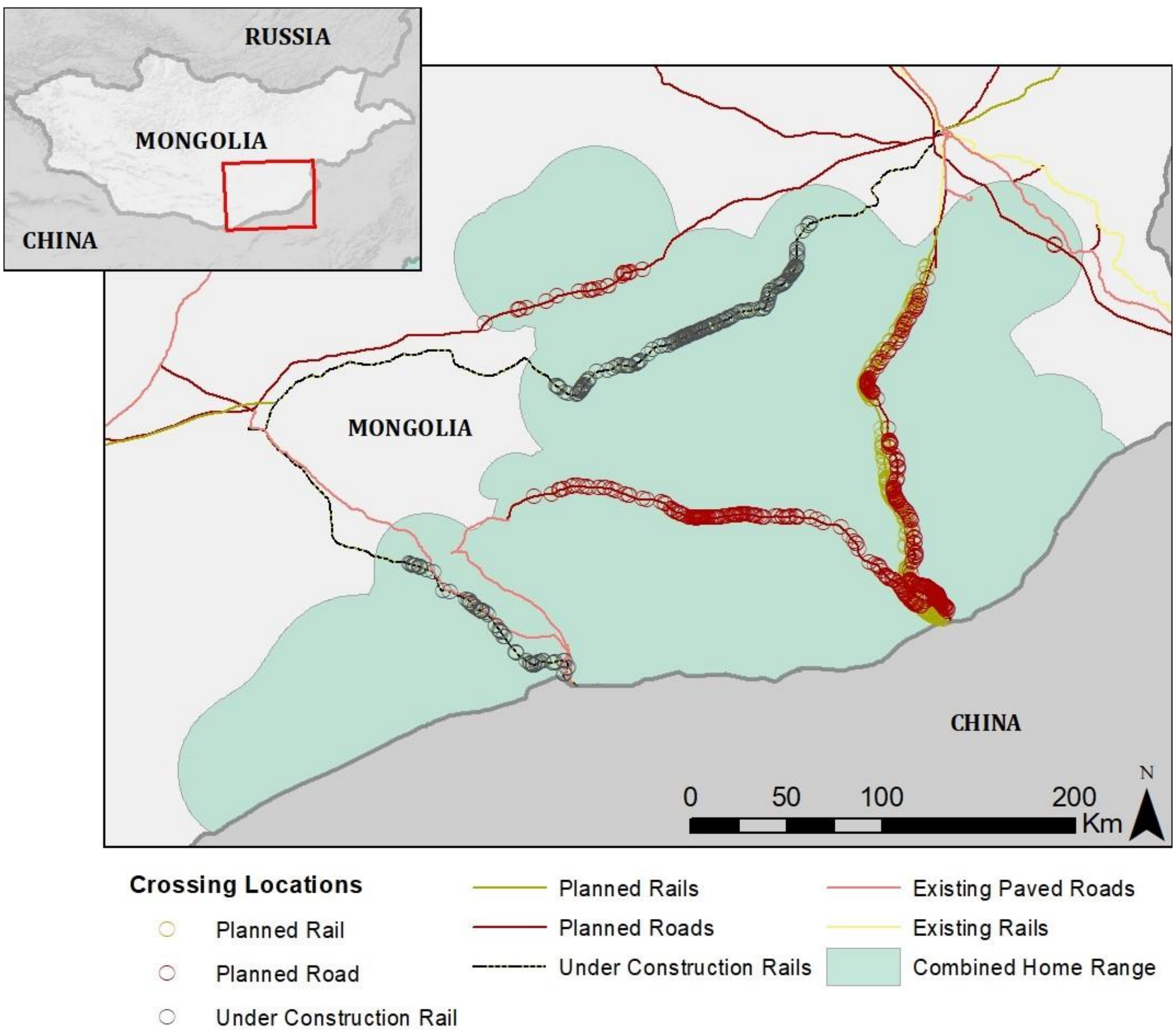

Figure 20: Locations where 20 khulan crossed planned rails, planned roads, and under construction rails.

Existing Roads

Both species crossed existing roads; during the two study periods, khulan crossed existing roads 176 times and gazelle crossed 69 times total. While these crossing were generally spread out along the lengths of existing roads, khulan showed some clustering in crossing locations on the western road, while gazelle showed more clustering on the eastern road (Figure 21).

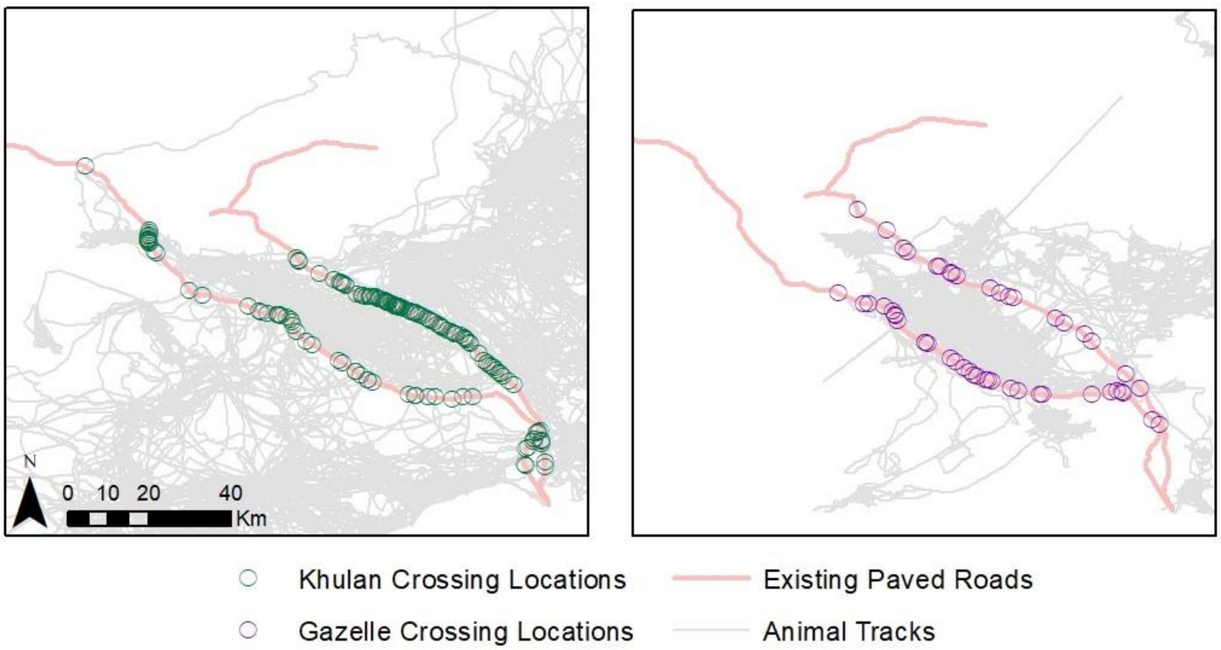

Figure 21: Crossing locations for khulan and goitered gazelle across existing paved roads.

DISCUSSION

Our analysis of a small sample of khulan and goitered gazelle suggests that populations of these species in southeastern Mongolia are likely to be impacted by planned LI. The alignments of multiple planned roads and rails cut directly through the middle of observed home ranges of sampled goitered gazelle and khulan individuals, potentially decreasing their ability to move across the landscape to find high-quality forage. Generally, it appears that railways will have greater impacts on both species than paved roads, as collared individuals of both species occasionally crossed existing paved roads but never crossed an existing railway. However, the majority of gazelle movement for these 20 individuals happened between the two existing roads in the southern home range, indicating that roads may act as partial barriers to gazelle movement. Khulan appear to be slightly less affected by roads but an examination of individual movement tracks shows that some khulan spend time travelling parallel to paved roads, perhaps looking for an opportunity to cross. The full impact of these roads on ungulate movement is also likely dependent on traffic volume (Gagnon et al., 2007); additional research involving more collared individuals is needed to confirm these findings.

