

PERSPECTIVE

Emerging Methods in Business and Biodiversity

A framework for capturing indirect impacts in site-level screening for biodiversity risks

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Abstract

1. Site-based industrial operations such as mining, oil and gas extraction and renewable energy development are associated with many direct and indirect impacts on biodiversity. Consideration of the full range of these impacts when selecting a buffer distance to approximate the Area of Influence (Aoi) of a project is critical for effective biodiversity risk screening.
2. Indirect impacts, however, are elusive despite often being more extensive than direct ones, both temporally and spatially. There is also limited clarity on the distinction between direct and indirect impacts, leading to the latter either being missed from screening analyses or misclassified as direct impacts.
3. Here we propose a definition of indirect impacts and a framework for incorporating them in risk and impact analyses. We define indirect impacts as those that are triggered by wider socio-economic and demographic changes induced by the project and not directly by project operations.
4. Indirect impacts manifest through three pathways: increased access to intact ecosystems, increased in-migration and settlement and increased viability of other economic activity. A range of factors, however, can act as predictors of the likelihood and intensity of indirect impacts and form the basis of a decision-making framework to select a buffer that captures their Aoi effectively.

KEYWORDS

area of influence, biodiversity impact assessment, environmental screening, indirect impacts, infrastructure development

1 | INTRODUCTION

Site-based industrial operations within the infrastructure, extractive and energy sectors can trigger a range of direct and indirect impacts on biodiversity (Lenzen et al., 2003). These occur at different spatial scales, leading to variation in the project's 'Area of

Influence' (Aoi), that is the distance around a project corresponding to the spatial extent to which impacts manifest. Capturing the full range of impacts with an appropriate distance buffer around a site (Figure 1) is critical for effective high-level risk screening, targeting more detailed site-specific impact assessments and for designing robust mitigation measures (Johnson et al., 2020; Laurance

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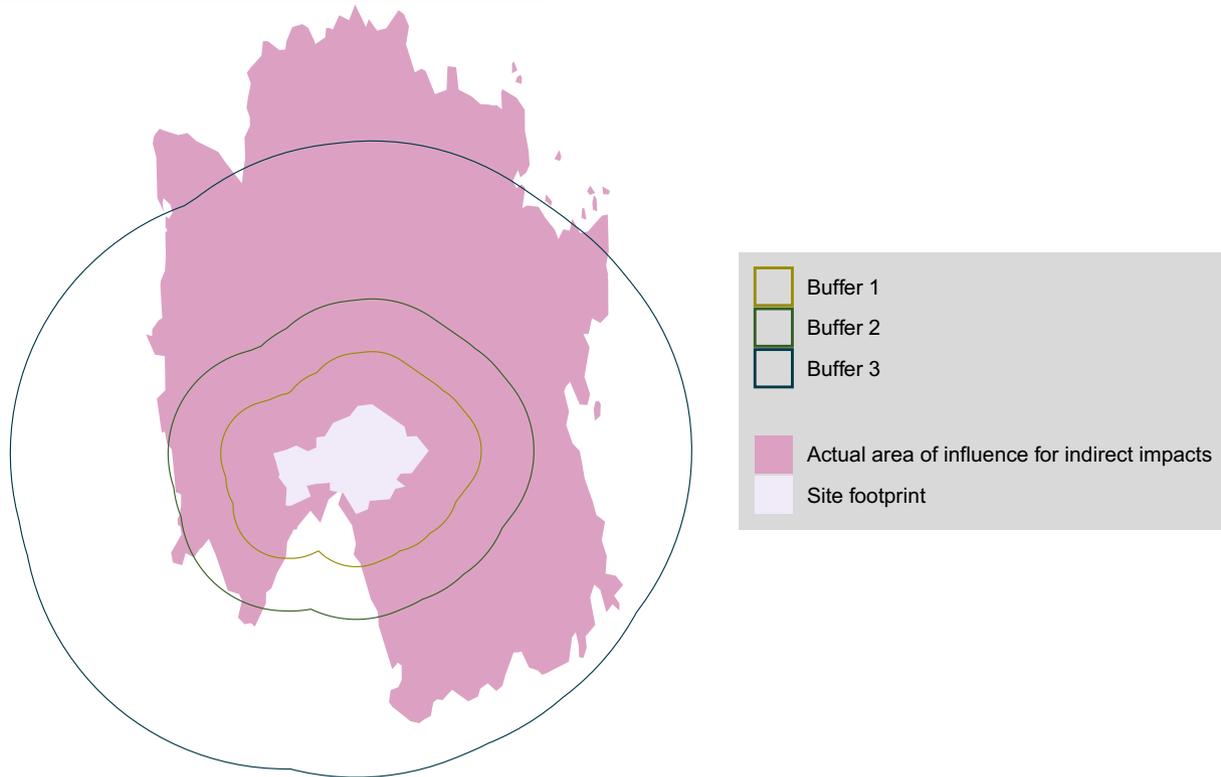


FIGURE 1 A visual illustration of area of influence (AoI) and buffers. A project will have a site footprint, within which occur most direct impacts. Indirect impacts can occur at a much greater spatial extent. A buffer is a set distance around the site footprint set to best approximate the actual (unknown) AoI of indirect impacts. In this example, Buffer 3 appears most appropriate for this purpose as it captures the largest area of the actual AoI. In reality, it is very difficult to determine the actual AoI.

et al., 2015). Fully capturing impacts at individual sites at the screening stage is also an important step towards a more integrated assessment and management of multiple sectors when planning shared landscapes.

