Title: Quantifying the conservation gains from shared access to linear infrastructure

Abstract

The proliferation of linear infrastructure such as roads and rail is a major global driver of cumulative biodiversity loss. Creative interventions to minimise the impacts of this infrastructure whilst still allowing development to meet human population growth and resource consumption demands are urgently required. One strategy for reducing habitat loss associated with development is to encourage linear infrastructure providers and users to share infrastructure networks. Here we quantify the reductions in biodiversity impact and capital cost under linear infrastructure sharing and demonstrate this approach with a case study in South Australia. By evaluating proposed mine-port links we show that shared development of linear infrastructure could reduce overall biodiversity impacts by up to 75%. We found that such reductions are likely to be limited if the dominant mining companies restrict access to infrastructure, a situation likely to occur without policy to promote sharing of infrastructure. Our research helps illuminate the circumstances under which infrastructure sharing can minimise the biodiversity impacts of development.

Introduction

The construction of linear infrastructure such as road, rail, pipelines, electricity corridors and shipping routes is an important driver of global biodiversity decline (Benítez-López et al. 2010). With expansion of linear infrastructure across the globe (Laurance et al. 2014), has come new approaches to quantify and address its impact on biodiversity. Consequently, environmental impact assessment and impact mitigation comprise core parts of the planning process for infrastructure development in most nations (Macintosh 2010). There are three key ways to reduce the environmental impacts of infrastructure projects, collectively referred to as the ‘mitigation hierarchy’ (Kiesecker et al. 2010). They comprise (i) minimising the total area impacted, (ii) choosing routes that avoid the largest impacts, and (iii) mitigating residual impacts through biodiversity offsets or wildlife-friendly design. These three strategies differ in their potential to reduce biodiversity impacts. An increasing interest in
landscape-scale strategic planning means focus is shifting from traditional mitigation measures (Gordon et al. 2015; Priemus 2007) towards options for avoiding and minimising the biodiversity impacts of infrastructure development (Kiesecker et al. 2010), although all three approaches are usually implemented to some degree. Avoidance can become an attractive option where biodiversity is spatially localised, highly valued or where loss is difficult to offset or mitigate (Kiesecker et al. 2010). In these cases avoidance can decrease impacts, and reduce mitigation and offsetting costs, while also reducing the risk of projects being derailed or delayed due to social and political opposition (Middle & Middle 2010). However, reducing impacts by rerouting or limiting development may involve a trade-off between development and biodiversity (e.g. Fortescue 2004). Subsequently, uptake of options for avoiding biodiversity impacts is often limited by political or economic concerns (Priemus 2007).

An alternate means to reduce the impact of development is to minimise proliferation of infrastructure by maximising efficiencies of use, such as through infrastructure sharing, where multiple users enter into shared development and/or use of linear infrastructure. Infrastructure sharing has been implemented to varying degrees of success in a number of settings. One successful example is the Central Queensland Coal Network, a privately-run, but government-regulated transport network linking over 50 mines with three ports in eastern Australia (Collier & Ireland 2015). Infrastructure sharing offers benefits to infrastructure users including minimising capital costs. Despite advantages, many factors can limit uptake, including the transaction costs involved in negotiating and maintaining access agreements, capacity constraints or a desire to maintain competitive advantage by excluding competitors from access to a region. Government strategies to facilitate sharing of linear infrastructure include setting up or legislating third-party ownership of infrastructure, financing extra capacity or regulating for shared use.

Recognition of the cumulative impacts of linear infrastructure (Raiter et al. 2014) means studies are now beginning to explore the environmental implications of large transportation networks (e.g. Jones et al. 2014). The impacts of roads and rail linking mines to markets can be as large as or larger than the direct impacts from the associated mines (Majer 2014). Having one high-capacity route may result
in better outcomes for biodiversity, such as reduced habitat loss or fewer barriers to species dispersal, than having many low capacity routes as the environmental impacts of linear infrastructure do not scale linearly with capacity (Rhodes et al. 2014). While the locations of conservation significance are generally fixed, linear infrastructure is usually more flexible, presenting opportunities for better biodiversity outcomes within a strategic, landscape-scale planning framework (Kiesecker et al. 2010). Through processes such the development of private-private collaborations between infrastructure users, infrastructure sharing has the potential to limit the amount of linear infrastructure and minimise its cumulative impacts. The potential environmental benefits arising from collaboration amongst private actors has received little attention in the conservation literature, despite the potential for this to minimise the cumulative impacts of development (Porter et al. 2013) and mobilize large amounts of capital (Armsworth et al. 2010).

