Contributed Paper

Effect of Planning for Connectivity on Linear Reserve Networks

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Abstract: Although the concept of connectivity is decades old, it remains poorly understood and defined, and some argue that habitat quality and area should take precedence in conservation planning instead. However, fragmented landscapes are often characterized by linear features that are inherently connected, such as streams and hedgerows. For these, both representation and connectivity targets may be met with little effect on the cost, area, or quality of the reserve network. We assessed how connectivity approaches affect planning outcomes for linear habitat networks by using the stock-route network of Australia as a case study. With the objective of representing vegetation communities across the network at a minimal cost, we ran scenarios with a range of representation targets (10%, 30%, 50%, and 70%) and used 3 approaches to account for connectivity (boundary length modifier, Euclidean distance, and landscape-value [LV]). We found that decisions regarding the target and connectivity approach used affected the spatial allocation of reserve systems. At targets $\geq$ 50%, networks designed with the Euclidean distance and LV approaches consisted of a greater number of small reserves. Hence, by maximizing both representation and connectivity, these networks compromised on larger contiguous areas. However, targets this high are rarely used in real-world conservation planning. Approaches for incorporating connectivity into the planning of linear reserve networks that account for both the spatial arrangement of reserves and the characteristics of the intervening matrix highlight important sections that link the landscape and that may otherwise be overlooked.

Keywords: connectivity metrics, corridor, linear feature, Marxan, sensitivity, systematic conservation, target-based conservation, traveling stock route

El Efecto de la Planeación para la Conectividad en Redes de Reservas Lineales

Resumen: Aunque el concepto de conectividad tiene varias décadas sigue poco entendido y definido y hay quienes discuten que la calidad de hábitat y área debería partir del planeamiento de conservación. Sin embargo los paisajes fragmentados caracterizados generalmente están por caracteres lineales que están inerentemente conectados, como arroyos e biberones de arbustos. Para éstos, tanto la representación como los objetivos de conectividad pueden ser enfrentados con pocos efectos en el costo, área, o calidad de los sistemas de la reserva. Evaluamos como las aproximaciones de conectividad afectan los resultados de planeación para sistemas de hábitats lineales utilizando el sistema de rutas de ganado de Australia como un estudio de caso. Con el objetivo de representar a las comunidades vegetales a través del sistema con un costo mínimo realizamos escenarios con un rango de objetivos de representación (10%, 30%, 50% y 70%) y utilizamos 3 aproximaciones que representaron la conectividad (modificadores de la longitud de frontera, distancia Euclidiana y valor de paisaje). Encontramos que las decisiones correspondientes al objetivo y a la aproximación de conectividad que se usaron afectaron la colocación espacial de los sistemas de reservas. En objetivos $\geq$ 50%, los...
Introduction

The concept of connectivity originally appeared in the conservation literature in the 1980s (Merriam 1984) and has been the subject of much debate since, particularly in relation to habitat corridors (Crooks & Sanjayan 2006). This is partly because its definition is fluid and varies between subdisciplines such as metapopulation ecology and landscape ecology (Mollanen & Hanski 2001). Recently, some authors have further emphasized the need to improve connectivity in the landscape due to shifts in distribution of species with climate change (Hannah et al. 2002).

A large number of metrics have been developed to quantify connectivity (Crooks & Sanjayan 2006; Kindlmann & Burel 2008). However, because it is extremely context specific, being a function of both the species of interest and the spatial arrangement, area, and quality of patches (Tischendorf & Fahring 2000), these metrics are associated with a high degree of uncertainty. Therefore, some argue that other measures more strongly related to biodiversity, such as habitat area and quality (Turner 2005), should take precedence over connectivity when designing conservation networks (Hodgson et al. 2009). Despite the lack of consensus on whether and how connectivity matters, large investments continue to be made to enhance it in the landscape. Projects such as Gondwana Link in Australia, Yellowstone to Yukon in North America, and the Mesoamerican Biological Corridor of Central America represent multimillion dollar endeavors and involve hundreds of partner organizations (Worboys et al. 2010). It is currently not known whether these funds could be better spent, and systematic methods for identifying cost-effective connected reserve networks have not been widely applied in these examples.