Direct impacts result from effects (such as animal collisions, barriers to movement, habitat loss and pollution) stemming directly from project operations. Indirect impacts, on the other hand, are facilitated rather than caused directly by project operations (Raiter et al., 2014). Indirect impacts can often be profound and enduring, which makes it important for them to be adequately assessed and mitigated (Laurance et al., 2015; Lenzen et al., 2003). For example, deforestation resulting from the land-use change and urbanisation triggered by mining in the Brazilian Amazon has been observed up to 70km from the boundary of the mine lease (Sonter et al., 2017). Similarly, Brazil's Belo Monte dam, which was completed in 2019, is expected to continue to lead to an additional 4000–5000km² of deforestation until 2031 due to the growing settlements around the dam (Lees et al., 2016). Indirect impacts can extend to a distance of several kilometres from the project and can continue to manifest for several years after project completion.

Despite the importance of indirect impacts, risk and impact assessment literature lacks clarity on the distinction between direct and indirect impacts. Some wind energy literature (Gove et al., 2013; Kuvlesky et al., 2007; Mascarenhas et al., 2018; Schuster et al., 2015), for example, classifies bird injuries or fatalities resulting from

collisions with wind farm infrastructure as direct impacts, whereas habitat loss, fragmentation and behaviour effects (e.g. avoidance) caused by the construction and operation of the same infrastructure are labelled as indirect impacts. Similarly, Butt et al. (2013) group together diverse pressures including soil erosion, water pollution and induced illegal hunting whilst describing the indirect impacts of fossil fuel expansion.

The elusiveness and complexity of indirect impacts means they are largely under-represented in impact assessment practice (Brownlie et al., 2013; Lenzen et al., 2003) even as leading international investment standards (e.g. International Finance Corporation, 2012) and national regulation (e.g. the European Commission's EIA Directive (1985)) require accounting for them.

Under-representing indirect impacts when estimating the AoI of a project can result in inaccuracies in both high-level biodiversity risk screening as well as in more in-depth impact assessment. Here we present a framework for incorporating indirect impacts in such assessments. Our focus is on site-based industrial projects, that is projects where hub infrastructure such as a mine, dam or power-plant is at the centre of operations, whereas linear infrastructure is ancillary, connecting the hub infrastructure to supply chains. We do not focus on projects where the main objective is the development of linear transport infrastructure or infrastructure corridors. In addition, whilst site-based industrial projects can also result in cumulative impacts, with impacts (both direct and indirect) from multiple

projects aggregating over time and space, this work, in its present scope, does not focus on such impacts.

We begin by defining what indirect biodiversity impacts mean in the context of site-based industrial operations within the extractives, energy and infrastructure sectors. Next, using hypothetical cases, we explore the key pathways through which indirect impacts manifest. Next, we present a decision-making framework for the selection of a buffer to approximate the Aol for risk screening and impact assessment such that it captures indirect impacts. To illustrate the decision-making framework, we prepare a global screening layer mapping the areas that trigger the application of precautionary buffer distances to capture indirect impacts. We also examine the literature to explore what buffer distances have been used for assessing indirect impacts.

2 | UNPACKING INDIRECT IMPACTS

Whilst direct impacts are attributable directly to project operations, indirect impacts are a step removed and occur beyond the immediate physical footprint of the project. Variouslly dubbed as induced, secondary or off-site impacts, indirect impacts result from the wider socio-economic and demographic changes triggered by the operations and involve third-party actors such as migrants (Johnson et al., 2020; Lenzen et al., 2003; Raiter et al., 2014). Some site-based industrial projects such as mines or oil and gas extraction are growth-inducing by design, that is they are strategically planned to stimulate spin-off economic growth. Such 'keystone projects' catalyse population influx and an increase in disposable incomes and consumption, which in turn change the extent and intensity to which local actors access and use natural ecosystems (Johnson et al., 2020). In the process, pressures such as induced or intensified bushmeat hunting, poaching, logging and land clearing occur beyond the project boundary, resulting in impacts on species and habitats that are spatiotemporally far-reaching (Jones et al., 2014). These impacts on species and habitats are what we term indirect impacts. We therefore refer to 'indirect impacts' as those triggered by the wider socio-economic and demographic changes induced by project operations and not by the project operations at the site itself. Indirect impacts should not be confused with those impacts that occur and accumulate through the entire lifecycle of a product from material sourcing to disposal, known in business as 'the value chain'. For example, the localised deforestation induced by the presence of a mine road constitutes an indirect impact. Whereas the deforestation in another country associated with the harvesting of timber for construction materials at the site constitutes an impact in the value chain.

