Integrating spatially realistic infrastructure impacts into conservation planning to inform strategic environmental assessment

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Abstract
Infrastructures such as roads and pipelines have environmental impacts that diffuse far beyond the local development footprint, including fragmenting habitat or changing hydrology. Broad-scale diffuse impacts are challenging to incorporate into conservation planning and strategic environmental assessment due to difficulties in determining how impacts spread across landscapes. We built curves representing expert-elicited magnitudes and spatial extents of direct and diffuse impacts of infrastructure on biodiversity groups, to incorporate these impacts into a spatial conservation prioritization. We demonstrate how different prioritization outputs inform different steps of the impact assessment mitigation hierarchy. In southern Australia we find the diffuse-impact footprint to be four times higher than direct (i.e., local) infrastructure impacts, with >75,000 km² of spatial priority areas for mitigation and >37,000 km² of spatial priority areas for offsets potentially missed if diffuse impacts are ignored. Understanding both direct and diffuse infrastructure impacts will avoid inefficient spatial allocation of environmental mitigation, restoration, and offsetting efforts.

KEYWORDS
anthropogenic threatening process, impact assessment, infrastructure development, landscape condition, road effect zone, spatial conservation planning, strategic environmental assessment, zonation

1 INTRODUCTION
Infrastructure development is ubiquitous and expanding (Laurance, Clements, & Sloan, 2014). Negative impacts on biodiversity include removing, fragmenting, and degrading vegetation and wildlife mortality (Fahrig & Rytwinski, 2009; Forman & Alexander, 1998). Species vary in responses to development and in many cases populations are not eliminated but undergo changes extending far away due to mechanisms such as pollution, barriers to movement, and clearing (Benitez-López, Alkemade, & Verweij, 2010; Forman, 2000; Torres, Jaeger, & Alonso, 2016). Poor knowledge of the processes through which infrastructure impacts biodiversity means important diffuse effects operating across large scales are often not dealt with in decision-making (Jaeger, 2015; Williams et al., 2013). The large regions and multiple species impacted by infrastructure means we cannot wait decades to learn species’ responses before they are considered in policy and planning. A landscape-scale approach that combines available knowledge of local and diffuse effects with biodiversity conservation priorities is urgently required to critically assess and mitigate infrastructure impacts.

Systematic conservation planning (SCP) is an approach to prioritize sites for conservation or compensatory actions...
while ensuring representation of suitable habitat for biodiversity (Gordon, Simondson, White, Moilanen, & Bekessy, 2009; Moilanen, Leathwick, & Quinn, 2011). Strategic environmental assessment (SEA), on the other hand, is a systematic process of a priori evaluating environmental impacts of a development policy, plan, or program by following the environmental impact assessment (EIA) mitigation hierarchy (Therivel, Wilson, Heaney, & Thompson, 2013). The EIA hierarchy aims to limit negative impacts on biodiversity from development by preferentially avoiding, then reducing, restoring, and finally offsetting impacts (Jaeger, 2015; Kiesecker, Copeland, Pocewicz, & McNeney, 2010), and has been formally integrated into legislation in many nations (e.g., USA National Environmental Policy Act 1970, Australian Environment Protection and Biodiversity Conservation Act 1999). Spatial prioritization tools such as Zonation (Moilanen et al., 2012) or Marxan (Ball & Possingham, 2000), built to inform SCP, can inform multiple stages of SEA and EIA, supporting strategic planning and management of landscape-wide and cumulative development impacts. During SEA, spatial prioritization can identify areas of high biodiversity value where development should be avoided (Bekessy et al., 2012). When overlaid by the proposed development footprint, outputs indicate areas for targeting minimization or restoration efforts (Whitehead, Kujala, & Wintle, 2017). Because threats (e.g., development footprints) can now be incorporated directly into spatial prioritizations (Santika, McAlpine, Lunney, Wilson, & Rhodes, 2015; Tulloch et al., 2015), outputs can also inform the last step of EIA mitigation by indicating the location of conservation priorities after habitats are degraded (Kiesecker et al., 2010).