A range of decision-support tools have been developed to facilitate the systematic spatial allocation of reserves (Mollanen et al. 2009). These tools address the fact that socioeconomic factors compete with the establishment of conservation areas (Carwardine et al. 2008) and use mathematical approaches to ensure that as many species as possible are protected while minimizing conflict with other human demands. They take into account not only what is to be conserved, but also how much—a measure known as the conservation target. Targets are frequently dictated by policy (Svancara et al. 2005) or are evidence based in that they represent empirically derived thresholds in population size or habitat area (Drielsma & Ferrier 2009). Expert elicitation can also be used to determine appropriate targets (Airame et al. 2003). In some cases, authors provide little or no justification as to how and why their targets were set (Carwardine et al. 2009). If solutions are sensitive to targets, their arbitrary allocation could greatly influence understanding of how certain parameters (such as connectivity) affect planning outputs.

Highly modified and fragmented landscapes are often dominated by linear habitat networks such as streams, hedgerows, and roadside reserves (McCollin et al. 2000; Hermoso et al. 2012), and species in these landscapes may benefit most from enhanced connectivity (Donald & Evans 2006). The configuration of linear landscape elements is inherently connected, so strategic planning that enhances both representation and connectivity may have little effect on the cost, area, or quality of the reserve network. However, examples of systematic conservation planning for these networks are scarce, and the effects of alternative connectivity approaches on costs are not known. To explore these issues further, we used the stock-route network of Australia as a case study. Stock routes constitute roadside strips of remnant vegetation and form a large-scale habitat network across New South Wales (Fig. 1). The management of this publicly owned and managed system is currently under review, with the potential that some sections could be sold to private landholders for agricultural production and others retained for conservation (Lentini et al. 2011a). Against this background, we aimed to determine the implications of including connectivity as a goal in conservation planning for linear networks and whether the level of ambition in representation targets interacts with the effects of connectivity approaches.

Methods

We used the Marxan conservation decision support tool (version 2.1.1) (Ball et al. 2009) for our analyses. Marxan addresses the minimum-set problem, which is to meet a set of targets at the lowest cost. Targets are set for each of the conservation features that are to be protected within the conservation reserve network. These could be the area of habitat for an individual species, vegetation...
community, or other features of the landscape. Marxan minimizes an objective function, via a process of simulated annealing, to select candidate reserves from a pool of potential areas (or planning units), taking into account planning-unit costs and the locations of the conservation features for protection (Ball et al. 2009). Each alternative set of runs of Marxan, where input parameters such as targets or conservation features are altered, are called scenarios.

Planning Units

Our analyses were carried out on a region of New South Wales, Australia, that covers 41 M ha of the state and has been heavily cleared for agricultural production (Fig. 1). Remnant vegetation primarily exists as isolated protected areas, scattered trees in fields, and as stock routes that cover 485,818 ha (1.2%) of the study area (Lentini et al. 2011b). We used the TSR Conservation Values spatial layer (provided by the New South Wales Office of Environment and Heritage [OEH] 2010) for our planning unit layer. Stock route polygons in this had already been subdivided into management units. This initial set of 4865 individual planning units ranged from 0.2 to 4300 ha (mean [SE] = 99.8 ha [1.43]). Stock routes often occur in low-lying portions of the landscape and support vegetation communities characteristically underrepresented in the protected-area system (Lentini et al. 2011b). Given that a key principle of systematic conservation planning is complementarity (Stewart et al. 2003), we took into account the fact that some communities are already well represented and others not. Using the “NSW National Parks and Wildlife Service Estate” layer from the OEH data download website (http://mapdata.environment.nsw.gov.au), we added the 333 protected areas of the region to the analyses as planning units. Protected areas were locked in, so solutions always included these 333 planning units (and the vegetation within them). Hence, in total we considered 5198 planning units.