We explore whether infrastructure sharing under collaborative intra-industry partnerships has the potential to reduce biodiversity impacts (a public benefit, i.e. those benefits flowing to people or communities) in addition to providing cost savings to industry (a private benefit, i.e. those benefits flowing to individuals or companies directly involved in a transaction). We demonstrate this approach with a case study in South Australia, where a number of mines and new ports are proposed for the state and plans are underway to develop linear infrastructure to support the expansion of the mining industry (GoSA 2014). The purpose of this analysis is to explore the potential for infrastructure sharing to improve biodiversity outcomes from a set of potential development scenarios which span a range within which many realistic scenarios would likely fall. While proposed development projects should be evaluated in light of multiple criteria, including economic, social and environmental criteria (Mandle et al. 2016), here we focus on just two – construction costs and biodiversity impact. We then discuss the barriers to infrastructure sharing by mining companies and the potential implications for efforts to facilitate collaboration in light of these barriers.

**Methods**
We explored the biodiversity impacts and the construction costs of infrastructure networks designed to deliver mining commodities to markets (in our case ports; Fig. 1) under three development scenarios: Scenario 1 assumes that each mining company develops infrastructure linking its mines to markets independently of other mines in the area (“Independent scenario”); Scenario 2 explores the outcomes where the five most profitable mining companies restrict access to shared infrastructure (“Restricted-access shared’’); and Scenario 3 assumes that where spatially feasible, mining companies collaborate to build shared infrastructure networks (“Shared’’). We then compared the difference in costs and impacts on biodiversity in these scenarios to illustrate the relative benefits of pursuing shared infrastructure development, compared with the outcomes when infrastructure sharing does not occur. To explore whether this comparison changes under different configurations, we ran a sensitivity analysis with variants on Scenarios 1 and 3 that explore the biodiversity outcomes where the mining companies whose associated linear infrastructure has the greatest impacts are not developed (“Low-impact independent’’ and “Low-impact shared’’; Appendix S3). We ignore the localized impact of mine and port development on biodiversity, which will be identical in all three scenarios, as the focus here is on the associated linear infrastructure and its terrestrial impacts.

**Study region**

The study region encompasses the Upper Spencer Gulf and associated regions of South Australia, stretching from the lower Eyre and Yorke Peninsulas into the South Australian Arid Lands, a region approximately 900 by 1200 km in size. The region is home to numerous threatened and iconic species, including malleefowl (*Leipoa ocellata*) and kowari (*Dasyuroides byrnie*), and threatened ecosystems such as Eyre Peninsula Blue Gum (*Eucalyptus petiolaris*) Woodland. Many endemic and threatened species and ecosystems in the region occur near coastal areas (Fig. 1a) coincident with the highest levels of human modification. This region has been identified as a priority for landscape-scale planning under the Australian Government Sustainable Regional Development Program (https://www.environment.gov.au/sustainability/sustainable-regional-development) due to the coincidence of a large number of species and ecosystems of national environmental significance, high human population growth, and development plans for industry, urban expansion and agriculture. Rich
ore deposits occur in the region, and a five-fold increase in the volume of mineral exports is expected in the next 20 years (GoSA 2014). In order to accommodate development and facilitate mining growth in the region, significant investment in upgrading and expanding linear infrastructure linking mines to export markets is currently underway (GoSA 2014).

Scenarios

We calculated biodiversity impacts and capital costs for mine-port links to 47 mine locations operated by 28 separate companies, drawn from current and developing South Australia Mining Projects “Minerals - Major Projects” and “Minerals - Developing Projects” datasets (https://sarig.pir.sa.gov.au/). Each of the 28 mining companies operates between one and five separate mines (Appendix S1). Three proposed port locations were provided by the Department of Planning, Transport and Infrastructure, South Australia (GoSA 2014). To construct potential infrastructure links we first created a 250-m resolution ‘cost surface’ raster of 17.28 million cells, in which cells were assigned values representing the “cost” for infrastructure passing through them. Cost was non-monetary, and was defined by both legislative and environmental suitability of land to host infrastructure (Bagli et al 2011; Appendix S2). This included avoiding natural hazards and protected areas, and favouring areas adjacent to existing infrastructure corridors as these locations are zoned for infrastructure expansion in government development plans and more likely to be used for future infrastructure. We then ran least cost path analysis on the cost surface raster to find possible mine-port routes, with each mine as a potential start point and the closest port the end point.