Several technical challenges and assumptions need to be dealt with so that SCP outputs are useful for SEA. For reasons of simplicity rather than technical constraints, conservation prioritizations typically assume that threats only have direct impacts (Eigenbrod, Heenar, & Fahrig, 2009; Jones, Bull, Milner-Gulland, Esipov, & Suttle, 2014), that impacts do not vary across taxa (e.g., Kujala, Whitehead, Morris, & Wintle, 2015; Laurance et al., 2014), and that biodiversity no longer persists in impacted sites (e.g., Bunton et al. 2015; Grantham et al., 2008). Historically, diffuse impacts were also poorly dealt with in EIA (Drayson, Wood, & Thompson, 2017). However, much EIA and SEA legislation around the globe now accepts that species respond differentially to development (Bigard, Pioch, & Thompson, 2017), and are impacted at locations away from the direct footprint (Ritter et al., 2017).

One issue is that both SCP and SEA are limited by poor data on species’ responses to development, and limited guidance on how to link responses to maps of where threats occur (Jaeger, 2015). Combining expert opinion with scientific data allows for rapid and adaptable decisions in the face of limited data (Burgman, Carr, & Godden, 2011; Tulloch, Sutcliffe, & Naujokaitis-Lewis, 2016). Here, we demonstrate how to use expert elicitation to obtain novel information on spatial and taxonomic variability in biodiversity responses to multiple types of infrastructure development. We use this information to derive taxon-specific diffuse-impact curves within an infrastructure effect zone (Forman & Deblinger, 2000). We evaluate how the expected effects of a development footprint on biodiversity change when diffuse impacts are considered in addition to direct impacts, across an area with extensive infrastructure in South Australia. We then incorporate direct and diffuse infrastructure impacts within an SCP framework to show how outputs of spatial prioritizations might inform SEA (Figure 1). Others have proposed to link SCP outputs to SEA (Kiesecker et al., 2010; Whitehead et al., 2017), but, like most historical EIAs, failed to consider indirect impacts (Jaeger, 2015). By linking outputs to the different steps of the EIA mitigation hierarchy and explicitly building in diffuse variable impacts, our framework supports identification of priority areas for avoiding, mitigating, or offsetting impacts of infrastructure development and operations.

2 | METHODS

We developed a five-step approach to spatial prioritization that accounts for diffuse impacts of infrastructure on biodiversity and produced outputs that directly inform SEA by addressing different steps of the EIA hierarchy (Figure 1). Our approach collects biodiversity data, infrastructure data, and expert-elicited diffuse impacts, then builds information into maps representing the condition, or quality, of the landscape for biodiversity, and incorporates maps into spatial prioritizations. We ran spatial prioritizations accounting for (1) no impacts (i.e., pre-infrastructure development, to explore priorities for avoiding or minimizing impacts), (2) direct and diffuse impacts of infrastructure (to explore potential locations for offsets), or (3) only direct impacts (to evaluate information gained from considering diffuse impacts). We used the conservation prioritization software Zonation v.4.0 (Moilanen et al., 2012) to estimate spatial conservation priorities for biodiversity under each scenario. Zonation uses a maximum-coverage approach to identify areas that maximize the representation of suitable habitat for multiple species, creating a hierarchical ranking of all sites according to conservation priority. Each biodiversity feature can be linked directly to a condition grid (Moilanen et al., 2011), which reduces the value of a cell to a value between 0 (100% reduction, no conservation value) and 1 (no reduction, good condition).

2.1 | Step 1: Collect biodiversity distribution data

The Upper Spencer Gulf in South Australia (614,000 km²) is dominated by arid and semi-arid ecosystems used
FIGURE 1 Framework for using outputs of spatial conservation prioritization (black boxes) to inform strategic assessment through different steps of the environmental impact assessment (EIA) mitigation hierarchy (blue boxes), showing five steps of (1) mapping biodiversity distributions, (2) mapping direct development impacts, (3) determining diffuse biodiversity impacts of development through expert elicitation, (4) mapping biodiversity condition under diffuse impacts using expert-elicited impact curves, and (5) incorporating biodiversity data and condition maps into spatial prioritizations to rank the landscape according to conservation values considering (a) no impacts (pre-infrastructure) or (b) diffuse impacts of infrastructure. Outputs of spatial prioritizations can be used in the EIA mitigation hierarchy to avoid impacts (using outputs from a pre-infrastructure prioritization), minimize impacts (using outputs from a pre-infrastructure prioritization overlaid with the development footprint), or inform where to offset impacts (using outputs of the diffuse-impacts prioritization).