Whilst much of the infrastructure/extractive industries literature emphasises human-mediated pathways (hunting, settlement, etc.), but indirect impacts also operate through ecological processes themselves, even in the absence of additional human action. In a broader, non-anthropocentric ecological context, indirect impacts can be understood as cascading effects of disturbance that

propagate through ecosystems beyond the immediate development footprint. For example, reductions in large predators or prey caused by disturbance can trigger trophic cascades that restructure entire food webs (Ripple et al., 2014). Similarly, linear clearings and fragmentation produce edge effects—altered light, temperature, wind and humidity regimes—that penetrate deeply into adjacent habitats, driving shifts in species composition, mortality rates and ecological processes such as pollination, decomposition and nutrient cycling (Didham & Lawton, 1999; Laurance et al., 2002).

3 | INDIRECT IMPACTS PATHWAYS

The key driver of indirect impacts in the case of site-based industrial operations such as mining, oil and gas and renewable energy development is the ancillary linear infrastructure and clearings (e.g. roads, railway lines, powerlines and seismic lines) associated with the nodal or hub infrastructure (Jones et al., 2014; Raiter et al., 2014). Although the direct footprint (physical area occupied) of the hub infrastructure, for example mine, dam or powerplant itself is usually small, the ancillary linear infrastructure often extends over several kilometres, connecting the project to raw material sources, population centres and markets and triggering a slew of pressures on biodiversity (Jones et al., 2014; Teo et al., 2019). Spurred by the ancillary linear infrastructure, indirect impacts of site-based industrial operations follow three temporally sequential and mutually reinforcing pathways (Figures 2 and 3):

1. *Increased access to habitats*—Ancillary linear infrastructure associated with site-based industrial projects induces new or deeper access of third-party actors such as bushmeat hunters, poachers and loggers into intact habitats, facilitating increased exploitation that is often unregulated or illegal. For example, increased access by poachers along oil exploration roads led to a collapse in Guanaco (a camelid native to South America) populations up to a distance of 20km from three surveyed sites in northern Patagonia over a period of 20 years (Radovani et al., 2015).
2. *In-migration and settlement*—The employment opportunities and the new access into ecosystems created by the project trigger population influx and settlement that change the dynamics and patterns of human habitation of areas, leading to pressures such as land clearing and overexploitation of wildlife and forest resources. Such a scenario played out with the opening of the Geita Mine, Tanzania's largest open-pit gold mine that resulted in the quadrupling of the population of the Geita township (Lange, 2006). An additional risk is that when contracts end, the lack of alternative livelihoods and adequate skills transfer (Lesutis, 2021) leads workers to engage in exploitative activities.
3. *Increased viability of other economic activity*—The increased access to raw materials and markets facilitated by the ancillary infrastructure of industrial projects makes other economic activity viable, triggering further exploitation of nearby ecosystems. For instance, improved