Conservation Features and Targets

We used 2 data layers to account for the major vegetation classes and the heterogeneity of these across the study region. The first was the Australia—Estimated Pre-1750 Major Vegetation Groups—NVIS Stage 1 (version 3.0) spatial layer created by the Australian Government’s National Land and Water Resources Audit, 2002. On the basis of this, 21 vegetation classes were identified. Using the Mitchell Landscape V3 layer (Eco Logical Australia 2008), we stratified each of these 21 vegetation classes according to the landscape type they fell within, of which there were 359 in the study region. In this way, the stock routes were classified into 1452 vegetation communities that were combinations of vegetation classes and landscape types (such as eucalypt woodlands of the Goonoo Slopes), which we used as conservation features (Table 1 & Supporting Information). In many cases an individual planning unit contained more than one vegetation community, and the proportional cover of each vegetation community and its condition was taken into account when we conducted our cost calculations (later). We also compared a range of conservation targets: 10%, 30%, 50%, or 70% of the current extent of each conservation feature in the stock routes and the protected areas. This was not intended to reflect what an adequate reserve network would be, but rather that it has been proposed that some stock routes will be sold and some protected, with no comment from relevant authorities on what the
extent of either of these actions may be. The protected areas included in the analysis already contained adequate amounts of some conservation features to meet representation targets, but proportional representation was lowest for the rarest conservation features (Supporting Information). This may have introduced some bias to the analyses or slightly affected the impact of the respective connectivity approaches (Supporting Information).

Cost

We combined a number of costs to determine the overall cost of taking conservation action in each of the planning units. Stock routes are publicly owned and thus have no purchase cost, but there would be an opportunity cost of reserving a stock route that may otherwise be sold (i.e., a lost sale price). For each planning unit, we estimated this opportunity cost using an unimproved-land-value layer at the local government scale, obtained from the Australian state land-valuation offices.

To account for differences in vegetation condition, we then added a restoration cost to planning units that contained degraded vegetation. We assumed that once this cost had been committed and restoration activities were complete that these planning units would have conservation values equal to those that were intact. We used the Vegetation Assets, States and Transitions (version 2) layer (Lesslie et al. 2010) to determine the current condition of each of our planning units and based restoration cost estimates for each vegetation class on information provided by Greening Australia (Gibson-Roy et al. 2010; see Supporting Information for detail of restoration calculations). No restoration costs were set for protected areas or for unknown, naturally bare, and aquatic vegetation types. The final cost of each planning unit was therefore the unimproved value plus restoration costs (ranging from $31.50 for 0.2 ha of open eucalypt forest to $6,414,372 for a stock route covering 4,675 ha of degraded tussock grassland and chenopod shrubland, mean [SE] = $207,171 [5,174]). All monetary units are in Australian dollars.

Incorporating Connectivity Approaches

We analyzed 16 different scenarios in Marxan, testing every combination of 4 connectivity approaches (no-connectivity, boundary length modifier [BLM], Euclidean distance, and landscape-value [LV]) with 1 of the 4 targets (10%, 30%, 50%, or 70% of the current extent of each conservation feature in the stock routes and protected areas). Although we implemented the connectivity approaches in Marxan, the theory supporting these approaches has been present in the literature for many years (Nicholls & Margules 1993; Urban & Keitt 2001), and they are compatible with most widely used tools for systematic conservation planning.

For the first set of scenarios, we did not use any measure of connectivity and hence called these the no-connectivity scenarios. The spatial allocation of reserves was based purely on the representation of conservation features in the most cost-effective way possible, irrespective of their spatial configuration.