Given previous findings that khulan never cross over the Trans-Mongolian Railroad to the east, it seems likely that the railways that are planned or currently under construction may also prove to be absolute barriers to ungulate movement, assuming they are similarly fenced. Alternatively, the new railways must include wildlife crossing infrastructure of sufficient design, size, placement, and frequency (spacing) to provide permeability for the species; after three sections of fencing were removed along the Trans-Mongolian Railway, a khulan was observed to cross (Kimbrough, 2020). For khulan, without railway or fence mitigation measures, the planned railway alignments would divide the combined home range for these 20 individuals into four new distinct areas, greatly reducing habitat connectivity. Based on the area where the greatest number of home ranges overlap, the collared khulan individuals would essentially be trapped between three railways and the border fence, potentially leading to genetic isolation. For goitered gazelle, the northern combined home range area of the collared individuals would be split in half; the southern combined home range of these individuals would be only slightly fragmented by a railway on the far west side, although gazelle crossed over that planned alignment 28 times. Our results are in accordance with previous research suggesting that habitat fragmentation could threaten the long-term survival of ungulate populations in this region (Huijser et al., 2013; Ito et al., 2013; UNEP/CMS, 2019).

Given that both ungulate species move nomadically through the landscape in search of forage, as opposed to following set migration paths, it is more difficult to know where to implement mitigation measures such as crossing structures. As the telemetry data show, both khulan and gazelle currently cross along the full length of planned alignments for new railways and roads; while there are certain areas of higher crossing density, further study is necessary with an increased sample size and more complete geographic representation to determine whether these crossing locations are consistent across years and should thus be targeted for mitigation.

In addition to crossing structures, previous studies have also suggested the removal or modification of fences along railways to allow for crossing over existing infrastructure, or the allocation of no-fence zones for existing infrastructure (Ito et al., 2013). Because fences are typically put in to prevent train-livestock collisions, these options might be especially feasible in areas not occupied by herders (Batsaikhan et al., 2014), although this solution would not eliminate collisions between wild ungulates and trains. Given the difficulties of mitigating LI impacts for nomadic species, the best overall strategy is avoidance, or the selection of LI alignments that are less likely to impact these species. Moreover, it is crucial to approach planning at the regional scale, accounting for the cumulative effects of both existing and planned infrastructure projects (Batsaikhan et al., 2014).

Finally, it is important to re-emphasize that potential LI impacts inferred from the movements of 40 individuals sampled from populations of tens of thousands of individuals may not be representative of impacts to the full populations. Khulan and goitered gazelle in southeastern Mongolia occupy a much more extensive area than is included in the individual home ranges shown above, and there is almost certainly additional overlap between proposed LI and ungulate habitat in the region that warrants concern. Our analysis confirms the potential impacts of planned LI to ungulates in the region and highlights the need to consider connectivity in future LI development; however, the small number of collared individuals makes it very difficult to discern population-level patterns in crossing locations, and thus to recommend specific mitigation measures. Further study of this region can illuminate the full geographic scope of potential LI impacts on khulan and goitered gazelle and guide decisions around specific locations for mitigation measures and other conservation actions.

CONTRIBUTIONS

Buuveibaatar Bayarbaatar, Narangua Batdorj, and Kirk Olson (WCS Mongolia) provided telemetry data for khulan and goitered gazelle and spatial data on planned and existing roads and railways and reviewed the report (pending). Grace Stonecipher (CLLC) conducted spatial analyses and drafted the report. Tyler Creech (CLLC) and Rob Ament (CLLC/WTI) also contributed to the report.

SYNTHESIS OF FINE SCALE ANALYSES

The six fine-scale analyses in Part II revealed several common lessons that may help guide future analyses of this type. Collaborating with local experts was essential for producing high-quality and useful analyses. Staff from conservation NGOs provided access to detailed biological and LI data that would not have been otherwise possible to obtain quickly. Perhaps more importantly, their expertise and understanding of the biological and sociopolitical context of LI development within the study areas helped focus the analyses on the most pressing and relevant threats to biodiversity.

Even rapid assessments using relatively simple analytical methods provided compelling evidence for likely harm to biodiversity or to individual wildlife species from proposed LI development. Many of our analyses were necessarily simplistic given time and data constraints; for instance, overlaying proposed LI routes with conservation features such as wildlife movement corridors or PAs. While analyses using more sophisticated methods (such as those reviewed in Part III of this annex) can provide more detailed information on likely impacts of LI on biodiversity, simple rapid assessments remain valuable because they can highlight potential threats from proposed LI projects while there is still sufficient time to incorporate biodiversity safeguards in the LI development process (e.g., by suggesting alternative routes, designing mitigation measures, or halting construction until more detailed environmental impact analyses can be completed).

PART III: REVIEW OF EXEMPLARY FINE-SCALE SPATIAL ANALYSES

Spatial analyses of the impacts of existing LI on biodiversity are now commonplace, and useful for documenting and explaining observed changes in wildlife populations or the habitats that sustain them. These retrospective studies help solidify our understanding of species' responses to LI development, identify areas where ongoing harm to biodiversity is greatest, and suggest actions to reduce or reverse this harm. Yet they have one major limitation: because they focus on effects of existing LI, retrospective studies cannot inform strategies to prevent harm to biodiversity before it occurs by designing LI in a wildlife-friendly manner or avoiding LI development altogether. Prospective spatial analyses that consider proposed routes of LI projects and their overlap with areas of biological importance are needed to provide this information, and these prospective studies remain relatively uncommon.

Part III of this annex explores existing efforts to proactively assess LI threats to biodiversity using spatial analysis methods. We summarize a selection of recently published prospective spatial analyses from scientific journals and the gray literature identified using an informal literature search. We focus on 11 exemplary studies that used spatial analyses to explore the potential impacts of proposed road, railway, or power line projects within a single country or a smaller landscape within a country. We only considered studies published from 2018 onward to focus on LI projects that are still likely in the planning or construction phases, meaning that study results remain highly relevant for preemptive conservation efforts. Below, we provide a brief synopsis of each study, followed by a synthesis describing key characteristics of studies and recommendations for future applications and advances.

EXEMPLARY STUDY 1: POTENTIAL IMPACTS OF ROADS AND RAILWAYS ON BIODIVERSITY IN INDONESIAN BORNEO (ALAMGIR ET AL. 2019)

Publication: Alamgir, M., Campbell, M. J., Sloan, S., Suhardiman, A., Supriatna, J., & Laurance, W. F. (2019). High-risk infrastructure projects pose imminent threats to forests in Indonesian Borneo. Scientific Reports, 9(1), 1-10. https://www.nature.com/articles/s41598-018-36594-8.

Study area: Indonesian Borneo (Kalimantan)

Focal species: None (species-neutral)

Infrastructure type(s): Roads and railways

Background: Borneo is widely recognized as a global biodiversity hotspot and contains one of the largest remaining concentrations of intact tropical forest habitat. It is also experiencing high rates of forest clearing and degradation due to LI expansion and related threats including logging, mining, oil palm plantations, and wildfires. Under the Indonesian Master Plan for the Acceleration and Expansion of Economic Development (2011–2025), the Indonesian portion of Borneo (Kalimantan) is expected to see a dramatic increase in road and railway construction by 2025 as part of the development of the Kalimantan Economic Corridor; this includes proposed upgrades to more than 3,000 km of the Trans-Kalimantan Highway and construction of nearly 2,000 km of new roads. Expansion of the road network is likely to increase human access to wildlands and further increase forest conversion. This study quantified the potential impacts of these proposed LI developments on the spatial structure, connectivity, and ecological integrity of Kalimantan's native forests.