predominantly for agriculture and mining. We subdivided the landscape into 250-m grid cells, which corresponds to the typical area of direct impact for an infrastructure corridor consisting of roads, railways, and pipelines (easement widths typically 30–200 m; Latham & Boutin, 2015; Schroeder, 2002; van Langevelde, van Dooremalen, & Jaarsma, 2009). We collated occurrence data from publicly accessible databases for 175 Australian threatened or migratory species and seven vegetation communities listed under the Commonwealth Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 (Table 1). We constructed raster grids with a resolution of 250 m representing relative habitat suitability for those biodiversity features (0–100% suitable) using species distribution modeling with MaxEnt v3.3.3k (Phillips, Anderson, & Schapire, 2006) for species with >20 occurrence records. Available range maps or point occurrence data were used to represent distributions of data deficient species and vegetation communities (see Supporting Information).
TABLE 1  Main data inputs to the analysis of conservation priorities

| Input item                  | Derivation                                                                                           | Data source                  |
|-----------------------------|-------------------------------------------------------------------------------------------------------|------------------------------|
| **Biodiversity feature distributions** | 1. Species distribution models derived using point data and MaxEnt (73 features)                       | ALA, eBird, BDBSA            |
|                             | 2. Reclassified range maps of EPBC-listed species derived from a combination of models and expert-elicitation (82 features) | Australian Government Department of the Environment (2014) |
|                             | 3. Point features converted to 0,1 raster grid (20 features)                                          | ALA, eBird, BDBSA            |
| **Threatened ecological communities** | Reclassified range maps of EPBC-listed vegetation communities (Communities of National Environmental Significance) derived from a combination of models and expert-elicitation (6 features) | Australian Government Department of the Environment (2014) |
| **Ramsar wetlands**         | Polygon of wetlands listed under the Convention on Wetlands of International Importance (Ramsar Convention) | Australian Government Department of the Environment (2012) |
| **Threat-similarity groups** | Six groupings of the 182 biodiversity features according to similarity in expected response to threats of vegetation clearing and infrastructure development: (i) Mammals (21 spp.), (ii) Ground-dwelling birds (four spp., excludes waterbirds), (iii) All other birds (78 spp.), (iv) Plants (62 spp., Ramsar wetlands, six vegetation communities), (v) Reptiles (nine spp.), and (vi) Amphibians (one sp.) | Expert elicitation (see Supporting Material) |
| **Infrastructure impacts**  | Distance-decay curves estimating the likely change in habitat suitability due to infrastructure development (ports, railways, roads, pipelines) under assumptions of diffuse impacts: 1 curve per infrastructure type (road, pipeline, port) per threat-similarity group (18 response curves in total). | Expert elicitation (see Supporting Material and Figure 2) |
| **Ecological condition**    | Estimates of ecological condition for every group in every planning unit, based on past impacts of vegetation clearing and existing infrastructure development. Combines information from existing infrastructure corridors and current vegetation cover (based on 100-m resolution data indicating extent of clearing). Impacts either: (a) Direct (homogenous response): zero condition under infrastructure pathway, 100% condition outside local infrastructure impact, for all features (one layer); (b) Diffuse (heterogeneous, variable response): distance-decaying condition that varies per threat-similarity group (six layers) | See Figure 1 and Appendix S3 |

*ALA, Atlas of Living Australia, http://www.ala.org.au/ (Australian Government and Global Biodiversity Information Facility); eBird, www.ebird.com.au (Cornell University, USA); BDBSA, Biological Databases of South Australia (Government of South Australia, Accessed 2014)

2.2  Step 2: Map direct impacts of infrastructure

We compiled maps of linear infrastructures (roads, railways, and pipelines) and point-based infrastructures (ports) and converted data to a 250-m resolution raster to map the direct (local) infrastructure footprint. Direct impacts represent the traditional approach to SCP in which developed locations are assumed to have no conservation value (e.g., Kujala et al., 2015; Whitehead et al., 2017). We converted the footprint to a map representing the current condition of the landscape for biodiversity accounting for direct impacts. This was a raster in which “cleared” cells (<1 ha remnant vegetation) plus those underlying infrastructure were reclassified to zero (completely degraded), and all other cells reclassified to one (100% condition; Table 1).