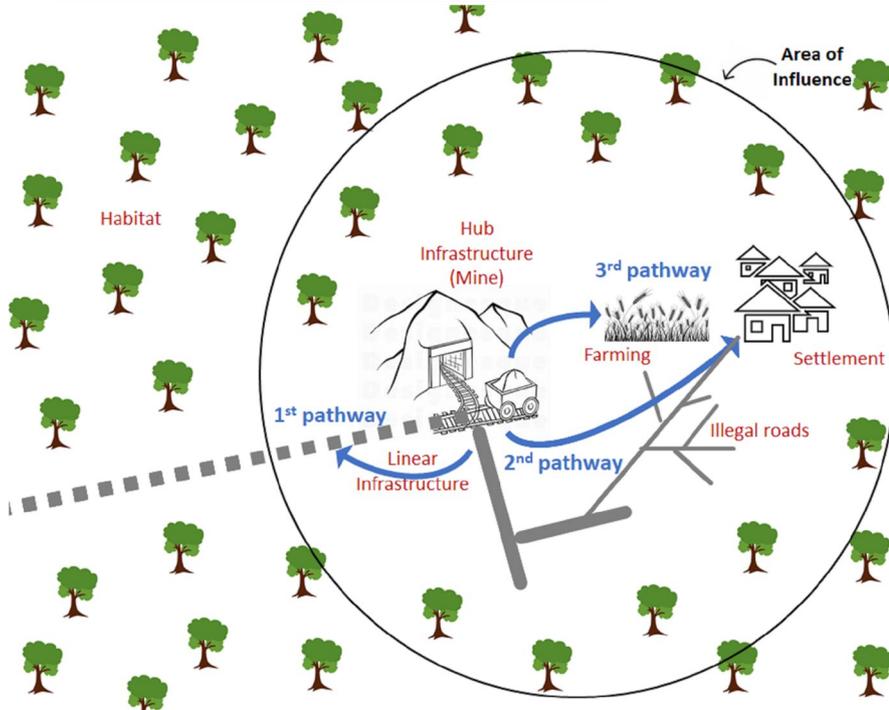


FIGURE 2 Illustration of indirect impact pathways and area of influence (AoI). In this example, indirect impacts of a mine located in a forest ecosystem manifest within the AoI through proliferation of illegal roads connecting to official ancillary infrastructure (first pathway), building of settlements to house mine workers (second pathway) and agriculture started to cater to a new market (third pathway).

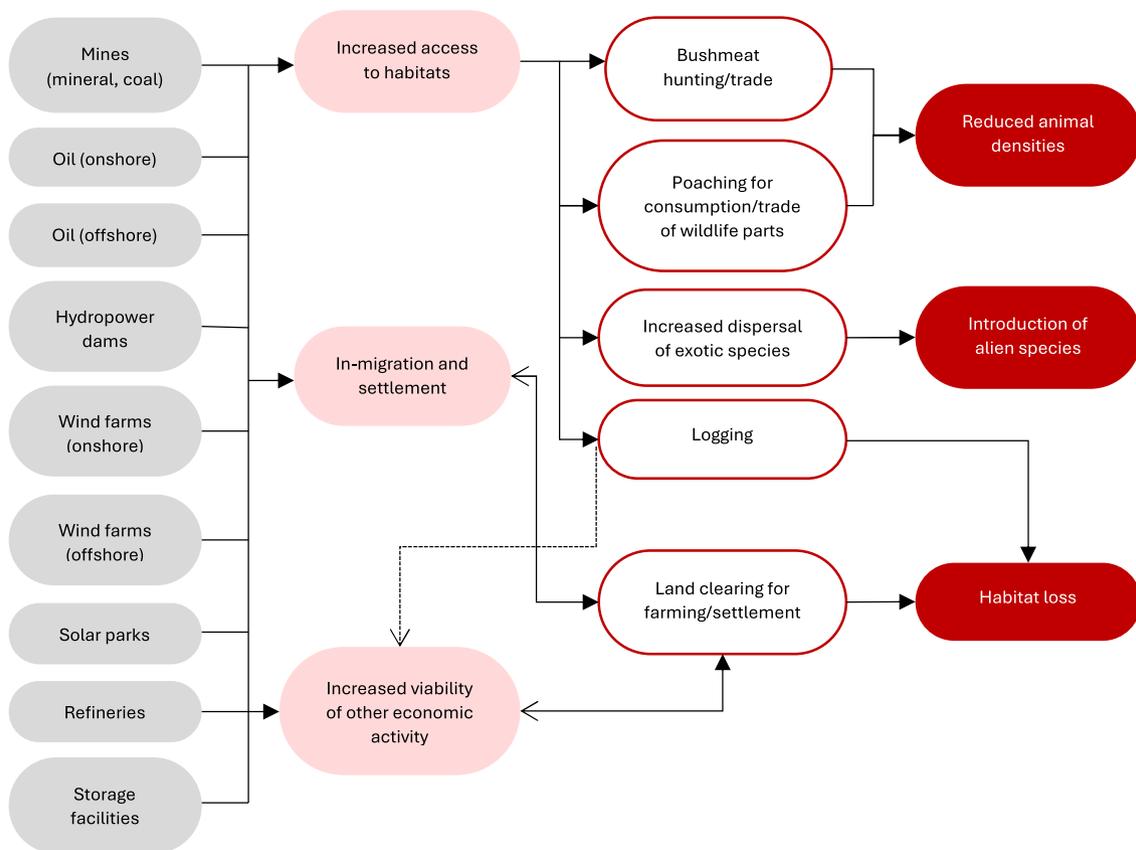


FIGURE 3 Indirect impact pathways of site-based industrial operations. Impact pathways with pressures induced and resultant indirect impacts for various industrial project asset types. Stages occur sequentially. However, in many cases, impact pathways, pressures and impacts incorporate feedback loops. For example, logging as a result of in-migration and settlement can also increase the viability of other economic activities.

TABLE 1 Indirect impact pathways: Evidence from literature.