The second set of scenarios incorporated the BLM, which is commonly applied in Marxan (Stewart et al. 2005) and other planning software (e.g., Moilanen & Wintle 2007). In these BLM scenarios, we accounted for the fact that 2 planning units adjacent to one another, if reserved at the same time, will form one reserve and the boundary between them will dissolve. The boundary cost of 2 adjacent units reserved together is therefore lower than 2 planning units of the same size that are reserved apart from one another. The BLM is actually the weight applied to the boundary-length component of the objective function to control the degree of aggregation across the reserve system. Increasing the BLM causes Marxan to more frequently select units adjacent to one

### Table 1. Vegetation classes included in analyses and the number of separate landscape types that each occurs in.

<table>
<thead>
<tr>
<th>Vegetation class</th>
<th>Number of landscapes</th>
<th>Landscape-value score¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalypt woodlands</td>
<td>295</td>
<td>WL</td>
</tr>
<tr>
<td>Eucalypt open forests</td>
<td>278</td>
<td>OF</td>
</tr>
<tr>
<td>Tussock grasslands</td>
<td>128</td>
<td>WL</td>
</tr>
<tr>
<td>Eucalypt open woodlands</td>
<td>101</td>
<td>WL</td>
</tr>
<tr>
<td>Callitris forests and woodlands</td>
<td>86</td>
<td>OF</td>
</tr>
<tr>
<td>Eucalypt tall open forests</td>
<td>80</td>
<td>OF</td>
</tr>
<tr>
<td>Other grasslands, herblands, sedgelands, and rushlands</td>
<td>66</td>
<td>WL</td>
</tr>
<tr>
<td>Casuarina forests and woodlands</td>
<td>61</td>
<td>OF</td>
</tr>
<tr>
<td>Mallee woodlands and shrublands</td>
<td>61</td>
<td>WL</td>
</tr>
<tr>
<td>Acacia forests and woodlands</td>
<td>53</td>
<td>OF</td>
</tr>
<tr>
<td>Other shrublands</td>
<td>49</td>
<td>WL</td>
</tr>
<tr>
<td>Heathlands</td>
<td>45</td>
<td>WL</td>
</tr>
<tr>
<td>Rainforests and vine thickets</td>
<td>44</td>
<td>CF</td>
</tr>
<tr>
<td>Chenopod shrublands, samphire shrublands, and forbs</td>
<td>35</td>
<td>WL</td>
</tr>
<tr>
<td>Naturally bare (sand, rock, claypan, mudflat)</td>
<td>16</td>
<td>WL</td>
</tr>
<tr>
<td>Eucalypt low open forests</td>
<td>15</td>
<td>OF</td>
</tr>
<tr>
<td>Acacia shrublands</td>
<td>12</td>
<td>WL</td>
</tr>
<tr>
<td>Inland aquatic (freshwater, salt lakes, lagoons)</td>
<td>9</td>
<td>WL</td>
</tr>
<tr>
<td>Acacia open woodlands</td>
<td>8</td>
<td>WL</td>
</tr>
<tr>
<td>Other forests and woodlands</td>
<td>5</td>
<td>OF</td>
</tr>
<tr>
<td>Unknown or no data</td>
<td>5</td>
<td>WL</td>
</tr>
<tr>
<td>Total number of conservation features</td>
<td>1452</td>
<td></td>
</tr>
</tbody>
</table>

¹For each planning unit, we calculated the landscape value that unit would have for fauna that were dependent on woodland or grassland (WL), open forest (OF), and closed forest (CF) (see Supporting Information for further detail of these calculations). We then determined the dominant vegetation type in each unit and assigned it the appropriate corresponding landscape-value score. For example, if a planning unit supported 10% Callitris forests and woodland and 90% Eucalypt open woodland, it was assigned the WL score. Column 3 lists whether each vegetation class was classified as WL, OF, or CF.
another, so this approach assumes that more clustered solutions are more connected. We used the ABPmer boundary tool (http://www.abpmer.net/downloads/) in ArcMap (version 10) (ESRI, Redlands, California) to calculate boundary lengths of all individual and adjacent planning units \((n = 7048\), range 0.002–1,713,309, mean [SD] = 10,461 [38,412]). Details of the calibration of the BLM for these scenarios, and also Euclidean distance scenarios, can be found in Supporting Information.