Methods: The authors compiled spatial data on proposed road and railway routes from a variety of government databases, reports, and previous studies. They used satellite imagery to map and classify forest patches (e.g., core forest and edge forest), and then overlaid proposed LI on forest patches to estimate changes in the total area and types of forest patches. They calculated a landscape connectivity metric called the Equivalent Connected Area index for the current landscape and the anticipated landscape after LI development to estimate the likely loss of landscape connectivity. The authors also overlaid proposed LI routes on the existing PA network. They classified all segments of proposed LI as very high, high, medium, or low environmental impact based on their intersection with PAs, primary and secondary forest, and peatland.

Conclusions: The study predicted considerable impacts to native forest habitat in Kalimantan if road and railway projects proceed as proposed. Approximately 237,000 ha of core forests would be transformed into other non-core forest categories of lower habitat quality, and 392,000 ha of existing "bridge" forest corridors that serve as connections between core forest areas would also be impacted. LI development would decrease landscape connectivity by 34 percent as measured by the Equivalent Connected Area metric. Twenty-five existing PAs would be intersected by new roads or railways, including Kayan Mentarang National Park, which is one of the region's largest remaining ecologically intact PAs. A further 17 PAs would be impacted by upgrades to existing roads. The analysis identified more than 3,300 km of proposed roads and railways that are expected to have very high, high, or moderate environmental impact. The authors recommended that proposed road and railway segments classified as very high impact should not proceed, and that environmental impacts of segments classified as high or moderate impact should be minimized via mitigation or offset measures and better law enforcement following development. The authors suggested that most of the proposed LI expansion in Kalimantan would not be considered cost effective if the full range of environmental, economic, and social factors were considered.

EXEMPLARY STUDY 2: POTENTIAL IMPACTS OF ROADS AND POWER LINES ON BIODIVERSITY IN SUMATRA, INDONESIA (SLOAN, ALAMGIR ET AL. 2019)

Publication: Sloan, S., Alamgir, M., Campbell, M. J., Setyawati, T., & Laurance, W. F. (2019). Development corridors and remnant-forest conservation in Sumatra, Indonesia. Tropical Conservation Science, 12, 1-9. https://journals.sagepub.com/doi/full/10.1177/1940082919889509.

Study area: Sumatra, Indonesia

Focal species: None (species-neutral)

Infrastructure type(s): Roads, power lines

Background: Major road expansion is proposed for the island of Sumatra as the Indonesian government seeks to boost economic growth through the development of economic corridors. Unlike LI development occurring in remote and ecologically intact landscapes in eastern Indonesia, LI development on Sumatra is occurring in an environment that has already experienced impacts from roads, agriculture, timber harvest, and mining. Thus, conservation efforts on Sumatra must focus on minimizing damage from a second wave of LI development to remnant forest patches that survived the initial development wave. The dominant feature of this second wave is a proposed 2,700-km Trans-Sumatran Highway (TSH) that is likely to increase pressure on remnant forest by promoting agricultural incursions. This analysis explored threats from the TSH and supporting roads to three remnant forest areas of exceptional biological value: (1) Kerinci Seblat National Park, which is Indonesia's second largest PA and part of a World Heritage Site; (2) the Leuser Ecosystem, which is the last remaining common habitat for endangered elephants, tigers, rhinoceros, and orangutans; and (3) the Batang Toru region, which is the last refuge for the critically endangered Tapanuli orangutan.

Methods: The study used simple spatial overlays of proposed highway routes with features of conservation interest to determine locations of potential conflicts between LI development and biodiversity. These conservation features included remnant primary forest patches mapped using satellite imagery, Tapanuli orangutan habitat patches, Tiger Conservation Landscapes, and PAs such as national parks and nature reserves. Highway routes were estimated from a map produced by the Executive Office of the Indonesian President.

Conclusions: The TSH would separate Kerinci Seblat National Park from an adjacent nature reserve and would likely reduce the geographic range of the Sumatran tiger because of road avoidance, increased vulnerability to poaching, and reduced habitat connectivity. The TSH would also pass the northeast flank of the Leuser Ecosystem, where it would likely expand and consolidate earlier agricultural incursions into formerly intact forests, most notably palm oil plantations. The Batang Toru region would be intersected by a highway (a supporting corridor of the TSH) and by power lines associated with a major hydroelectric development, jeopardizing the conservation status and habitat quality of local forests. This could negatively impact the endangered Tanapuli orangutan population negatively, which has been reduced to ~800 individuals living in three forest fragments. The authors recommended that the status of remnant forest should be legally reinforced, and that regulations that currently discourage road development in core forest should be extended to non-core forest. Environmental regulations developed for nationally strategic roads (e.g., the TSH) should also be applied to local road proposals aligned with these larger roads, which may be responsible for many of the impacts to remnant forest. The authors strongly advocated for rerouting of proposed highway sections likely to negatively impact forests of high conservation priority and endangered wildlife species.

EXEMPLARY STUDY 3: POTENTIAL IMPACTS OF ROADS ON BIODIVERSITY IN MALAYSIAN BORNEO (SLOAN, CAMPBELL ET AL. 2019)

Publication: Sloan, S., Campbell, M. J., Alamgir, M., Lechner, A. M., Engert, J., & Laurance, W. F. (2019). Trans-national conservation and infrastructure development in the Heart of Borneo. PLOS One, 14(9), e0221947. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0221947.

Study area: Malaysian Borneo (Sabah)

Focal species: None (species-neutral)

Infrastructure type(s): Roads

Background: The Heart of Borneo initiative (HoB) was established in 2007 to enhance cooperation among Malaysia, Indonesia, and Brunei as these countries work toward the conservation of a transboundary network of PAs and other natural areas on the island of Borneo. Since its establishment, PA coverage has more than doubled, connectivity among PAs has increased, and logging impacts have been reduced. However, the trilateral HoB is threatened by unilateral LI development schemes driven by federal economic agendas, such as the Sabah Development Corridor, which includes plans for expanding a Pan-Borneo highway network in Malaysian Borneo. This expansion includes approximately 1,300 km of proposed new roads and a further 1,300 km of proposed road upgrades, and much of this expanded network would either directly intersect PAs or interrupt animal movement between PAs. This study examined potential impacts of Pan-Borneo highway construction and upgrades on the ecological integrity of the HoB in Sabah, with a focus on loss of connectivity among PAs and intact forest areas.

Methods: The authors overlaid proposed highway routes from the Sabah Structural Plan for 2033 with PAs and intact forest patches mapped using satellite imagery. They determined which PAs were currently connected by corridors of intact forest, and then identified connections that would be severed by proposed road development. They used a network theory metric, the Integral Index of Connectivity (IIC), to estimate (1) the expected change in overall connectivity of the PA network if all proposed road construction and upgrades were to be completed, and (2) the relative importance of individual corridors to overall connectivity in the post-development landscape, which should help to prioritize locations for mitigation measures to facilitate connectivity for wildlife (e.g., crossing structures).

Conclusions: Proposed road development would fragment the largest intact forest patch in the HoB, disconnecting PAs in Sabah from those further south in the HoB. Ecological connections among 10 PAs would be lost. Plans for mitigating the effects of highway development in Sabah call for highway underpasses for wildlife aligned with forest corridors, but the authors expressed doubts about whether this strategy will be enough to prevent loss of connectivity or whether there will be sufficient funding to implement it. To maximize benefits of this strategy, locations of forest corridors and wildlife overpasses should be determined by surveys of animal movements or biodiversity, not based on construction convenience as in the past. The authors recommended that Malaysia, Indonesia, and Brunei develop a HoB master plan that would designate regional priority conservation networks, corridors, and buffer zones with trilateral consensus. They also suggested better integration of conservation and development planning so that conservation efforts are not undone by development, as may be the case with the Pan-Borneo Highway and HoB.