Impact pathway	Asset type	Pressure	Impact	Aol (km)	Citation	
Increased access to habitats	Mines (mineral, coal)	Bushmeat hunting/trade	Reduced animal densities		Owusu et al. (2018); Suárez et al. (2009)	
		Logging	Reduced animal densities		Owusu et al. (2018)	
	Oil (onshore)	Bushmeat hunting/trade	Reduced animal densities		Thibault and Blaney (2003)	
		Increased dispersal of invasive alien species	Introduction of invasive alien species		Adesipo et al. (2020)	
	Wind farms (onshore)	Poaching for consumption/trade of wildlife parts	Reduced animal densities		20 km	Radovani et al. (2015)
		Increased dispersal of invasive alien species	Introduction of invasive alien species			Numbere (2018)
		Increased dispersal of invasive alien species	Introduction of invasive alien species			Page et al. (2006)
		Increased dispersal of invasive alien species	Introduction of invasive alien species			Keehn and Feldman (2018)
		Increased dispersal of alien species	Introduction of invasive alien species			Kerckhof et al. (2016)
		Land clearing for farming and settlement	Habitat loss		70 km	Sonter et al. (2017)
In-migration and settlement	Mines (mineral, coal)	Land clearing for farming and settlement	Habitat loss		Finer and Jenkins (2012)	
	Hydropower dams	Land clearing for farming and settlement	Habitat loss		Kitula (2006)	
Increased viability of other economic activity	Mines (mineral, coal)	Land clearing for farming and settlement	Habitat loss			

TABLE 2 Predictor variables for the likelihood of indirect impacts and associated examples of datasets.

Factors influencing indirect impacts	Supporting evidence	Predictor	Example dataset	Discretionary threshold
Existing roads (first pathway)	Ibisch et al. (2016)	Degree of roadlessness of the site	Global map of roadless areas (Ibisch et al., 2016)	Areas further than 1 km from any road
Existing settlement (second pathway)	Chomitz and Grey (1996); Laurance et al. (2002)	Settlement classification of the site	Global Human Settlement Degree of Urbanization Settlement Model Grid (GHS-SMOD), (Schiavina et al. 2023)	Cells identified as low or very low density rural
Existing economic development (third pathway)	Pfaff et al. (2018); Chomitz and Grey (1996); Faria and Almeida (2016); Jaffé et al. (2021)	GDP per km ² of the site	Grid of total economic activity in millions of dollars per km ² pixel (Kummu et al. 2025)	<USD 2 million per km ²
Accessibility to markets/urban areas	Rideout et al. (2013)	Travel time to cities from the site	Global map of travel time to cities (Nelson, 2022)	A travel time of more than 24 h to a settlement of >50,000
Current human modification (habitat state)		Overlap of site with low modified land	Global map of low modified lands (Theobald 2024)	Cells with lower than 0.1 modification
Biodiversity value (habitat sensitivity)		Overlap or proximity of site to critical habitat	Global critical habitat screening layer (UNEP-WCMC, 2025)	Likely or potential critical habitat

infrastructure in the form of roads and powerlines makes marginal agricultural lands more profitable (Lees et al., 2016). Communities around Tanzania's Geita gold mine have reported an increased market for their agricultural products due to population influx at the mine site (Kitula, 2006). Development of 'keystone' infrastructure also facilitates/subsidises growth of upstream and downstream operations which come with their own set of biodiversity impacts. The cheap electricity from Canada's Northwest Transmission Line, for example, is expected to result in a boom in metal mining in the mineral-rich region of north-western British Columbia (Pollon, 2011). Another example is that of illegal artisanal mining: commercial mines of precious commodities such as gold and diamonds often propagate the development of unregulated and illegal artisanal mining in the vicinity, which creates pressures such as soil and water pollution and deforestation. Illegal gold mining in the Brazilian Amazon is a case in point. The deforestation induced by artisanal mining increased by 90% from 2017 to 2020, a rate much higher than that within industrial mining leases (Siqueira-Gay & Sánchez, 2021).

Scholarly literature documenting these indirect impact pathways associated with industrial operations suggests that bushmeat hunting, poaching, logging and increased dispersal of invasive alien species are the key pressures, whilst land clearing is the main pressure associated with the second and third pathways (Table 1). In the case of offshore energy (oil and gas and wind), dispersal of invasive alien species was seen as the key pressure. Evidence from literature on indirect impacts of solar energy is sparse, as is that on mineral processing, refining and storage facilities.

4 | FACTORS INFLUENCING INDIRECT IMPACTS

The exact spatial extent (kilometres) to which indirect impacts of site-based industrial operations manifest is limited (e.g. Radovani et al., 2015; Sonter et al., 2017). Evidence exists, however, on how some broad-scale socio-economic and demographic factors (such as population density, prior development) can act as a proxy for the degree to which indirect impacts (such as deforestation) can be triggered by (ancillary) linear infrastructure. Although the relationships between these broad-scale factors and indirect impacts are not fixed and definitive, an overall positive or negative correlation can be discerned. These factors can thus act as high-level predictors of the likelihood of occurrence and intensity of indirect impacts within an initial screening process. For example, roadless areas are more sensitive to ecological damage than areas that have already been impacted by the presence of roads (Ibisch et al., 2016). The presence of existing roads is thus negatively correlated to the extent of indirect impacts (e.g. through deforestation) that can be triggered by a new project. The degree of roadlessness of an area can thereby act as a predictor of the occurrence of indirect impacts. Table 2 lists six key socio-economic and demographic factors that influence indirect impacts and the