The impacts of each mine-port link were calculated as follows:

1. **Independent scenario.** Each of the mining companies develops an independent infrastructure link to the nearest of three ports (Fig. 1b). A mining company may operate more than one mine, and where the routes overlapped we allocated them a single link to the nearest port, otherwise each mine was allocated an independent link to port. Capital costs and biodiversity impacts for each mining company were summed across all infrastructure lines for mines operated by that company.
2. **Restricted-access scenario.** Mines associated with the five mining companies with the highest economic value are developed first and share infrastructure, with routing and impact calculation as per scenario 4. Each of the remaining mining companies are excluded from shared infrastructure and develop independent links to the nearest of three ports based on the least cost paths (Fig. 1c). This resulted in two shared lines, with two and three collaborating partners respectively, and 23 unshared lines. Economic value was approximated from the expected amount of ore from each mine (DMITRE 2014), and 2015 commodity prices ([http://www.worldbank.org/en/research/commodity-markets](http://www.worldbank.org/en/research/commodity-markets)).

3. **Shared scenario.** Mines link to one of three ports via the nearest shared infrastructure corridors (Fig. 1d). Initially, several shared corridors were identified in consultation with state government officials and referring to the Regional Mining Infrastructure Plan (GoSA 2014) to minimise the Euclidean distance of any individual mine from the shared path to port, whilst still accounting for landscape barriers and attempting to place the shared path close to existing infrastructure corridors. The corridor with the lowest total summed length (including all tributaries from individual mines and the shared component) was selected.

In each scenario, capital costs and biodiversity impacts (detailed below) were allocated proportionally to each mining company as a function of the length of infrastructure from their mine/s to port, divided by the number of mining companies sharing each section of infrastructure. For instance, if two companies share 80km of a 200km line, and are then joined by a third company for an additional 120km, the first two companies were each allocated \((80\times \frac{1}{2}+120\times \frac{1}{3})/200=0.4\) of the total cost (or impact) and the third company \((120\times \frac{1}{3})/200=0.2\) of the total cost (or impact).

**Capital costs**

We calculated capital costs incurred by each mining company for infrastructure construction as the sum of construction costs, compensation payments for lost agricultural profitability (i.e., opportunity cost of agricultural profits) and the transaction costs arising from negotiations with the impacted landholders for each linear infrastructure route. For simplicity, we ignored operating expenditure and
assumed construction costs are fixed irrespective of projected capacity (i.e., the volume of product transported) for each route. We also assumed that landholders were compensated only for the loss of land directly impacted by infrastructure development (i.e., a 250-m strip along each line).

Construction costs of rail infrastructure were calculated at $4 million per km, based on estimates from the South Australian Regional Mining and Infrastructure Plan (GoSA 2014). We evaluated construction costs for rail only, as this has been identified as the modality of choice across most of the study region, although a mixed strategy of rail, road and pipeline may also be feasible in areas of this study region close to ports, or where the volume of product is low (GoSA 2014). We ignored water crossings as there are no permanent water flows and the costs of water crossings are difficult to assess without site assessments of hydrology (Deloitte 2013), and assumed no additional cost for inclines as the study region is of low profile and predominantly on sandy soil.

Property boundaries were drawn from the 2014 South Australian Digital Cadastral Database (Department of Environment, Water & Natural Resources) and landholder-negotiation costs borne by the mining companies were set at $10,000 per property impacted by infrastructure. Current literature provides little guidance on landholder-negotiation costs (transaction costs) and our sensitivity analyses using alternate transaction costs did not alter the comparative ranking of mines and had minimal impact on overall capital costs (Appendix S4). An estimate of the cost of compensation was drawn from the net present value of lost agricultural productivity from land impacted by infrastructure and calculated using agricultural profit at full equity for the period 2005-2006 (Marinoni et al. 2012). We adjusted for inflation to September 2014 (ABS 2014) and determined the net present value of foregone annual agricultural profitability assuming total loss of agricultural outputs at the infrastructure impact site and a real discount rate of 5%. Areas with negative profitability were assigned a net present value of zero. Agricultural loss was summed across the area impacted by each infrastructure route (Appendix S5). All calculations were in Australian dollars.