EXEMPLARY STUDY 4: POTENTIAL IMPACTS OF ROADS AND RAILWAYS ON TIGERS IN INDIA (PARIWAKAM ET AL. 2018)

Publication: Pariwakam, M., Joshi, A., Navgire, S., & Vaidyanathan, S. (2018). A policy framework for connectivity conservation and smart green linear infrastructure development in the Central Indian and Eastern Ghats tiger landscape. Wildlife Conservation Trust, Mumbai. https://www.wildlifeconservationtrust.org/wp-content/uploads/2018/11/Vol-1-Policy-Framework-CI-and-EG-Landscape-Low-Res-.pdf.

Study area: Central India and Eastern Ghats

Focal species: Tiger (*Panthera tigris*)

Infrastructure type(s): Roads, railways

Background: The Central India and Eastern Ghats landscape supports approximately one-third of India’s tiger population and includes 23 tiger reserves and 46 other PAs occupied by tigers. The tiger population in this landscape is the most genetically diverse in the world, but rapid development of LI and resulting habitat loss and fragmentation threatens its long-term health. Approximately 22 km of new roads are constructed per day in India, which increasingly restricts movement of tigers among habitat patches and reduces gene flow. Many of the movement corridors used by tigers and other wildlife in this landscape have not yet been identified or widely recognized, making it difficult to assess existing or potential impacts of LI development on connectivity or implement appropriate mitigation measures. This study addressed this information gap by (1) using connectivity models to identify wildlife corridors among PAs and forest blocks occupied by tigers, and (2) determining where proposed road and railway projects would intersect these corridors and prevent movements among habitat patches by tigers.

Methods: The authors used spatial data on human settlements and land cover to estimate the landscape's resistance to tiger movement, and then used connectivity models to map optimal movement paths between PAs and forest blocks where tigers are known to be present. They reviewed nearly 1,700 recent proposals for LI development (including roads and railways) submitted to the Ministry of Environment, Forests, and Climate Change for diversion of forest land, and they extracted spatial data on proposed LI routes from these proposals. By spatially overlaying these routes on the map of tiger corridors derived from connectivity models, they were able to identify proposed LI routes that would intersect tiger corridors and could interfere with connectivity among tiger habitat patches.

Conclusions: Nearly 400 LI development proposals included segments that passed through or bisected a tiger corridor. However, 86 percent of these proposals denied the requirement for a "wildlife clearance" (i.e., approval from the National Tiger Conservation Authority and National Board for Wildlife) despite their likely impacts to tigers. Many of the corridors identified in the study extend beyond the boundaries of PAs and Eco-sensitive Zones that trigger the requirement for a wildlife clearance; the authors therefore suggested that regulations should be updated so that the tiger corridors identified in the study can serve as the basis for requiring a wildlife clearance. They also recommended that a small fraction of total LI project budgets be spent on incorporating suitable wildlife mitigation measures in the initial planning stages of projects, which may lead to overall savings by avoiding costly project delays that occur when plans must be modified after construction has started to accommodate mitigation measures. Overlaying proposed project alignments on a map of tiger corridors at the outset of the planning process would allow agencies to better predict and incorporate costs of mitigation measures into project plans.

EXEMPLARY STUDY 5: POTENTIAL IMPACTS OF POWER LINES ON BENGAL FLORICANS IN CAMBODIA (MAHOOD ET AL. 2018)

Publication: Mahood, S. P., Silva, J. P., Dolman, P. M., & Burnside, R. J. (2018). Proposed power transmission lines in Cambodia constitute a significant new threat to the largest population of the Critically Endangered Bengal florican Houbaropsis bengalensis. Oryx, 52(1), 147-155. https://www.cambridge.org/core/journals/oryx/article/proposed-power-transmission-lines-in-cambodia-constitute-a-significant-new-threat-to-the-largest-population-of-the-critically-endangered-bengal-florican-houbaropsis-bengalensis/363AD7029432E2FFC81726FE8568274E

Study area: Cambodia

Focal species: Bengal florican (*Houbaropsis bengalensis*)

Infrastructure type(s): Power lines

Background: The Bengal florican is a critically endangered bustard subspecies and the only bustard taxon in Southeast Asia, where it is restricted to the Tonle Sap floodplain of Cambodia. The florican population has declined steeply in recent years, and the development of hydropower dams and associated power lines in the region may exacerbate this decline because bustards and other large birds are especially vulnerable to mortality from collisions with power lines. The Cambodian government plans to construct 230-kV power lines along the northern edge of the Tonle Sap floodplain, adjacent to breeding grounds used by 81percent of the florican population and possibly across migratory paths between breeding and non-breeding areas. This study collected information on florican movement and mortality to estimate the impacts that proposed power lines could have on the florican population.

Methods: The authors used telemetry transmitters to track the movement paths of 17 individual floricans over a five-year period. They conducted a literature review of previous studies on bustard mortality from power lines to estimate the average rate of fatal collisions expected per kilometer of new power line. They overlaid proposed power line routes on observed migratory paths and breeding areas to determine where floricans are likely to experience elevated mortality rates due to collisions with power lines.

Conclusions: Floricans tagged with transmitters crossed the proposed power line route twice in each non-breeding season, indicating high potential for collision mortality. Some individuals had breeding areas located close enough to the proposed route that they would likely come into contact with power lines much more frequently. The literature review revealed an average rate of 0.69 detected bustard collision fatalities per km of power line per year from previous studies. Although it is problematic to directly apply these rates to the florican population in the Tonle Sap floodplain, the authors suggested that a similar rate of collision fatalities in this population could lead to further decline of the only significant population of the Southeast Asian subspecies of florican. Other vulnerable bird species could also be affected, including the sarus crane, spot-billed pelican, and several stork and ibis species. The authors recommended rerouting sections of the proposed Tonle Sap power line that are likely to become collision hotspots and installing bird flight deflectors or line markers where rerouting is not feasible.

EXEMPLARY STUDY 6: POTENTIAL IMPACTS OF ROADS AND RAILWAYS ON CLOUDED LEOPARDS IN MYANMAR (KASZTA ET AL. 2020)

Publication: Kaszta, Ż., Cushman, S. A., Htun, S., Naing, H., Burnham, D., & Macdonald, D. W. (2020). Simulating the impact of Belt and Road initiative and other major developments in Myanmar on an ambassador felid, the clouded leopard, Neofelis nebulosa. Landscape Ecology, 1-20. https://link.springer.com/content/pdf/10.1007/s10980-020-00976-z.pdf.

Study area: Myanmar

Focal species: Clouded leopard (*Neofelis nebulosa*)

Infrastructure type(s): Roads, railways

Background: Myanmar has the most extensive remaining forest cover of any nation in South or Southeast Asia and is a global biodiversity hotspot, but it is experiencing rapid deforestation associated with natural resource extraction and large-scale agricultural and industrial development. Myanmar's rich natural resources and strategic location between South and Southeast Asia make it an important target of China's BRI, which seeks to develop a series of economic corridors (including road and rail infrastructure) across Asia. Three large proposed LI projects in particular—the India-Myanmar-Thailand Trilateral Highway, BRI Silk Road, and BRI Pipeline Railroad—are likely to pose significant risks to Myanmar's biodiversity by increasing habitat loss and fragmentation, roadkill, and access for wildlife trafficking. This study analyzed the potential impacts of these development scenarios using the clouded leopard, a wide-ranging and charismatic top predator, as an umbrella species and indicator of forest biodiversity in the region.