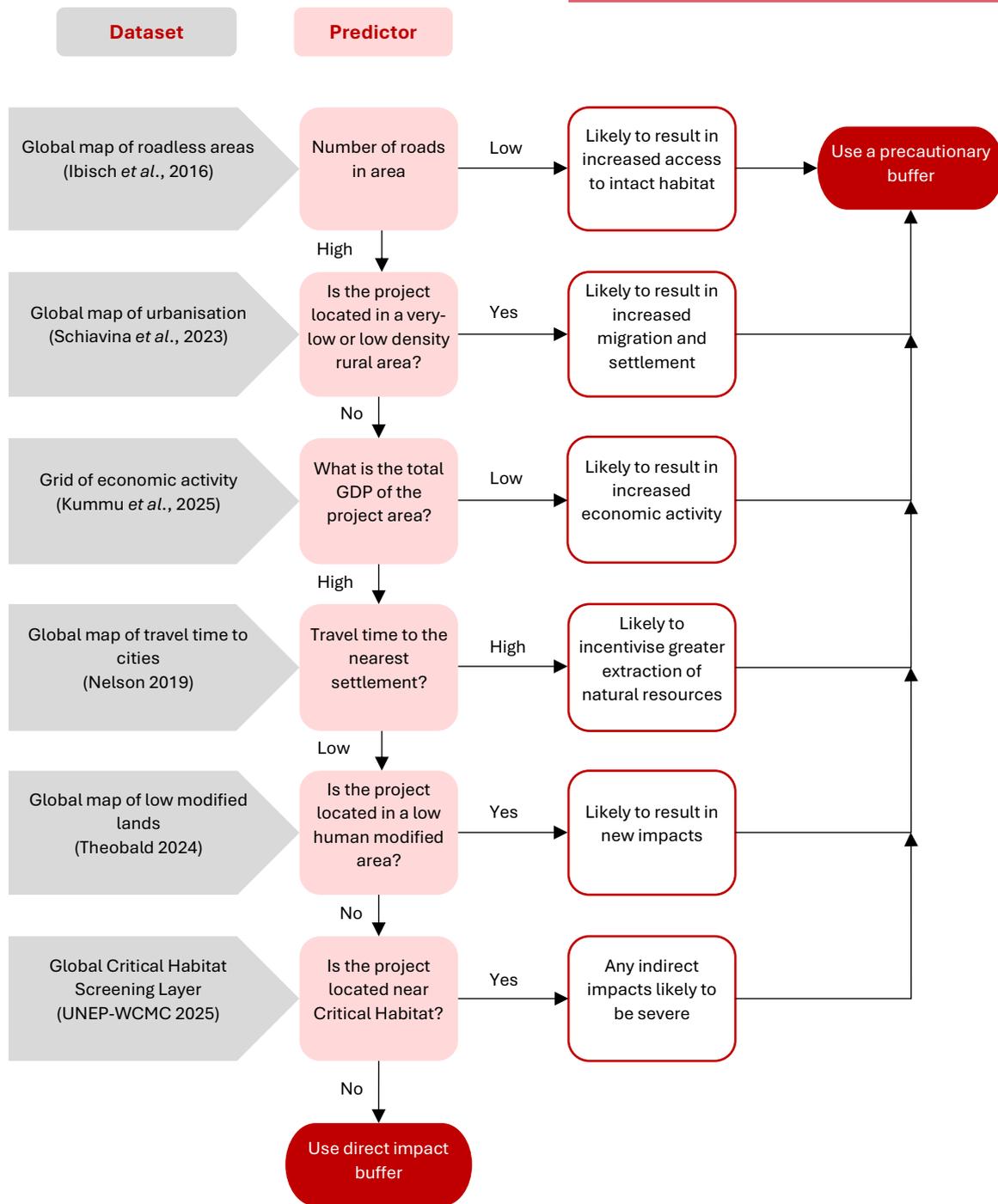


FIGURE 4 Decision-making framework for selection of area of buffer type. The framework presents an approach to better capture indirect impacts and suggests datasets that could be used to determine whether the evaluation of site impacts should be calculated using a precautionary buffer.

predictors they translate into. These include: existing roads, existing settlements, existing economic development, accessibility to markets/urban areas, current human modification and biodiversity value. Each of these factors is spatially explicit (non-spatial factors, such as commodity prices, have not been included) and has open-access global spatial datasets that can be used to ascertain the corresponding predictors of indirect impacts for each project or portfolio of projects under consideration (Table 2).