In many circumstances, planning units that are close to each other will be more connected than units that are far from each other even if they are not spatially touching. The BLM approach did not account for this. An alternative is to calculate the straight line (Euclidean) distance between pairs of sites and then attempt to minimize the overall distance between sites (Nicholls & Margules 1993). Also referred to as the nearest-neighbor approach, this has been used in a wide range of conservation planning problems to control the degree of reserve clumping (Moilanen & Nieminen 2002). For the Euclidean-distance scenario, we calculated the distance between centroids of all pairs of sites within 100 km of each other and treated these distances as boundary lengths (\(n = 1,045,928\), range 154–99,999 m, mean [SD] = 64,304 [24,610]). This planning-unit centroid and boundary-length scenario is equivalent to the node and edge arrangement in graph-theoretic frameworks (Minor & Urban 2008). We adjusted the BLM in our analyses so that sites close to each other would be prioritized.

In the final set of scenarios, we used the LV metric developed by the New South Wales Office of Environment and Heritage. This addresses a limitation of the BLM-type approaches, which is that they do not account for the nature of the landscape between the planning units. LV mapping aims to highlight linking areas, where conservation of existing vegetation, improvement of the condition of degraded vegetation, or rehabilitation of cleared areas are most likely to contribute to maintaining or enhancing functional connectivity across a region.

A graph-theoretic approach (Urban & Keitt 2001) was used to derive LV. Habitat linkages were systematically modelled across a broad range of ecological scales. The connectivity measures used were colonization potential (Hanski 1999; Drielsma et al. 2007b) and neighborhood habitat area (NHA) (Hanski 1999; Drielsma et al. 2007a).

Colonization potential of a grid cell \(i\) was calculated as follows:

\[
C_i = \left[ \sum_j H_i H_j e^{-\alpha d_{ij}} \right],  \tag{1}
\]

where \(H_i\) is the vegetation condition of the focal cell, \(H_j\) is the vegetation condition of a neighborhood location \(j\), \(d_{ij}\) is the effective distance from the focal cell \(i\) to \(j\), \(1/\alpha\) is a movement parameter, \(y\) sets the relative influence of spatial context and site attributes, \(e\) is Euler’s constant.

NHA was calculated as

\[
NHA_i = \left[ \sum_j H_j e^{-\alpha d_{ij}} \right],  \tag{2}
\]

where \(H_j\) is the vegetation condition of a neighborhood location \(j\) (\(j\) can equal \(i\)), \(d_{ij}\) is the effective distance from the focal cell to cell \(j\), and \(1/\alpha\) is a mobility parameter.

LV was calculated for each planning unit (Table 1) and ranged from 0.0 to 844.25 (mean [SE] = 133.83 [1.08]) (Supporting Information). To incorporate these values into the analyses, we treated LV as a separate conservation feature and set the target appropriate for each scenario (i.e., if the conservation target for vegetation communities was 30%, then the target for LV was also 30%). For both the no-connectivity and LV scenarios, the BLM was set to zero so boundaries had no effect on reserve selection.

Analyses in Marxan

For each scenario, we ran Marxan 1000 times; each run produced a near-optimal solution. The best solution for each scenario was that which met all objectives at minimum cost. Irreplaceable planning units were those included in all 1000 solutions for a scenario; thus, they were essential for meeting representation targets. When there are more irreplaceable planning units in a scenario, there are also fewer options to swap and substitute areas, so irreplaceability acts as an indicator of scenario flexibility. We present data only for the stock-route planning units selected because protected areas were locked in and therefore common to every solution. For each of the planning units selected in each of the solutions, we calculated what amount of the total cost of that planning unit was dedicated to purchasing land (unimproved valued) and what amount, if any, we had determined was required for restoration. Finally, to determine how each of the connectivity approaches affected the degree of clumping (or aggregation) in the reserve network, we calculated the perimeter of the entire network for each of the best solutions. This perimeter was divided by the number of reserves formed by clumped planning units (so adjacent planning units selected together were counted as one reserve in the calculations). Lower perimeter:reserve count values indicate a higher degree of aggregation across the network.