Methods: The authors used spatial data on environmental variables, LI, and human development to estimate the landscape's resistance to clouded leopard movement, and then ran connectivity models to simulate movement among areas of suitable habitat for clouded leopards. By running connectivity models for pre- and post-development scenario landscapes, the authors were able to estimate the change in landscape connectivity for clouded leopards that would be expected if each proposed LI project were completed. They also calculated a series of landscape fragmentation metrics for pre- and post-development scenario landscapes to estimate potential changes to clouded leopard habitat fragmentation. Finally, they used a genetic simulation program to explore how LI development scenarios could restrict clouded leopard gene flow and influence genetic diversity and population size.

Conclusions: The Trilateral Highway would fragment the two largest core habitat patches for clouded leopards in Myanmar and bisect the corridors linking these cores. The Silk Road would increase landscape fragmentation by up to 39 percent. The Pipeline Road would intersect an area of high movement density in an important core area, and genetic simulations suggested that it would significantly decrease genetic diversity of the clouded leopard population. The predicted individual impacts of these three LI development scenarios on clouded leopard population size were modest, but in combination with impacts of new hydropower dams and urban growth in Myanmar, they could decrease clouded leopard population size by as much as 25 percent. The results of this study of clouded leopards in forest ecosystems provide strong evidence of potential harm from proposed new roads and rails, but the authors recommended that similar analyses for different focal species and ecosystems will be needed to understand the full impacts of LI development on biodiversity in Myanmar.

EXEMPLARY STUDY 7: POTENTIAL IMPACTS OF ROADS ON SNOW LEOPARDS IN NEPAL (WWF 2018)

Publication: World Wildlife Fund. (2018). Infrastructure assessment in snow leopard habitat of Nepal. WWF Nepal, Kathmandu. https://wwf.panda.org/discover/knowledge_hub/?340154/Infrastructure-Assessment-in-Snow-Leopard-Habitat-of-Nepal

Study area: Nepal

Focal species: Snow leopard (*Panthera uncia*)

Infrastructure type(s): Roads

Background: The northern Himalayan region is a global priority landscape for conservation of the snow leopard, a flagship species that is considered an indicator of the health of high mountain ecosystems. Nepal supports approximately seven percent of the global snow leopard population, but LI development in the country is an emerging threat to the snow leopard. Public demand to expand the road network along Nepal's northern boundary is strong, and national policymakers generally support this expansion to boost Nepal's economic growth by increasing connectivity with the fast-growing economies of neighboring China and India. At least 13 North-South (N-S) roads linking Nepal's lowlands with China are proposed or under construction and would intersect critical habitat for snow leopards. These roads and associated human colonization along their routes are likely to fragment the landscape, reduce gene flow among snow leopard populations, and increase access to snow leopard habitat by poachers.

Methods: The authors conducted an extensive review of academic research, government policies and development plans, and news articles to identify LI development projects in the snow leopard range. They mapped the current density of roads within snow leopard habitat in Nepal and compared this to predicted future road density assuming completion of all proposed N-S roads. Areas of high, moderate, and low risk to snow leopards from roads were identified on the basis of road density. The authors also assessed predicted changes in the density of four other types of infrastructure (mines, trails, settlements, airports, and hydropower), but an expert panel rated roads as a higher risk to snow leopards than these other infrastructure types.

Conclusions: If all proposed N-S roads are completed, the total area of snow leopard habitat impacted by roads would increase by approximately threefold from 5,725 to 17,775 km^2. Impacts were classified as low or moderate for existing roads, but new road development would create 600 km^2 of high impact area and 175 km^2 of very high impact area. The anticipated impacts on snow leopards are likely to extend to many additional species of conservation concern that occupy the same high mountain habitat, including other predators such as the Himalayan wolf, Tibetan fox, and golden jackal, and prey species such as the blue sheep, Himalayan tahr, Himalayan argali, Himalayan serow, goral, and musk deer. The authors suggested that improvements in environmental impact assessments during planning, incorporation of mitigation measures during construction, and monitoring and corrective measures during operation are needed to ensure the sustainability of LI development in Nepal.

EXEMPLARY STUDY 8: POTENTIAL IMPACTS OF ROADS ON TIGERS IN CENTRAL INDIA (THATTE ET AL. 2018)

Publication: Thatte, P., Joshi, A., Vaidyanathan, S., Landguth, E., & Ramakrishnan, U. (2018). Maintaining tiger connectivity and minimizing extinction into the next century: Insights from landscape genetics and spatially-explicit simulations. Biological Conservation, 218, 181-191. https://www.sciencedirect.com/science/article/abs/pii/S0006320717307346.

Study area: Central India

Focal species: Tiger (*Panthera tigris*)

Infrastructure type(s): Roads

Background: India contains 65 percent of the world's tigers, and conservation and management efforts in the country have increased its tiger population by 30 percent over the past 30 years, making it an important stronghold for the species. However, India's tigers occur in PAs and other natural areas in small populations that may not remain viable unless they are sufficiently connected to allow for gene flow. With a rapidly growing economy and a human population expected to double by 2050, India is experiencing strong demand for better road and railway connections among cities. The expansion and upgrading of India's transport network is likely to disrupt connectivity among tiger populations. This study explores how changes in landscape connectivity under future road development scenarios could reduce genetic diversity and increase extinction probability of tiger populations over time.

Methods: The authors collected genetic data from 116 tigers across Central India and used landscape genetic methods to estimate the effects of landscape variables, including road traffic intensity, human settlements, and land use, on tiger dispersal. They then used a genetic simulation program to model mating and dispersal of tigers across the landscape over a 100-year period under a variety of future development scenarios, and to record the expected change in genetic diversity and extinction probability of the tiger population under each scenario. Development scenarios considered in the analysis included the widening of two national highways (NH6 and NH7) such that they would act as barriers to tiger dispersal unless wildlife crossing structures were also constructed.

Conclusions: Models suggested that widening NH7 without wildlife crossing structures would increase genetic differentiation between the Kanha Tiger Reserve and Pench Tiger Reserve populations on either side by a factor of four. Widening of NH6 without crossing structures would increase genetic differentiation between the Nagzira and Nawegaon populations on either side by up to 65-fold. The authors recommend that in cases where proposed roads cannot be rerouted to minimize disruptions to tiger dispersal, mitigation structures such as wildlife overpasses or underpasses should be installed prior to road construction or expansion. Development plans in India must focus on conserving biodiversity and landscape connectivity for wildlife as well as human development goals, and modeling studies such as this one can help identity populations that would be vulnerable to impacts of LI and other forms of development.

EXEMPLARY STUDY 9: POTENTIAL IMPACTS OF ROADS AND RAILWAYS ON CLOUDED LEOPARDS IN MALAYSIAN BORNEO (KASZTA ET AL. 2019)

Publication: Kaszta, Ż., Cushman, S. A., Hearn, A. J., Burnham, D., Macdonald, E. A., Goossens, B., Nathan, S. K. S. S., & Macdonald, D. W. (2019). Integrating Sunda clouded leopard (Neofelis diardi) conservation into development and restoration planning in Sabah (Borneo). Biological Conservation, 235, 63-76. https://www.sciencedirect.com/science/article/abs/pii/S0006320718309480.