2.3  Step 3: Expert elicitation of diffuse impacts of infrastructure on biodiversity

We used expert elicitation to estimate impact curves representing the likely magnitudes of impacts of three infrastructure types (roads/railways, ports, and pipelines) on different taxa at increasing distances from infrastructure (Torres et al., 2016). At a workshop, experts assigned each biodiversity
feature to one of six threat-similarity groups (ground-dwelling birds; other birds; mammals; plants; reptiles; amphibians), in which species were expected to be similarly impacted by vegetation clearing and infrastructure (Corey & Waite, 2008; González-Suárez, Zanchetta Ferreira, & Grilo, 2018). Sixteen experts contributed to elicitation (average 4.5 experts per group). Data were collected via a modified Delphi process, with expert predictions returned to experts to allow them to refine predictions in a second round of elicitation (Burgman et al., 2011). For each threat-similarity group, we asked experts to estimate the percentage reduction in habitat suitability at increasing intervals from an infrastructure development up to a threshold indicating the limit of the infrastructure “effect zone.” As there were no published studies of road effects for the region, we limited the effect zone using global literature validated by experts (Appendix S3). We averaged expert estimates of post-development habitat suitability in each interval to produce the final infrastructure impact curve for each threat-similarity group and infrastructure type.

2.4 | Step 4: Map biodiversity condition accounting for diffuse impacts of infrastructure

We used expert-elicited impact curves to build maps representing the condition of the landscape for biodiversity accounting for direct and diffuse impacts of existing infrastructure. For diffuse impacts, we assumed that the infrastructure footprint in any raster cell was influenced by (a) expert-elicited variation in impacts with distance from infrastructure, (b) proportion of cell cleared historically, and (c) expert-elicited variation in impacts across biodiversity. We developed diffuse-impact condition rasters for each threat-similarity group. Cell values were the product of the value from the relevant expert-elicited diffuse impact curve in Step 3 (0: 100% loss of suitable habitat, to 1: habitat unaffected) and the proportion of remnant vegetation in each cell (0: completely cleared, to 1: intact). Diffuse-impact rasters thus incorporate a larger footprint of impacts compared with the direct-impact raster that assumes no spreading of impacts. While the direct-impacts raster has condition values of zero within the infrastructure footprint, diffuse-impact rasters can have values higher than zero in these cells if experts estimate that biodiversity may persist within the direct infrastructure footprint (here 250-m).

2.5 | Step 5: Incorporate impacts of infrastructure development into spatial prioritization

Biodiversity distribution maps and condition rasters were incorporated into spatial prioritization scenarios to develop outputs addressing different steps of the EIA hierarchy. Our first scenario included only biodiversity and no infrastructure layers in prioritization, allowing us to identify priority locations pre-infrastructure development. The output map addressed the first EIA step (Figure 1)—ideally, infrastructure paths should avoid the most important locations for biodiversity. To inform EIA minimization and restoration within the infrastructure footprint, we extracted the top 30% of cells from scenario 1 located within the diffuse-impacts infrastructure effect zone. The resulting map indicated high-priority locations likely to be impacted by infrastructure that might be recommended for actions such as pollution barriers, watercourse protection, or restoration. To inform potential sites for offsetting or compensation, our second scenario incorporated diffuse infrastructure impacts that varied across biodiversity (different diffuse-impacts condition layer linked to each threat-similarity group; Steps 3 and 4, Figure S3b). We extracted the top 30% of cells from scenario 2 to find high-priority locations post-development that could be set aside for compensation. To compare to the traditional approach ignoring diffuse impacts, our third scenario repeated the post-development prioritization but incorporated only direct infrastructure impacts (one direct-impacts condition raster linked to every threat-similarity group; Step 2, Figure S3a).

To compare the impact of direct- versus diffuse-impact scenarios, we calculated two metrics: (1) total area of the region under infrastructure footprint, and (2) weighted impact accounting for variation in impact intensity across space and taxa. The weighted impact was the sum of each cell’s individual impacts:

\[
\text{Weighted footprint} = \sum_{i \in N} \left( 1 - c_i \right),
\]

where \( N \) is the set of cells in the infrastructure effect zone (either the direct or diffuse footprint), \( c_i \) is the condition value of cell \( i \), and \( (1 - c_i) \) gives the impact. For direct impacts, \( c_i \) was always 0 within and 1 outside of the footprint, with no difference across threat-similarity groups. For diffuse impacts, \( c_i \) was a value between and including 0 and 1, with a different weighted impact for each threat-similarity group.