**Biodiversity impacts**
Biodiversity impact under each scenario is defined as the proportional habitat loss per species summed across 183 biodiversity features of conservation concern found in the study region (comprising the 176 species and 7 vegetation communities or wetlands listed under national environmental legislation; (EPBC 1999); Appendix S6). We represented the distribution of biodiversity features using spatial distribution data from Tulloch et al (2015). As described in Tulloch et al (2015), the data were generated at a resolution of 250m by one of the following approaches, depending on data availability for each feature: (i) Habitat suitability maps were generated from actual species occurrences using species distribution modelling software Maxent (73 biodiversity features) and, where sufficient species occurrence data was not available, we used (ii) Range maps from polygon and point data representing the known distribution of biodiversity features, obtained from the Commonwealth Department of the Environment (110 biodiversity features).

We summed direct and diffuse loss of habitat to generate the impacts of each infrastructure route on biodiversity features. We assumed the impacts of each infrastructure corridor decrease with increasing distance from the infrastructure, with the rate of the decrease dependent on the sensitivity of the species to impacts (Benítez-López et al. 2010). Impacts were summed across four infrastructure effect zones of increasing distance from the impact (ranging from direct losses of 100% for all biodiversity features in the zone up to 125 m from infrastructure, through to diffuse losses ranging from 18-96%, dependent on distance and taxa, in the zone up to 1000 m) using expert-elicited taxon-specific responses (we assigned species to taxa of birds, ground-birds, mammals, plants, reptiles or frogs) as described in Tulloch et al. (2015). For instance, in the 125 to 250 m zone, habitat loss ranges from 77% (plants) to 96% (ground-birds). We compare proportional rather than absolute habitat loss to standardise loss across both wide-ranging and range-restricted species.

Scenario evaluation

We define averted capital costs as the difference between the cost of construction under a scenario (Scenarios 2, 3) and the cost of construction under the Independent scenario (Scenario 1), divided by the total project cost under the Independent scenario. Averted biodiversity impact is the absolute
difference in biodiversity impact (which is defined as proportional habitat loss per biodiversity
feature, summed across all features) between the Independent scenario and each of the other two
scenarios. We make the simplifying assumption that the value of lost habitat is linearly related to the
amount of lost habitat, i.e. that nine species losing 10% of their habitat (a biodiversity impact of 0.9)
is equivalent to one species losing 90% of its habitat, though the marginal value of habitat may
increase as it becomes rarer.

We allocated each mining company to one of five regional mine-port groups (B1, B2, H1, H2 and
M1; mines that shared a mine-port link under the shared scenario were grouped, see Appendix S1 for
groupings) and evaluated the benefits across these five groups for each of the three scenarios.

This work was conducted in ArcGIS 10.2 (www.esri.com), Python version 2.7.3 (www.python.org),
the GDAL package for Python (http://gdal.org/python), R version 3.1.1 (R Core Team 2014). We
include a glossary of terms in Appendix S7.

Results

Shared scenario

We found that both the private and public benefits from collaborative development and sharing of
linear infrastructure are high. The overall capital cost of the Shared scenario ($13.0 billion) is less
than a third of the cost of the Independent scenario ($36.5 billion) with an average saving per mining
company of $840 million (Table 1). The capital costs are heavily influenced by the length of each
infrastructure link, as construction costs make up the bulk of the capital costs. The total length of
infrastructure (3,246 km) under the Shared scenario is 36% of that under the Independent scenario
(9,073 km; Table 1).

The sharing of infrastructure reduced both the total biodiversity impact and the capital cost associated
with infrastructure for each individual mining company (Fig. 2). Compared to the Independent
scenario, shared infrastructure reduced the total biodiversity impact from 4.78 to 1.12 (measured as a
sum of the proportional losses for each feature; see Methods); a 76% average reduction, and between
34% and 99% for individual mining companies (Table 1, Fig. 2). Similar results were seen for the low-impact scenarios, where sharing reduced biodiversity impact by an average of 65%, ranging from 18% to 93% per mining company (Table S1, Fig. S4). The number of species affected by development dropped from 129 under the Independent scenario to 118 under the Shared scenario. Of the species impacted by development, each species lost an average of 3.75 ± 5.38% of its habitat under the Independent scenario, dropping to 0.95 ± 1.09% under the Shared scenario; or 2.61% vs 0.61% averaged across all 183 species. The proportional reduction in biodiversity losses from infrastructure sharing was greater than the reduction in capital costs, with a 1.2% reduction in impact on species for every 1% reduction in capital cost (Table 1).