We used a map of planning units selected in the best solution for each of the no-connectivity, Euclidean-distance, and LVs scenarios to investigate potential changes to the spatial arrangement of reserves. This map covered an 85 × 75 km section of the study region (Supporting Information). We also determined the percent overlap of individual planning units selected in the best solution for each scenario.
Results

Number and Area of Planning Units

Conservation reserves increased in area as the conservation target increased, but a proportionally greater area was required to meet the 50–70% targets for the Euclidean-distance and LV scenarios (Fig. 2a). A proportionally greater number of individual planning units were also required to meet targets for the Euclidean-distance approach at targets ≥50% and to a lesser extent for the LVs approach at targets ≥30% (Fig. 2b). Even at the 10% target level, where 59% of the conservation features were already adequately represented by the protected area system alone, Marxan still included 766–842 stock-route planning units to the solution to meet targets (Supporting Information).

It appears that the increase in the number of planning units required to meet targets for the Euclidean-distance and LV scenarios was met by incorporating smaller individual parcels of land into the reserve system. The average area of planning unit included in the reserve network was smaller at targets ≥50% for the Euclidean-distance scenarios and at targets ≥30% for LV scenarios (Fig. 3a). This is not simply because all of the large planning units had been exhausted: at targets ≥50%, the average planning unit not included in solutions for Euclidean-distance and LV scenarios was much larger than for no-connectivity and BLM scenarios (Supporting Information).

Cost

Patterns in the financial cost of solutions closely followed the number and area of planning units. Overall, relative costs remained almost unchanged across the connectivity approaches when the target was ≤30%, but this pattern changed in the 50%- to 70%-target scenarios (Fig. 2c). The best solution for the Euclidean-distance approach increased from being 4% more expensive than no-connectivity at the 10% target to being 20% more expensive at the 70% target (Table 2). By comparison, at the 70% target level, the LV scenario was only 5% more expensive than the no-connectivity approach.

Both targets and connectivity affected the cost of the individual planning units selected. At 10–30% targets, the Euclidean-distance approach selected more expensive planning units, but this switched at targets ≥50% (Fig. 3b). The LV approach consistently resulted in the selection of cheaper planning units, irrespective of targets. Finally, the way in which funds were allocated was only subtly affected by connectivity. All approaches generally allocated equal amounts to protection and restoration in each scenario (Fig. 3c), with the exception that the Euclidean-distance approach resulted in proportionally greater investment in protection than restoration at the 70% target.

Irreplaceable Planning Units

Only the inclusion of the Euclidean-distance approach had a strong effect on the number of planning units that were completely irreplaceable, and this was only
Spatial Arrangement, Overlap, and Aggregation of Planning Units

As the conservation target increased, the connectivity approaches selected increasingly different planning units (Fig. 4). Those in the no-connectivity and BLM scenarios were most similar, and the BLM and Euclidean-distance scenarios were the least similar. In assessing aggregation of the best solution for each scenario, at targets \( \geq 50\% \) the
Table 2. Outline of each of the 16 planning scenarios run in Marxan and the associated outcomes (protected-area planning units not included in the values listed).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Target (%)</th>
<th>Connectivity measure</th>
<th>Outputs: best solution&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Outputs: irreplaceability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost&lt;sup&gt;c&lt;/sup&gt;</td>
<td>SM&lt;sup&gt;e&lt;/sup&gt; spent purchasing</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>no-connectivity</td>
<td>111.95</td>
<td>60.93</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>BLM&lt;sup&gt;f&lt;/sup&gt;</td>
<td>112.35</td>
<td>60.46</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Euclidean</td>
<td>116.65</td>
<td>63.19</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>landscape-value</td>
<td>112.11</td>
<td>60.63</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>no-connectivity</td>
<td>218.28</td>
<td>109.70</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>BLM&lt;sup&gt;f&lt;/sup&gt;</td>
<td>218.77</td>
<td>111.32</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>Euclidean</td>
<td>226.12</td>
<td>113.67</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>landscape-value</td>
<td>221.46</td>
<td>109.44</td>
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<td>9</td>
<td>30</td>
<td>landscape-value</td>
<td>373.17</td>
<td>189.27</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>no-connectivity</td>
<td>375.93</td>
<td>188.95</td>
</tr>
<tr>
<td>11</td>
<td>50</td>
<td>Euclidean</td>
<td>436.82</td>
<td>214.57</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>landscape-value</td>
<td>390.32</td>
<td>192.53</td>
</tr>
<tr>
<td>13</td>
<td>70</td>
<td>no-connectivity</td>
<td>568.72</td>
<td>290.37</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>BLM&lt;sup&gt;f&lt;/sup&gt;</td>
<td>571.65</td>
<td>291.31</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>Euclidean</td>
<td>687.04</td>
<td>324.53</td>
</tr>
<tr>
<td>16</td>
<td>70</td>
<td>landscape-value</td>
<td>599.06</td>
<td>300.47</td>
</tr>
</tbody>
</table>