3 | RESULTS

3.1 | Expert elicitation of likely infrastructure impacts

Expert-predicted responses of threat-similarity groups to infrastructure varied depending on whether infrastructure was linear (roads, railways, pipelines; Figures 2a and 2b) or point-based (ports; Figure 2c). Experts predicted that port effect zones led to greater declines in habitat suitability for reptiles, frogs, and plants (mean 52%, 56%, and 58% declines, respectively), whereas road effect zones led to greater declines...
for mammals, ground-dwelling birds, and other birds (57%, 53%, and 39% declines, respectively). At 1 km from infrastructure, the average reduction in habitat suitability across all taxa was 30% $\pm$ 11 SD near roads (range 18–44%) and 40% $\pm$ 9 SD near ports (range 25–53%). This impact was roughly halved 2 km from direct impacts (14% $\pm$ 9 SD near roads and 23% $\pm$ 11 SD near ports; Figure 2). Frogs were estimated to suffer the greatest impacts up to 1 km from all infrastructure types (70–77% declines). Very close to infrastructure, ports were expected to reduce habitat suitability for some groups (mammals, reptiles, frogs, and plants) more than road or pipeline impacts (e.g., 77% reduction for plants 250–500 m from ports vs. 54% from roads and 49% from pipelines).

### 3.2 Using conservation prioritization outputs to inform SEA

The locations of priority areas changed depending on whether conservation prioritization outputs targeted avoidance, minimization/mitigation, or offsetting/compensation development impacts (Figure 1). The best locations to minimize diffuse impacts of infrastructure were in the south and east of the heavily impacted Eyre Peninsula and across the dense infrastructure corridors of the Yorke Peninsula (Figure 3a). The highest priority locations for potential offsets/compensation included additional areas on the western and eastern coastlines and inland (Figure 3b).

### 3.3 Effect of ignoring diffuse impacts

Diffuse impacts of infrastructure occurred on more than five times the area of direct impacts (219,112 km$^2$ vs. 40,228 km$^2$, respectively; Table 2). The average weighted areal footprint under diffuse impacts was 152,840 km$^2$ (range 134,678–170,742 km$^2$; Figure 4a); an additional 112,613 km$^2$ (379%) compared with the direct footprint.

Overlap in conservation priorities and infrastructure impacts (for minimizing or mitigating environmental impacts) decreased by 75,443 km$^2$ when prioritization was based only on direct impacts, due to the different sizes of the infrastructure footprints (Table 2). Similarly, the location of the top 30% of priority areas for potential offset/compensation locations changed by 37,833 km$^2$ when prioritization was based only on direct rather than diffuse impacts (Table 2, Figures 3c and 3d).
TABLE 2  Differences between direct- and diffuse-impact scenarios of infrastructure within the USG region, showing the infrastructure footprint (total area or weighted by proportional impact), cumulative percentage of the study area likely to be impacted under either direct or diffuse impacts, area of conservation priorities for minimizing/restoring impacts (determined from overlaying footprint with top 30% of priority cells in baseline prioritization ignoring infrastructure) or offsetting impacts (determined from prioritization that included either direct or diffuse infrastructure footprint). The impact-weighted footprint is the areal footprint multiplied by the proportional impact; a binary 0 or 1 for direct impacts, or a continuous value of 0 (no impact) to 1 (complete impact) for diffuse impacts. Also showing average percentage of feature distributions underlying the infrastructure footprint under direct versus diffuse impacts (± SD), and comparisons of the expected vulnerability of biodiversity features to loss of habitat extent if protected in the top 30% of cells of a spatial conservation prioritization aimed at identifying high-priority locations for conservation. A description of the layers used to inform the approaches can be found in the Methods section and Supporting Information.

| Input condition and retention layers (number of input spatial layers to prioritization) | Impact scenario |  |
|---|---|---|
| | Direct impacts | Diffuse impacts |
| | Direct (local) condition (1) | Diffuse condition (6) |
| Areal footprint of infrastructure (km²) | 40,228 | 219,112 |
| (cumulative % of USG region) | (6.55) | (35.69) |
| Average impact-weighted footprint (areal footprint × proportional impact, km²) (±SD for diffuse impacts due to footprints differing across threat-similarity groups) | 40,228 | 152,840 ± 16,746 |
| Area (km²) of conservation priorities for minimizing/restoring environmental impacts | 18,014 | 93,547 |
| (% of USG region) | (2.95) | (15.24) |
| Area (km²) of priority cells for offsetting not shared with direct-impacts scenario | NA | 37,833 |
| (% of priority cells) | | (20.6) |
| Average (±SD) percentage of the distribution of each biodiversity feature impacted by infrastructure footprint (range in values) | 41.8 ± 28.7 | 46.0 ± 25.0 |
| Average (±SD) percentage of feature distributions in top 30% of cells | 45.2 ± 27.1 | 44.1 ± 24.9 |
| Number of features with <25% of habitat in top 30% of cells | 31 | 44 |
| Number of features with 100% of habitat not in top 30% of cells | 13 | 0 |