Despite overall savings under shared infrastructure, the financial benefits of shared infrastructure are not shared equally among companies. Some companies are likely to benefit strongly from reductions in capital costs under infrastructure sharing, and others less so. Benefits range from an 86% to 22% reduction in capital infrastructure costs per mining company (hereafter referred to as averted capital cost; Fig 2, Table 1), depending on the distance to the nearest shared infrastructure line, the number of mines sharing each stretch of line, and the length of shared lines.

We found little evidence for a meaningful relationship between the reduction in biodiversity impacts (a public benefit) and reduction in capital cost (a private benefit) from infrastructure sharing (Fig. 5) (0.003 decrease in biodiversity loss for every 1% reduction in capital costs, intercept 0.380, Adjusted $r^2 0.191, p 0.012 df 26; though this relationship disappears when the point on the top left of figure 4 which showed high heteroscedasticity is removed; Adjusted $r^2 0.007, p 0.286, df 25).

Restricted-access scenario

Under the Restricted-access scenario, where larger miners exclude smaller companies from shared infrastructure, benefits of infrastructure sharing were modest and spatially localized (Fig. 3). Total biodiversity impact was reduced only slightly from the Independent scenario (4.78 to 4.20) and capital expenditure dropped from $36.5b to $33.7b (Table 1).

Relationship between corridor length and biodiversity impact
Biodiversity impacts are disproportionately distributed among mining companies with impacts from individual companies ranging from less than 1% of total impact up to 15.9% (Table 1). These losses are related to the length of the infrastructure corridor. There is significant variability in the relationship between length and biodiversity impact due to the spatial heterogeneity in distribution of conservation features (Fig. 4; biodiversity impact 0.0460 per 100km, intercept set to zero. Adjusted $r^2$ 0.579, $p < 0.0001$, $df = 31$. We excluded one mine-port line of 1501km from the model of corridor length against biodiversity impact after evaluating residuals for heteroscedasticity, this value is included in Appendix S8). For instance, one mine-port line with length 46km has approximately the same impact as one 764km line.

**Discussion**

Reducing the impacts of linear infrastructure on biodiversity is a major challenge for conservation (Laurance et al. 2014). In many parts of the world, particularly sub-Saharan Africa, large areas of previously intact landscapes are threatened by development of infrastructure projects (Edwards et al. 2014). Exploring options to reduce biodiversity impacts is a priority both for conservation organisations and for governments in these regions. Our results indicate that there can be significant gains to be had from systematic, landscape-scale sharing of linear infrastructure routes. We demonstrate that policies that facilitate shared infrastructure will deliver better outcomes for biodiversity than those that allow independent development, while also providing potential benefits to infrastructure users. Infrastructure sharing reduced landscape-wide biodiversity impact by 76% while providing a 65% reduction in the total capital cost of infrastructure. Landscape-wide planning schemes, such as the South Australian Regional Mining and Infrastructure Plan (GoSA 2014), provide a means of critically examining the cumulative impacts of mining development, arising from mines, ports and related linear infrastructure, and support for landscape-scale planning should be a priority for conservationists.