<sup>a</sup>Average outputs across the 1000 near-optimal solutions for each scenario are listed in Supporting Information.

<sup>b</sup>Representation targets are for vegetation communities in protected areas and stock routes across the study region.

<sup>c</sup>All costs are in Australian dollars.

<sup>d</sup>Planning unit.

<sup>e</sup>Boundary length modifier.
Euclidean-distance and LV scenarios reduced the ratio of the entire reserve perimeter to the number of reserves; hence, these approaches appeared to increase the degree of clumping to a greater extent than no-connectivity and BLM (Table 2 & Supporting Information).

**Discussion**

**Incorporation of Connectivity into Planning Linear Networks**

Decisions regarding which specific approach to use to incorporate connectivity into linear reserve planning will affect the final reserve system. The BLM, one of the most commonly used approaches for adjusting connectivity, had almost no effect on solutions. This is because stock routes are transected by roads and streams and therefore are not spatially continuous, and the boundaries they do share are very narrow. Therefore, the standard BLM may not be appropriate when planning for connectivity in linear networks, where planning units are not directly adjacent or share very narrow boundaries. In these situations, the BLM should be used in more sophisticated ways, but examples of this in the literature are rare (but see Hermoso et al. 2012). We addressed this issue by using the Euclidean-distance approach, which increased the aggregation of reserves (Supporting Information) at the cost of both monetary resources and reduced size of the remnants selected (Figs. 2 & 3). Aggregation of habitat is important in low-cover fragmented landscapes (Radford et al. 2005). Such as our study region, but this will only boost functional connectivity if reserve spacing does not exceed the dispersal threshold of target species (Doerr et al. 2011). Only the LV approach addresses these thresholds because it takes into account the vegetation outside the planning units; therefore, it may be most effective in promoting actual functional connectivity. Moreover, the LV approach resulted in a far lower reserve cost than Euclidean-distance scenarios (Fig. 2c).

Given the potential trade-offs of connectivity with individual reserve area, an important question is how much connectivity should drive reserve selection. The creation of smaller reserves appears to go against conventional conservation wisdom (e.g., Bender et al. 1998), but in our example groups of smaller reserves were also more spatially connected; thus, they created functionally larger clumps. When executed with sufficient consideration, planning that accounts for connectivity should provide conservation benefits beyond representation by ensuring adequate performance of the reserve network. For example, Olds et al. (2012) reported that fish abundance in marine protected areas differs from unprotected areas only if the protected areas are sufficiently connected to adjacent mangrove habitat; without connectivity the reserves are not serving their purpose. Although we know larger reserves are often needed to ensure the persistence of viable populations (Nicholson et al. 2006), if a catastrophic event causes extinction within an isolated reserve it cannot be recolonized from other source populations (Fahrig & Merriam 1994). For this reason, Doerr et al. (2011) argue that planners need to account for both “habitat for settlement” and “habitat for dispersal”; smaller patches, thus, effectively link core habitat patches. In highly fragmented landscapes, small parcels of land and even individual trees can increase functional connectivity (Fischer & Lindenmayer 2002a; Geert et al.
2010; Gillies & St. Clair 2010), so a balance of both large and small remnants may be optimal.