Considering only direct impacts underestimated the number of biodiversity features affected by diffuse impacts (Figure 4). Under diffuse impacts, species habitat became scarcer even in top-ranked parts of the landscape, due to expected habitat degradation up to 5 km from infrastructure. Consequently, the number of features with less than 25% of their habitat remaining in priority locations rose to 44, compared to 31 under direct-impacts (Table 2). Mammals and ground birds had more of their ranges impacted (Figure 4b) and consequently lower representation on average in priority conservation areas (Figure 4c) under diffuse impacts.

4 | DISCUSSION

Despite recent advances linking development impacts and spatial conservation prioritization (Bunton et al. 2015; Milt, Gagnolet, & Armsworth, 2016; Whitehead et al., 2017), important landscape-scale effects of infrastructure caused by diffusion of impacts from the direct footprint are generally poorly known and therefore ignored. We address this gap by combining expert-elicited impact curves relating distance from infrastructure to reduction in habitat suitability, with spatial data on the distribution of biodiversity. This makes our approach valuable in the common situation where data on biodiversity responses to infrastructure are limited. Our results indicate the most effective areas for applying different steps of the EIA mitigation hierarchy. We show that priorities for offsetting/compensation differ from priorities for minimization/mitigation, but differences are less pronounced when diffuse impacts are incorporated. The results support suggestions that only considering local-scale impacts of development underestimates biodiversity impacts (Raiter, Possingham, Prober, & Hobbs, 2014). Our framework allows conservation planners to realistically account for diffuse impacts of infrastructure and create outputs that are useful for informing SEA (Figure 1). This approach could aid critical biodiversity assessments and planning for large-scale infrastructure projects, such as China’s Belt and Road Initiative (Ascensão, Fahrig, & Clevenger, 2018).

A key advance of our approach is expert elicitation to build distance-decay curves of infrastructure impacts on
Differences in landscape priorities identified by spatial conservation prioritization approaches considering either direct impacts, i.e., ignoring diffuse infrastructure impacts and assuming homogenous responses of biodiversity, or diffuse impacts, incorporating expert-elicited functions of impact spread across the landscape and assuming heterogeneous responses of biodiversity. Showing (a) the difference in priorities for minimizing/restoring impacts when diffuse impacts (scenario 2) versus direct impacts (scenario 3) are incorporated into decisions, (b) the difference in priorities for offsets when diffuse impacts (scenario 2) versus direct impacts (scenario 3) are incorporated into decisions, (c) difference map showing where conservation priorities determined pre-infrastructure development (scenario 1) change if only direct impacts are also considered (scenario 3), and (d) difference map showing where pre-infrastructure conservation priorities (scenario 1) change if diffuse impacts are also considered (scenario 2). Note that the top 9% of the landscape retains the same high value across all scenarios due to forcing Zonation to allocate highest priorities to protected areas.
FIGURE 4 Effects of using direct (orange) versus diffuse (purple) approaches to conservation prioritization for different biodiversity groups. (a) Impact-weighted footprint of infrastructure, measured as the mean (±SE) percentage of the distributions of features within the group overlaid by the development footprint. (b) Weighted impact of infrastructure on each species’ distribution, averaged across each threat-similarity group. (c) Threat-similarity groupings of the average (±SE) extent of feature distributions in the top 30% of cells in the landscape (including the 9% already in conservation areas)

loss of 13 features predicted under direct impacts indicates that areas such as small remnants within the direct infrastructure footprint may provide suitable habitat; with appropriate mitigation actions, these species may be able to persist despite the close presence of infrastructure.

Human populations are expanding, and with them the need for resources, associated infrastructure, and improved impact assessment. By evaluating only direct impacts, traditional planning will miss efficient conservation opportunities where biodiversity persists in the locality of development, and underestimate overall infrastructure impacts if biodiversity declines occurring at considerable distances away from develop-

ments are not considered. Our framework supports a rapid whole-of-landscape approach to SEA that enables systematic application of the mitigation hierarchy and accounts for diffuse and variable impacts of development on biodiversity.

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**SUPPORTING INFORMATION**

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

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