The biodiversity impacts attributed to each mining company under the different scenarios vary across the study area (Fig. 3). While biodiversity impact increases with length of infrastructure, the variance
in the relationship is high (Fig. 4), due to the spatial heterogeneity in biodiversity features and consistent with other findings (Friedrich, 2015). Nonetheless, some small lengths of infrastructure have disproportionally high impacts. For instance, one 46km length of infrastructure has a biodiversity impact of 0.76% of summed habitat lost per km, vastly exceeding the average loss of 0.05% per km. The disproportionate cost to the public of infrastructure development associated with high-impact corridors (such as from costs associated with threatened species recovery) in relation to the public benefits (taxation revenue), may make associated mines a ‘no-go’ option under landscape-wide strategic planning. Excluding the five mine-port links responsible for highest biodiversity losses from development reduced infrastructure-related impacts to biodiversity by 45% and would also avoid the direct impacts from construction of each of those mines. While averting mine impacts by not developing mines may be preferable from a ‘no impact’ point of view, this is likely to be met with strong opposition from industry and government, both in this particular study region, and many others around the world (Priemus 2007). Attitudes in the region are very much utilitarian in nature and recent closures of several key industries have left the region economically and politically unstable. Recent political events in Australia have indicated that even averting a coal mine of questionable economic viability and documented ecological impacts on both an endangered species and a flagship ecosystem is challenging (Grech, Pressey & Day 2016). In light of this, we include these scenarios to enable fuller understanding of the benefits from shared infrastructure. In our opinion, when developing models and scenarios such as those presented here, it is important to consider the viewpoints of the range of stakeholders likely to enact the conservation actions being proposed, who may have contrasting value systems and political views. We also believe our role as conservation scientists, is to propose a range of solutions encompassing those that are pragmatic, as well as those that may be idealistic. The key message of our manuscript is that infrastructure sharing can help avert the worst impacts of mining infrastructure.

The relative costs and benefits of infrastructure sharing at a local scale will depend on the spatial patterning of both biodiversity and infrastructure. Spatial patterning of resources has previously been recognised as a factor in decisions about whether or not to invest in shared infrastructure (Toledano et
al. 2014; Collier & Ireland 2015). Our findings show that the reductions in capital cost under infrastructure sharing are high, at least when capacity constraints are ignored (Fig 2); in some cases, returning over 40% reduction in capital cost. Despite this, the greatest reduction in capital cost were not correlated with the greatest reductions in biodiversity impact for individual mining companies under a shared scenario (Fig. 5). For instance, one company received lower benefits from sharing infrastructure (22% reduction in capital cost compared to average of 65%; Fig. 5 top left), a result of the large distance between this company’s mines and those of its nearest neighbour (and thus there is a high proportional responsibility borne by this mine for capital costs associated with the shared mine-port link). Despite limited private benefits to this isolated company from collaborating with neighbouring companies, infrastructure sharing dramatically reduced the biodiversity impacts of this company. Differences in rewards from collaboration have also been found in cross-national conservation initiatives (Mazor et al. 2013).

While infrastructure sharing has the potential to deliver strong reductions in biodiversity impact, in our case study those benefits are greatly reduced when only a small subset of the companies share infrastructure. Where development is staged, and in the absence of government policy preventing anti-competitive behaviour, the first mining company into an area will often have strong incentives to block access to infrastructure from competitors (Collier & Ireland 2015). The companies excluded from shared access must then develop their own infrastructure, increasing impacts on biodiversity. Such a situation will likely occur often in the real world (Collier & Ireland 2015). For instance, the large mining companies in the Pilbara region of Australia have restricted access of smaller (junior) mining companies to their rail networks, citing loss of capacity and flexibility (Koshy & Kenyon 2007), and circumventing government policy aimed at promoting open access to (or sharing of) infrastructure. Our results indicate that such behaviour can undermine the public benefits of infrastructure sharing. Enactment and enforcement of legislation aimed at promoting infrastructure sharing and limiting anti-competitive behaviour might therefore be highly beneficial for both conservationists and governments.
Infrastructure developers and users will have private incentives both for and against infrastructure sharing, and these will depend on the size of the company, their access to capital, whether they are new to an area, and landscape features along the proposed routes. Although we considered only the influence of capital costs on infrastructure sharing, there may be additional private incentives for infrastructure sharing. Small, low profit mining companies that lack the financial capacity to invest in infrastructure are most likely to support or seek opportunities for infrastructure sharing (Toledano et al. 2014). For instance, junior miners in the Pilbara region of Australia, which were historically excluded from access to infrastructure, are now exploring options for collaborative development of a rail network (Ker 2012, Collier & Ireland 2015). Low commodity prices may also promote infrastructure sharing by increasing mining companies’ incentives to reduce costs, though they may also increase competitive behaviour. More detailed consideration of the influence of these factors would be a worthwhile avenue for future work.