Study area: Sabah (Malaysian Borneo)

Focal species: Sunda clouded leopard (*Neofelis diardi*)

Infrastructure type(s): Roads, railways

Background: The Sunda clouded leopard is the apex terrestrial predator in Borneo and genetically distinct from clouded leopards in mainland Southeast Asia. As an area-restricted species with habitat-restricted dispersal, the clouded leopard may serve as an umbrella for other forest-dependent species and an indicator of ecosystem health in the state of Sabah, Malaysia. The Sabah population of clouded leopards has declined to ~750 individuals because of rapid deforestation, and proposed LI development in the region threatens to further fragment its habitat, reduce gene flow, and increase mortality. This study uses a variety of modeling techniques to explore the potential impacts of road and rail developments on clouded leopards and their forest habitat across Sabah.

Methods: The authors compiled spatial data on proposed road and railway developments from the Sabah Structure Plan for 2033, including 16 new four-lane highway segments, 15 road segments to be upgraded to highways, and 10 new railroad segments. They used GPS telemetry data for clouded leopards to estimate the landscape's resistance to leopard movement as a function of land cover, forest characteristics, and roads. They ran connectivity models to simulate movement among areas of suitable habitat for clouded leopard, assuming either the current pre-development landscape configuration or a scenario in which the proposed LI developments were completed, and then compared the results of these pre- and post-development scenarios to estimate impacts to clouded leopards. The authors calculated a series of landscape fragmentation metrics for pre- and post-development scenario landscapes to estimate potential changes to leopard habitat fragmentation. Finally, they used a genetic simulation program to explore how LI development scenarios could restrict leopard gene flow and influence genetic diversity and population size, using a method that incorporated the direct mortality effects of LI development (i.e., roadkills) as well as effects on connectivity. For LI developments with especially large impacts, they also predicted impacts to leopards if these developments were rerouted to minimize impacts to leopard habitat suitability.

Conclusions: Two new road segments, one road upgrade, and one new railway segment were predicted to have significant negative impacts on clouded leopard connectivity and to substantially increase landscape fragmentation, with a 23 percent decrease in connectivity predicted across all LI developments. Genetic simulations predicted decreases in clouded leopard population size (up to 63 percent) across Sabah under the LI development scenario relative to the base scenario, including extinctions of some subpopulations, as well as substantial loss of genetic diversity. Realignment of the five most disruptive proposed LI segments would improve connectivity by three percent but would not improve genetic diversity or population size. The authors emphasized that analyses accounting for increased direct mortality associated with LI, not just reductions in connectivity, are needed to understand the full impacts of LI development on wildlife populations. They also noted that their model predictions of impacts to clouded leopards should be considered conservative because they did not account for the increases in human disturbance, poaching, land conversion, and smaller road construction associated with highway and railroad development.

EXEMPLARY STUDY 10: POTENTIAL IMPACTS OF ROADS ON BIODIVERSITY IN LAOS (DANYO ET AL. 2018)

Publication: Danyo, S., Dasgupta, S., & Wheeler, D. (2018). Potential forest lost and biodiversity risks from road improvement in Lao PDR. Policy Research Working Paper 8569. Development Research Group, Development Economics and the Environment and Natural Resources Global Practice, World Bank Group. https://openknowledge.worldbank.org/handle/10986/30321?locale-attribute=en.

Study area: Laos

Focal species: None (species-neutral)

Infrastructure type(s): Roads

Background: The vast majority of passenger and freight transport in Laos is served by roads, but only about 16 percent of the country's road network is paved. Improving road quality would lower transport costs and increase the profitability of agricultural production in Laos, but it would also increase the clearing of forests for agricultural development in newly profitable corridors surrounding improved roads. This forest clearing could be detrimental to the country's biodiversity, especially to species that rely on intact forest habitat. Policymakers would benefit from spatially explicit information on the biological impacts of potential road improvements to make better decisions about where and how to pursue economic development while protecting biodiversity. This study explored these trade-offs between economic benefits and biodiversity losses associated with improvement to the nationwide road network of Laos.

Methods: This study used spatial data on Laos's existing road network and historical forest clearing patterns to model how forest clearing rate has been influenced by road type and proximity, legal protection status, economic characteristics, and landscape characteristics. The authors then used this model to predict the amount and location of future forest clearing that would occur if all secondary and tertiary roads in Laos's road network were eventually upgraded to primary roads. They also mapped biodiversity value across the country using a composite biodiversity index that combined information on biome status, species density, endemicity, and extinction risk, and which they adjusted for past forest clearing. Lastly, the authors multiplied this clearing-adjusted biodiversity index by the predicted increase in forest clearing predicted by their model under the complete road upgrading scenario to identify areas of high expected biodiversity loss.

Conclusions: Econometric models indicated that secondary roads lead to greater forest clearing than tertiary roads, and primary roads lead to greater clearing still. Upgrading of Laos's secondary and tertiary roads was predicted to cause significant increases in forest clearing, particularly in the country's northern region, where the percent of forest clearing would increase by up to 14 percent in some 500-m grid cells. The biodiversity impacts of forest clearing from road upgrading were predicted to be substantial and broadly distributed across the country. The results of this study could help direct road upgrading investments to transportation corridors where damage to biodiversity will be minimized, while also highlighting areas where more stringent land protection measures will be needed to avoid major biodiversity losses. They noted that the methodology used in their analysis could also be used to assess the environmental impacts of road improvements at smaller spatial scales (e.g., project-level analyses) or the impacts of proposed new roads that do not yet exist.

EXEMPLARY STUDY 11: POTENTIAL IMPACTS OF ROADS AND RAILWAYS ON BIODIVERSITY IN THE TERAI ARC, NEPAL (SHARMA ET AL. 2018)

Publication: Sharma, R., Rimal, B., Stork, N., Baral, H., & Dhakal, M. (2018). Spatial assessment of the potential impact of infrastructure development on biodiversity conservation in Lowland Nepal. ISPRS International Journal of Geo-Information, 7(9), 365. https://www.mdpi.com/2220-9964/7/9/365.

Study area: Terai Arc, Nepal

Focal species: None (species-neutral)

Infrastructure type(s): Roads, rails

Background: Nepal is a global leader in biodiversity conservation and has been recognized for successfully conserving species that require large, intact ecosystems. The transboundary TAL along the Nepal-India border is an especially important landscape for biodiversity conservation because it contains critical habitat for many endangered wildlife species, including mega-fauna such as tiger, elephant, and rhinoceros. The TAL is also an agriculturally productive landscape with high human population density in some areas, and the Nepalese government's Strategic Plan proposes new LI development in the area. The plan includes the Postal Highway and East-West Railway running the full length of the TAL and passing through several PAs, which could threaten the region's biodiversity if not designed properly to minimize environmental impacts. This study forecasted and mapped the effects of proposed LI development in the TAL on biodiversity, using changes in habitat quality as a proxy for impacts to species and populations.

Methods: The authors acquired spatial data from government agencies on existing and proposed roads and rails. They used the habitat quality modeling program InVEST to predict changes in habitat quality associated with development of roads and rails (plus human settlements and agriculture) as a function of habitat suitability and the characteristics of these development threats. Input from government and NGO experts on biodiversity and ecological modeling was included in this process. Habitat changes were modeled under three habitat protection scenarios that assumed different levels of human access (and resulting anthropogenic threats such as poaching, illegal logging, and invasive species) to existing PAs and buffer zones surrounding them. The authors categorized habitat quality scores for the TAL into poor, low, moderate, good, and high classes, and forecasted changes in the spatial distribution of these habitat quality classes resulting from development.