5 | DECISION-MAKING FRAMEWORK FOR BUFFER SELECTION: ACCOUNTING FOR INDIRECT IMPACTS

In the absence of exact kilometre figures of the spatial extent to which indirect impacts manifest, broader predictors (listed in Table 2) can be used to decide whether a precautionary buffer should be applied to approximate the Aol of both indirect and direct

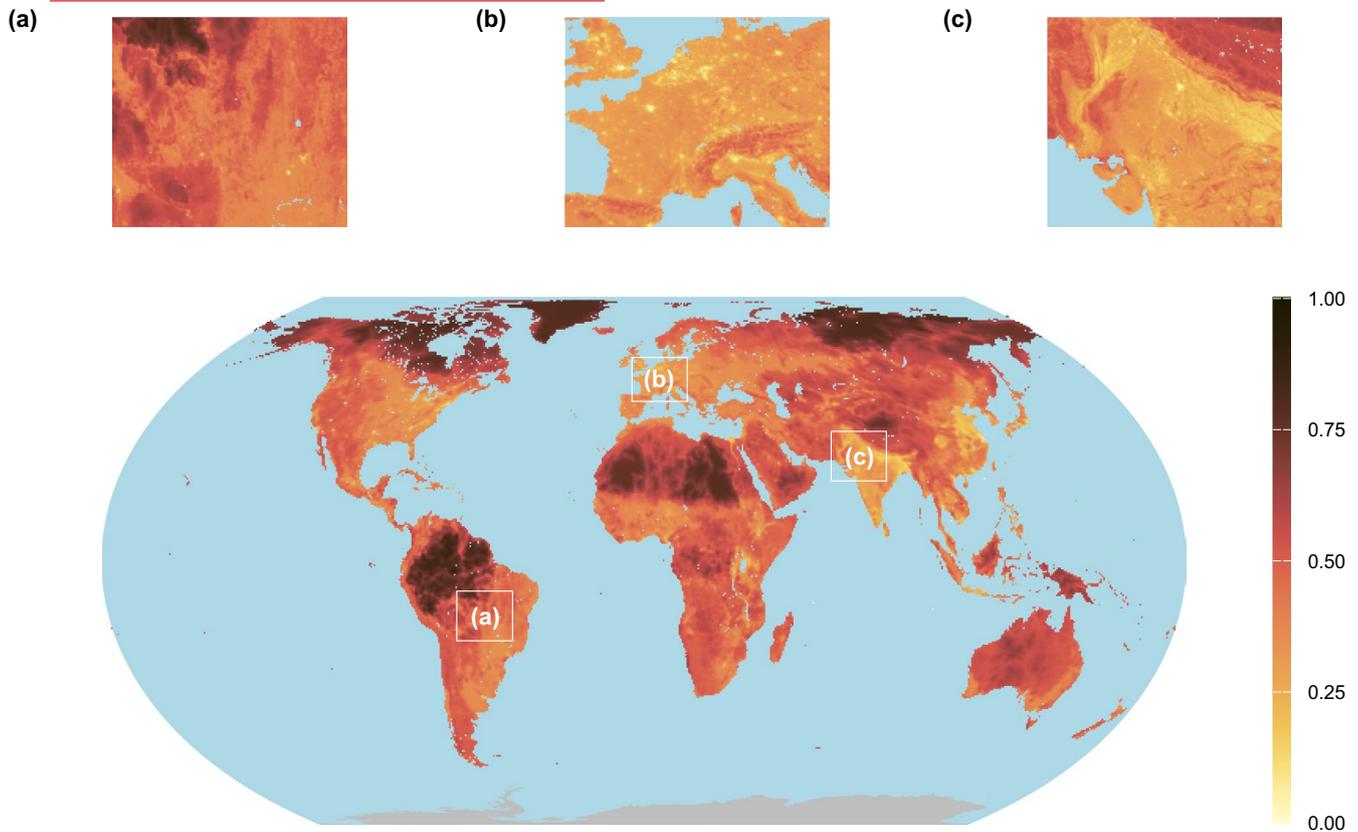


FIGURE 5 Global likelihood map for requiring precautionary buffers for indirect impact analysis. An illustrative example of how the decision-making framework, combined with readily available open datasets, can aid indirect impact analysis. Six input datasets are standardised from 0 to 1 by fitting a logistic curve around discretionary thresholds and combined using the mean of all layers to produce the output. Insets provide more detail for (a) South America, (b) Western Europe, and (c) South Asia. Data aggregated from 1 to 10 km resolution in Equal Earth projection (EPSG:8857) for visibility.

impacts or a more moderate one that captures only direct impacts. A justifiable distance for a precautionary buffer might be the maximum range indirect impacts have been observed in the literature, for example for mining, 70 km (Table 1). These predictors are organised into a structured decision-making framework in Figure 4. An exemplar global screening layer following this framework is presented in Figure 5. The screening layer was produced by assigning fuzzy membership logistic functions to the six input datasets around discretionary thresholds (Table 2). This results in a ‘fuzzier’ threshold that better reflects real-world uncertainty than a binary outcome. For categorical datasets, classes were manually assigned values 0–1. The mean of the six input datasets is then taken, as no one predictor is thought to be more important than others, to produce a likelihood layer. Alternatively, the framework can be used to produce a binary output (Figure S1), a standardised approach that does not use thresholds (Figure S2), or the input datasets can be weighted when combined to highlight the importance of certain predictors over others (Figure S3).