Even with these benefits, and the possible addition of widespread publicly-funded policy interventions to encourage private collaboration (e.g., regulating for shared infrastructure or negotiating for a single entity to manage haulage), widespread collaboration may not eventuate. While our results indicate large decreases in capital costs with infrastructure sharing, these will be offset to some degree by transaction costs in negotiating, maintaining and enforcing agreements, and potential losses of convenience or capacity for some companies relative to a private line. Mining companies are less likely to share existing infrastructure where independent infrastructure provides them a strategic advantage over competitors, where they have the financial capability to fund their own infrastructure, or where their investment in infrastructure is already high (Toledano 2014; Collier & Ireland 2015). Furthermore, in cases where partners’ projects may be held up by funding constraints or environmental approvals, companies may perceive the uncertainties and risks of collaboration as too high (Levin et al. 2013; Porter et al. 2013). Decisions on whether to collaborate or not will also be influenced by the costs of adding capacity to existing corridors or capacity for handling different commodities as well as loss of control over transport schedules and expansion potential. We ignored these factors in our analysis as they require detailed knowledge on each mining operation which is
outside the scope of this study, but a consideration of these disincentives will be important when
designing real-world infrastructure-sharing schemes.

Different parameterization of the deterministic model assessed here may shift the relative benefits of
infrastructure sharing, though we would expect general patterns of reduced impacts under shared
scenarios to hold. While subject to uncertainty, the parameters used in this case study represent the
likely information available to government and infrastructure proponents during early stages of
infrastructure planning. The predictions of species distribution for multiple biodiversity features will
be subject to differing amounts of uncertainty, and this may shift the relative impacts of infrastructure.
Greater understanding of how and whether additional species monitoring would alter the routing or
outcomes of infrastructure development is urgently required. We ignored impacts arising from
fragmentation of habitat as we expect fragmentation to have a small impact in this study region given
the large study area and that the infrastructure fragmentation effects are likely to be primarily local in
nature. However, in certain landscapes fragmentation from linear infrastructure can have large
impacts on biodiversity (Rhodes et al. 2014). The aim of this paper is to assess the potential
conservation benefits from shared infrastructure, rather than to develop a detailed infrastructure plan
for the study region. As such, we use best currently available information on species distributions and
make a number of simplifying assumptions about routing.

Our research demonstrates that infrastructure sharing has the potential to reduce impacts of
development on biodiversity, while at the same time providing potential reductions in the cost of
infrastructure development. However, these benefits are tempered in situations where infrastructure
sharing is only undertaken by a few partners, or when the dominant mining companies restrict access
to infrastructure. Previous work on the public benefits of shared infrastructure suggest that it can
deliver significantly higher benefits compared to independent development (Toledano 2014; Collier &
Ireland 2015). These include opening up a region to agricultural markets, higher tax revenue or
mining revenues, or enabling the development of otherwise stranded assets. Consequently, the public
arguments for shared infrastructure may be multiple, though any advantages will be tempered by the
publicly-borne costs in facilitating shared access to infrastructure (Kiesecker et al. 2010; Pannell et al.
By illustrating circumstances under which infrastructure sharing can provide better outcomes for both biodiversity and development, our research opens the way for a more nuanced conversation about the merits of avoiding rather than merely mitigating the impacts of infrastructure on biodiversity and other natural assets.

**Supporting Information**

Maps of the study region (Appendix S1), expanded methods (Appendix S2), additional scenarios of impacts (Appendix S3), sensitivity analyses (Appendix S4), infrastructure impacts on agriculture (Appendix S5), model summary for biodiversity features (Appendix S6), glossary of terms (Appendix S7) and biodiversity impacts of shared mine-port lines (Appendix S8) are available online. Supporting code is online at [https://github.com/rungec/USG-Infrastructure-sharing](https://github.com/rungec/USG-Infrastructure-sharing). The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.
Literature cited


Government of South Australia (GoSA). 2014. South Australian Regional Mining and Infrastructure Plan.


Table 1. Costs and impacts of infrastructure linking each of 28 mining companies to one of three ports under three scenarios for infrastructure development.

Biodiversity impact is defined as proportional habitat loss per species summed across all conservation features.