Conclusions: Proposed LI would cross and degrade high-quality habitat in the TAL regardless of the protection level, causing the habitat quality score to decline in up to 12 percent of the areas currently classified as high quality. The extent and magnitude of habitat quality loss was dependent on the level of protection afforded to PAs and their buffer zones. Even under current protection levels, the models predicted reduced habitat quality in some PAs, such as Suklaphanta National Park, Chitwan National Park, and Blackbuck Conservation Area. Road and rail development could reduce habitat quality by up to 40 percent in areas within or near three national parks. The authors suggested that predicted hotspots of habitat loss from this study could be used to direct conservation efforts to especially vulnerable locations. The results could also serve as the basis for developing a strategic environmental assessment for future LI development in the TAL, which would have a broader spatial and temporal scope than the environmental impact assessments that are traditionally conducted for LI projects but are often inadequate for assessing the full extent of environmental impacts associated with LI.

SYNTHESIS OF EXEMPLARY STUDIES

Below, we provide a brief overview of key characteristics of the existing fine-scale studies and suggest how future spatial analyses can build on these studies to fill current gaps in our understanding of potential impacts of proposed LI projects in Asia.

DIVERSITY OF STUDIES

All the studies we reviewed were from South Asia (India, Nepal) or Southeast Asia (Cambodia, Indonesia, Laos, Malaysia, Myanmar). Approximately half of the studies were species-neutral analyses that did not focus on any particular species, and the remainder focused on large felids (tiger, clouded leopard, snow leopard), except for one study that focused on a bird species (Bengal florican). Nearly all studies considered impacts of roads, while half considered railways, and only one study considered power lines. Approximately two-thirds of the studies were published in peer-reviewed science journals, while the remaining third were released as white papers or reports. Co-authors from academia and environmental NGOs each contributed to approximately two-thirds of the studies, while governmental agency staff co-authored approximately one-third of the studies, and multilateral development bank staff contributed to one study.

These characteristics of existing high-quality studies suggest that representation of fine-scale, prospective spatial analyses of LI impacts could be improved by expanding geographic coverage within Asia, particularly in East and Central Asia; expanding taxonomic coverage to include more studies of focal species other than large mammalian carnivores (e.g., birds, herbivorous mammals, reptiles); increasing emphasis on LI modes other than roads, particularly power lines; and more directly involving staff from government agencies and multilateral development banks, who may be largely responsible for approving, planning, and funding LI projects likely to impact biodiversity.

IMPACTS TO BIODIVERSITY

Most studies considered impacts of LI on biodiversity by characterizing predicted changes in the environment experienced by wildlife. The most commonly considered impact was landscape fragmentation, or conversely, loss of connectivity, which nearly two-thirds of studies addressed. Approximately half of the studies considered the effects of proposed LI on the amount or quality of habitat in the landscape, with habitat defined either for individual species or for the biological community in general. Studies of population-level responses of wildlife to LI (such as changes in population abundance, mortality rate, genetic diversity, or extinction risk) were less common; fewer than half of the studies considered one or more of these wildlife responses. Although impacts to landscape composition and structure from proposed LI are often easier to measure and predict, more studies of expected wildlife responses to the landscape changes resulting from LI development are needed to understand the threat posed to biodiversity.

LINEAR INFRASTRUCTURE DATA

Spatial data on proposed LI used in fine-scale studies were obtained from many different sources. Government planning documents were the most common source, but study authors also relied on government and NGO databases, news articles, and permit applications to compile spatial data on proposed LI. The detail and spatial accuracy of LI data appear to have varied widely; some studies mentioned having to digitize data from relatively coarse-scale maps of proposed LI routes in government documents, which can introduce spatial error and limit the potential for fine-scale analyses.

Efforts by government agencies and LI project funders (e.g., multilateral development banks) to improve public accessibility and quality of spatial data on proposed LI would enable easier, faster, and more accurate studies of potential biodiversity impacts of LI development. Ideally, proposed LI routes would be easily obtained via an online database or simple data request; would be provided in a geospatial data format (i.e., a GIS shapefile) to maximize accuracy; would be available early in the planning process to allow sufficient time for studies to be conducted prior to initiation of design and construction; and would contain additional information on the characteristics of proposed LI (e.g., number of road lanes, road surface, presence/absence of fencing, power line voltage, railway track gauge) to allow for more nuanced assessment of LI impacts.

BIOLOGICAL DATA

A wide range of biological data types were used to assess potential impacts of LI development. Maps of designated PAs, forest reserves, and other administrative units that are managed for conservation were used in approximately half of the studies to identify areas where proposed LI could harm biodiversity. Remotely sensed data on land cover and vegetation characteristics were also used frequently to identify locations inside and outside of designated PAs that are likely to support high levels of biodiversity and may be vulnerable to LI development, such as intact forest patches, wetlands, or riparian areas. Many studies also relied on spatial data for other environmental and anthropogenic landscape variables (e.g., land cover, topography, and human development) to infer habitat quality or resistance to animal movement.

Several studies used empirical field data on wildlife occurrence or movement to assess potential impacts of LI. Researchers used telemetry data from Bengal floricans tagged with tracking devices to document existing migration routes in Cambodia, and data from GPS-collared clouded leopards to develop connectivity models for Malaysian Borneo. Camera-trapping data were used to model habitat suitability and develop connectivity models for clouded leopards in Myanmar. Genetic samples collected from tigers in India were used to infer landscape resistance to movement and map wildlife corridors. The time and expense required for collecting field data such as camera trap images, telemetry locations, and genetic samples can be considerable, but these data enable detailed, species-specific analyses of potential LI impacts that can be well worth the extra effort if resources allow. Funding for pre-construction wildlife data collection initiated as early as feasible in the planning process could lead to more robust analyses on LI impacts, such as occurred in these studies.

Although not included in any of the studies we reviewed, data on current patterns of wildlife mortality (i.e., roadkill) and wildlife crossing behavior along existing roads and railways can also inform prospective analyses of the impacts of LI upgrades (e.g., road paving or widening). These data can be used to map current LI segments with high rates of wildlife mortality where mitigation measures to prevent collisions with wildlife should be included in project upgrade designs, as well as current locations of frequent wildlife crossings where connectivity should be maintained by installing wildlife crossing structures such as underpasses and overpasses during LI expansion.

ANALYSIS METHODS

About half of the studies used simple spatial overlays of proposed LI routes with features of conservation interest (e.g., PAs, intact forest patches, biodiversity hotspots, critical habitat, wildlife corridors) to identify potential conflict areas. This approach can often be implemented with minimal data requirements and provides a useful first step for highlighting locations where significant impacts to biodiversity from LI development are likely.

Other studies used more quantitative and data-intensive approaches to predict more specific impacts to biodiversity. For instance, several studies used landscape fragmentation or connectivity metrics to predict how land cover changes or barrier effects associated with proposed LI would affect the potential for wildlife movement across the landscape. Other studies used data on animal occurrence, movement, or genetics to develop species-specific connectivity models to predict movement patterns across the landscape as a function of LI and other environmental and anthropogenic variables. By modeling and comparing connectivity for pre- and post-LI development scenarios, these studies predicted changes in the spatial patterns and amount of animal movement likely to result from LI development. Genetic simulations were used in several studies to predict how changes in landscape connectivity and direct mortality (e.g., wildlife-vehicle collisions) associated with proposed LI would affect genetic diversity, population abundance, and extinction risk of wildlife populations.

The most comprehensive studies in our review combined multiple quantitative methods to predict multiple types of biodiversity impacts. For instance, Kaszta et al. (2019) used connectivity models, genetic simulations, and landscape fragmentation metrics to explore potential changes in landscape structure and connectivity, genetic diversity, and abundance of clouded leopards in Malaysian Borneo. Comprehensive studies such as this require considerable data, expertise, time, and resources to conduct, but they can provide a much more detailed picture of potential LI impacts than simpler methods such as spatial overlays.