Interaction of Effects of Connectivity Approaches and Conservation Targets

Our findings demonstrate that connectivity considerations have their greatest effect at representation targets $\geq 50\%$, at which point there was also comparatively higher irreplaceability in the Euclidean-distance and LV scenarios (Supporting Information). This indicates there were fewer options available to meet both the vegetation representation and connectivity requirements. Because of this, Marxan was forced to select planning units that were smaller and less cost-effective (Figs. 3a & b). In reality, targets $\geq 50\%$ are rarely used. In their review of the conservation planning literature, Svancara et al. (2005) found that on average, policy-driven targets are set at 13.3%, those based on conservation assessments at 30.6%, and those on threshold analyses at 41.6%. These targets refer to the entire historical extent of vegetation communities or other conservation features. We, however, assessed only the stock routes and protected areas. In our study, stock routes covered only 1.2% of the region, so even if all were set aside as reserves, we would still not meet a typical policy-based landscape target, let alone reach an ecologically adequate level of representation. But if unambitious targets such as those listed are the norm, concerns regarding effects of connectivity metrics on reserve network costs may not be warranted. These findings are likely to be relevant to any conservation planning problem where one can choose to conserve more or less of the area available. For example, in maximum coverage problems, where one has to prescribe a budget, the allocation of a large budget will result in a greater area being set aside for conservation (Fig. 2c). Therefore, budget size is likely to interact with connectivity approaches in the same way that targets did in our example (i.e., there will be a greater effect of connectivity approaches with larger budgets).

Applying Conservation Planning to Real-World Linear Networks

We conducted our study in a developed country, which is ecologically well studied. Despite this, we found spatially explicit data suitable for our purposes to be scarce: vegetation community and condition data for NSW were only accessible at a national scale. On the basis of the knowledge of P.L. and P.G., it was clear that some of the areas reported as degraded actually had high conservation value and that some vegetation communities had been misclassified. For this reason, our solutions are not intended to be prescriptive; rather, they present an exploration of how connectivity can alter the results of planning exercises for linear networks. However, this highlights an important issue. There are often calls in the literature for less data and more action. It is argued that resources currently allocated to collecting data could be better spent implementing conservation actions instead (Knight et al. 2010). Sometimes this assessment is fair, especially when not taking action risks the future viability of species or reserves (Martin et al. 2012). In our example, however, the action to be taken is not only the protection, but also the sale of what are potentially the most intact examples of the most highly threatened vegetation communities in Australia. In this case, better spatial data or ground truthing is needed to complement these decisions.

Stock routes are all currently publicly owned and do not require purchasing, and the allocation of funds over a protracted period does not need to be taken into account. Instead, the primary costs involved are lost opportunities in selling the land and ongoing management. With an ever-increasing emphasis on connectivity when planning for global change, stock routes offer a compelling example where for typical reservation targets both connectivity and representation of threatened vegetation can be gained in highly fragmented landscapes for little additional financial cost. This scenario is the same for preestablished linear networks around the world. Many authors note that these linear features hold value for biodiversity conservation and should be the subject of landscape planning (Leon & Harvey 2006; Lundy & Montgomery 2010). Although linear features are now often integrated into conservation programs such as agri-environmental schemes across Europe (Kleijn & Sutherland 2005), examples of systematic conservation planning for terrestrial linear networks in the literature are scarce (but see Burel & Baudry 1995; Hirt et al. 2011).

We found that incorporating connectivity into planning for linear networks is unlikely to have strong effects on the financial cost of solutions when representation targets are up to 30% and may provide additional benefits in the form of improved reserve performance. In situations where targets are to be set higher, planners will have to carefully weigh the benefits of connectivity against the habitat area needs of target species and budgets for prescribed actions that may be costly (such as restoration). The LV metric we used took into account not only the spatial location of potential reserves, but also the characteristics of the intervening matrix and involved moderately greater cost only at high (50–70%) representation targets. Such approaches also highlight smaller areas that link the landscape and that may otherwise be overlooked in systematic conservation planning.

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Supporting Information

Details of how we determined conservation features and targets (Appendix S1), calculated the estimates used for restoration costs (Appendix S2), calibrated BLM values (Appendix S3), and calculated Landscape-value (Appendix S4) are available online. 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


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