<table>
<thead>
<tr>
<th></th>
<th>Independent</th>
<th>Restricted-access shared</th>
<th>Shared</th>
<th>Averted cost or impact (Shared scenario compared to Independent scenario)</th>
<th>Proportional averted cost or impact (Shared scenario as % of Independent scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capital cost ($bn)</td>
<td>36.5</td>
<td>33.7</td>
<td>13.0</td>
<td>23.5</td>
<td>64.5 %</td>
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<td>Mean cost per mining company ($bn)</td>
<td>1.30</td>
<td>1.20</td>
<td>0.46</td>
<td>0.84</td>
<td>64.5 %</td>
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<td>Cost per mine ($bn; min-max)</td>
<td>0.19–2.56</td>
<td>0.19–2.56</td>
<td>0.06–1.72</td>
<td>0.099–1.63</td>
<td>22.5–85.6 %</td>
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<tr>
<td>Length of infrastructure (km)</td>
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<td>8372</td>
<td>3246</td>
<td>5827</td>
<td>64.2 %</td>
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<tr>
<td>Agricultural loss ($m)</td>
<td>145</td>
<td>140</td>
<td>33</td>
<td>112</td>
<td>77.4 %</td>
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<tr>
<td>Number of species impacted</td>
<td>127</td>
<td>126</td>
<td>118</td>
<td>11</td>
<td></td>
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<tr>
<td>Mean habitat loss per species (as % of total habitat)</td>
<td>2.61</td>
<td>2.29</td>
<td>0.61</td>
<td>2.00</td>
<td>76.6 %</td>
</tr>
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<td>Total biodiversity impact</td>
<td>4.78</td>
<td>4.20</td>
<td>1.12</td>
<td>3.66</td>
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<tr>
<td>Mean biodiversity impact per mining company</td>
<td>0.17</td>
<td>0.15</td>
<td>0.04</td>
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<td>76.6 %</td>
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<td>Biodiversity impact attributed to</td>
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<td>0.01–0.43</td>
<td>&lt;0.01–0.18</td>
<td>0.02–0.53</td>
<td>33.9–98.8 %</td>
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Biodiversity impact per mining company, as proportion of total impact for that scenario (%; min – max)

<table>
<thead>
<tr>
<th></th>
<th>0.6–14.7%</th>
<th>0.3%–10.3%</th>
<th>0.4–15.9%</th>
<th>0.6–14.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>each mining company (min – max)</td>
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Figure legends

Figure 1. Study region and infrastructure scenarios a) spatial distribution of biodiversity features (comprising the 176 species and 7 vegetation communities or wetlands listed under national environmental legislation) b) the locations of mines and ports with infrastructure routes under independent development of mine-port links c) infrastructure routes under restricted-access development of mine-port links d) infrastructure routes under shared development of mine-port links.

Figure 2. Capital infrastructure costs and biodiversity impacts of each of 28 mining companies are lower under shared development of mine-port links than independent development. For each company, the grey dot represents the Independent scenario, which is linked by a line to the result for the same company for the Shared scenario (black dot).

Figure 3. Biodiversity impact under each of the three scenarios, summarised for each of the five regional sets of mines sharing a mine-port link under the shared scenario (H1, H2, B1, B2, M1). Infrastructure sharing offers consistent reductions in biodiversity impact across all five regions as compared with the Independent scenario. However, such benefits are spatially localised under the Restricted-access scenarios. Biodiversity impact is defined as proportional habitat loss per species summed across all conservation features.

Figure 4. The infrastructure length and biodiversity impact of each mine-port link. The trendline approximates the relationship between biodiversity impact and infrastructure length (biodiversity impact 0.0460 per 100km, adjusted $r^2$ 0.579, $p < 0.0001$, df = 31. We excluded one mine-port line of 1501km from the model after evaluating residuals for heteroscedasticity, this value is included in Appendix S8. 95% confidence intervals are shown in grey). Heterogeneity in biodiversity distribution introduces variance to that relationship. The y-axis represents the impact attributed to a single mining company under independent development of mine-port links (circles), or the impact associated with each of the five shared port links (i.e. shared by multiple mines; triangles) under shared development. Biodiversity impact is defined as proportional habitat loss per species summed across all conservation features.
Figure 5. Comparison of averted biodiversity impacts, and averted capital cost arising from the development of shared mine-port links for each of 28 mining companies, as compared to independent development of mine-port links. Each of the five shared corridors is represented by a different symbol (H1=blue square, H2= blue circle, B1=yellow triangle, B2=green triangle, M1=grey square). Mines with the greatest reduction in biodiversity impacts from infrastructure sharing do not necessarily show large reductions in capital costs (adjusted $r^2$ -0.017, trendline not shown).
Figures

Figure 1
Figure 3
Figure 5