RECOMMENDATIONS AND CONCLUSIONS

Several general recommendations and conclusions emerged among the studies we reviewed. First, study authors stressed the importance of improving coordination between entities responsible for LI development and entities responsible for biodiversity conservation within a country or landscape. In some cases, development and conservation plans seemed to be working at cross purposes, and spatial analyses of impacts to biodiversity under alternative development scenarios could help to bridge this gap. Second, early consideration of potential impacts to biodiversity during the LI planning phase, enabled by spatial analyses, is critical for avoiding or minimizing harm. Some studies noted that this early consultation could reduce overall project costs because it is more expensive to redesign LI or install mitigation structures to safeguard biodiversity after initial planning or construction is complete. Third, many studies emphasized that secondary effects of LI development may extend well beyond the physical footprint of construction, but they are not well captured in most spatial analyses. For instance, new road construction may lead to increased poaching and illegal logging in the surrounding landscape by making it easier for humans to access previously remote and ecologically intact areas. Finally, although many spatial analyses focused on the impacts of LI development on a single focal species, study authors frequently noted that the impacts predicted by their analysis will not be limited to the focal species; rather, they expect many other species in their study area to experience similar impacts from LI development.

CONTRIBUTIONS

Tyler Creech (CLLC) conducted reviews of exemplary studies. Rob Ament (CLLC/WTI), Tony Clevenger (WTI), and Grace Stonecipher (CLLC) edited the reviews.

KEY FINDINGS

Many common themes emerged from the three parts of our spatial analyses. The following reflects the most important findings:

1. Spatial analyses are currently constrained by limited availability and poor quality of data on proposed LI. Spatial data on LI project routes have generally not been systematically compiled in spatial databases, and this information often must be cobbled together opportunistically by researchers and other interested parties using planning documents and media reports. This can lead to imprecise route locations, outdated project details, and unintentional omission of LI projects from spatial analyses.

2. Both coarse- and fine-scale spatial analyses play an important role in characterizing threats to biodiversity from LI and designing and prioritizing safeguards. Coarse-scale studies can inform the selection of priority areas at the continental or regional scale for pursuing efforts to avoid or minimize harm to the biological community. Fine-scale studies offer insights into potential impacts of individual LI projects on species or habitats of concern at sufficient resolution to inform project planning and mitigation or compensation strategies and their implementation.

3. Power line effects on biodiversity have been understudied relative to the adverse effects of roads and railways, and very few spatial analyses of LI development have considered power lines. However, extensive power line development is proposed across Asia, and much of it is in areas of high biodiversity or near PAs.

4. Spatial approaches for estimating impacts of proposed LI are diverse. Approaches vary with respect to spatial scale (extent and resolution), analytical methods, biodiversity elements considered (e.g., populations, species, and ecosystems), and types of LI impacts considered (e.g., habitat degradation, landscape fragmentation, and reduced population abundance). There is no single best approach—rather, approaches are context-specific and constrained by the availability and quality of biodiversity data and LI data.

5. Species-neutral spatial analyses of potential LI impacts are common and may be necessary when considering very large spatial extents, when impacts to the broader ecological community are of primary interest, or when biological data for species of conservation concern are not available. However, species-specific analyses can provide more direct estimates of wildlife responses to LI development (e.g., changes in population abundance, geographic distribution, or extinction risk) that may resonate more with planners and the public than species-neutral analyses.

6. Cumulative effects and secondary effects may not be receiving adequate consideration in spatial analyses. Cumulative effects are the incremental impacts of a proposed LI project when added to other past, present, and future development (e.g., existing roads in a landscape). Secondary effects are the indirect impacts of other threats that are heightened by LI development, such as illegal logging and poaching that occur in remote areas accessed by new roads. Relatively few spatial analyses explicitly consider cumulative and secondary effects, which may be difficult to quantify, but their impacts on biodiversity can be significant.

7. Existing peer-reviewed spatial analyses have largely focused on South and Southeast Asia, which is understandable because these regions are likely to experience the most severe LI impacts given their rapid pace of LI development and high biodiversity value. However, this narrow geographic focus of spatial analyses limits our understanding of potential LI impacts to biodiversity in other regions of Asia, where the species, habitats, and ecological processes that are threatened may be different (e.g., disruption of long-distance migration routes used by ungulates in the steppes of Central Asia).

8. Existing analyses at the global or continental scale have also focused largely on LI projects associated with China's BRI. However, our coarse-scale analysis suggests that proposed LI funded by other regional economic development initiatives (e.g., SASEC, CAREC, ASEAN) is at least as extensive as proposed BRI-funded LI within Asia. The impacts of these non-BRI projects on Asian biodiversity will be considerable, and in many countries cumulative with BRI impacts.

9. LI development impacts are expected to occur across Asia, but tropical and subtropical forests of Southeast and South Asia may be especially severely impacted. High-profile ecosystems (e.g., Terai Arc, Bornean, and Sumatran rainforests) are threatened by proposed LI, but so are many lower-profile ecosystems with similarly high biodiversity value but less public recognition. For instance, many areas within the Mekong Basin have exceptional biodiversity and a high density of proposed LI.

RECOMMENDATIONS

We offer the following recommendations to improve spatial analyses of threats to biodiversity from proposed LI development. Implementing these recommendations would increase accuracy, comprehensiveness, and ultimately the effectiveness of spatial analyses to inform LI plans and projects and safeguard biodiversity.

1. *Financial institutions, regional infrastructure partnerships, and governments should dedicate resources to create and maintain geospatial databases of proposed LI projects*. These spatial data are currently difficult to efficiently access and obtain, which limits the potential for conducting spatial analyses during the planning phase that could ensure effective biodiversity safeguards are included in LI design. Databases should include the route location in a geospatial data format and as much information on LI characteristics (e.g., road width and surface type, railway gauge, and power line voltage) as possible. Databases should also be updated regularly as project plans change, should be easily accessible to the public, and should include detailed metadata.

2. *Spatial analyses should be conducted as early as possible to inform the design of safeguards*. Although we found examples of exemplary studies that predicted impacts of proposed LI projects using spatial analyses, nearly all studies of LI impacts are conducted retrospectively and instead document damage to biodiversity that has already occurred. Prospective studies conducted early in the planning and design of LI projects provide information that can lead to avoidance, minimization (e.g., rerouting), or implementation of mitigation or compensation measures for projects likely to harm biodiversity.

3. *LI planners, funders, and developers should partner with biological experts from academia, NGOs, and wildlife agencies to identify potential for LI to harm biodiversity and to conduct spatial analyses.* A disconnect often exists between those with expertise designing and constructing LI and those with expertise assessing impacts to biodiversity, which limits the ability to implement effective safeguards. Cooperation between these two groups from the outset of LI development plans would lead to better outcomes for biodiversity and could potentially save time and money.

4. *More attention should be given to power lines in spatial analyses.* Power lines deserve greater consideration given that they comprise a significant proportion of proposed LI development in Asia, particularly in areas of high biodiversity. Other LI modes not covered in this report, such as canals, fences, and pipelines, can also have large impacts on biodiversity and should be considered in spatial analyses.

5. *The geographic and taxonomic scope of spatial analyses should be expanded.* Spatial analyses focusing on regions other than Southeast Asia and taxa other than large mammals are needed to broaden our understanding of potential LI impacts in Asia and the best ways of assessing those impacts.

6. *All sources of LI projects should be combined in large-scale spatial analyses evaluating impacts to biodiversity.* This includes projects funded by other international economic development initiatives (e.g., SASEC, CAREC, ASEAN) and projects funded at the national or subnational level, which, like the BRI, could have a large impact on Asian biodiversity.

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