The following are two hypothetical cases that demonstrate how the decision framework and screening layer can be applied:

Case 1: Bauxite mine A is sited in a tropical dry forest (e.g. Figure 2), with a few forest villages in the vicinity, inhabited

by Indigenous communities. The nearest paved road is located 20 km away. The key economic activity of the local communities is the collection of non-timber forest products. It takes 2 days to travel to the nearest city. The site is located within a distance of 25 km from the boundary of an IUCN Category Ia Protected Area.

Overlaying the coordinates of the project onto the global screening layer returns a value of 0.8, with a mean of 0.75 in the surrounding area. It is likely that the protected area may be impacted by the site through indirect impacts. A precautionary buffer to capture the indirect impacts should therefore be applied for risk screening.

Case 2: Bauxite mine B is sited near an aluminium industrial cluster, with another mine and several ancillary and downstream facilities such as smelters already present. The habitats within 1 km of the mine are not classified as critical habitat. The cluster is strategically well connected by roads and railways. A major port is also located at a distance of approximately 175 km. People from the nearby township are employed within the cluster. The mine site is also 25 km from the boundary of an IUCN Category Ia Protected Area.

Overlaying the coordinates of the project onto the global screening layer yields a value of 0.2, with a mean of 0.32 in the surrounding

area. This may mean that the protected area is assessed as not at risk of being impacted by the site. Whilst indirect impacts should not be ignored, a moderate buffer that captures direct impacts can be applied for the purposes of high-level risk screening.

Application of the decision tree may not always yield obvious high or low values, in which case it is recommended that a precautionary buffer is the default to ensure all potential risks are captured. The framework presented here represents just one step in impact assessment—screening—that must be adequately complemented by additional, more detailed methods such as field surveys.

6 | CONCLUSION

Indirect impacts of industrial development have remained a grey area in terms of how they are defined, identified and captured in biodiversity risk screening and impact assessment. This leads to the possibility of impacts on important biodiversity features being missed during screening processes. There may also be mistrust in the use of more precautionary buffers due to unclear justifications. The definition of indirect impacts provided here offers greater clarity on the pathways these indirect impacts follow and the factors that determine their extent and can therefore help ensure more comprehensive screening, a more trusted assessment of risks from indirect impacts and thereby more robust decision-making on project development, financing and impact mitigation. The decision-making framework we present for selecting a buffer to approximate the Aol has applicability for risk screening at both project level (for businesses) and portfolio level (for financial institutions). Additionally, from a development planning perspective, individual sites incorporating the potential for indirect impacts in their screening processes is an important step towards a more integrated and systematic assessment approach of multiple sites within shared landscapes.

AUTHOR CONTRIBUTIONS

Divya Narain and Jacob Bedford conceived the ideas and designed methodology; Aime Rankin, Elspeth Grace and Alfred Muge collected the data; Elspeth Grace, Alfred Muge and Sebastian Dunnett analysed the data; Divya Narain and Jacob Bedford wrote the original draft, Sebastian Dunnett and Matthew I. Jones reviewed and edited. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

Sebastian Dunnett is a guest editor of this special issue of *Methods in Ecology and Evolution* but took no part in the peer review and decision-making processes for this paper.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.70162>.

DATA AVAILABILITY STATEMENT

Code used to generate the data has been archived at <https://doi.org/10.5281/ZENODO.16997585> (Dunnett, 2025b) and the corresponding data are also available at three different resolutions—1, 10 and 50 km in Equal Earth (EPSG:8857) projection—and in three different formats via <https://doi.org/10.5281/ZENODO.17093377> (Dunnett, 2025a):

1. `fz_screening_layer_*.tif`: Six input datasets are transformed to follow a logistic distribution centred on a pre-defined threshold. The mean of these six datasets is then taken to produce a gridded layer with values 0–1 showing the likelihood of needing a precautionary buffer.
2. `std_screening_layer_*.tif`: Six input datasets are standardised to a range of 0–1. The mean of these six datasets is then taken to produce a gridded layer with values 0–1 showing the likelihood of needing a precautionary buffer.
3. `binary_screening_layer_*.tif`: Six input datasets are transformed to binary TRUE/FALSE grids based on their values vs. a pre-defined threshold. If any of the datasets present TRUE for a particular grid cell, the combined layer will also show TRUE, indicating a precautionary buffer is needed.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Global screening layer for requiring precautionary buffers for indirect impact analysis.

Figure S2. Global likelihood map for requiring precautionary buffers for indirect impact analysis.

Figure S3. Plots illustrating the effect of weighting the six input variables (standardised to 0–1) on the overall screening layer.

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