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From static connectivity modelling to scenario-based planning at local and regional scales

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Abstract

Despite the proliferation of connectivity modelling approaches, static models have limited usefulness for decision-making by policy-makers and land managers, particularly where significant changes in land uses might be expected into the future. This study presents a flexible, scenario-based approach for modelling fine-scaled connectivity using graph-theory with least-cost paths for modelling connectivity at the regional scale and Circuit theory at the local scale. The method allows for the assessment of a range of scenarios based on varying land use practices. Using the Lower Hunter region, Australia as a case study we tested five scenarios that describe the impact of different development choices on connectivity, ranging from high rates of urbanisation to revegetation of a designated green corridor. The changes in connectivity from the current state were assessed by visualising component boundaries and link locations and calculating patch- and landscape-scale graph metrics. In the Lower Hunter we found the green corridor scenario increased connectivity both visually and quantitatively as shown by a 105% increase in the integral index of connectivity (IIC) which measures habitat availability (reachability) at the landscape scale. While the urbanisation scenario resulted in a decrease in connectivity, with a 39% decrease in the IIC. The approach outlined in this paper is flexible, enabling a range of interests to be included, depending on the datasets available and the issues that need to be addressed. Such methods can be readily and rapidly applied by consultants or government agencies, in this region and elsewhere, to incorporate connectivity modelling into development plans.

Keywords: Connectivity; land use planning; wildlife corridors; scenario; Graph metrics; Circuitscape

Introduction

Changes to the extent and condition of native vegetation due to human land use results in an altered mosaic of habitat for native species. The constriction of species movement caused by increased habitat fragmentation or decreased connectivity reduces population viability and increases extinction risk beyond that caused by habitat loss alone (Brook, Sodhi, & Bradshaw, 2008; Caughley, 1994; Fischer & Lindenmayer, 2006). Management of the patterns and types of land cover is thus important for reducing the impact of fragmentation on connectivity.

Despite the proliferation of connectivity modelling approaches, static outputs from these models characterising existing connectivity networks may have limited usefulness for decision-making by policy-makers and land managers (Bergsten & Zetterberg, 2013; Whitten, Freudenberger, Wyborn, Doerr, & Doerr, 2011), particularly where significant changes in land use might be expected into the future (McHugh & Thompson, 2011). It is critical for these models to be dynamic and able to be readily modified and updated in response to future land use planning decisions, changes in available spatial data and knowledge of species dispersal characteristics.

A scenario planning approach can be useful for considering the potential impact of land use changes on connectivity across a region and at local scales. Different scenarios, representing a range of stakeholder interests, can be simulated by modifying the spatial data inputs to the connectivity model (Lechner, Brown, & Raymond, 2015). Land use change can have a positive or negative influence on connectivity by changing the number or size of patches; changing dispersal costs as a result of altering land cover types (e.g. converting grazing land to urban), or by adding or removing elements that are important for structural connectivity, such as scattered trees (Fig. 1). The impact of different scenarios can be visualised qualitatively, as well as quantified using metrics such as patch-scale graph metrics, and landscape scale graph metrics (Clauzel, Girardet, & Foltête, 2013; J.-C. Foltête, Girardet, & Clauzel, 2014; Zetterberg, Mörtberg, & Balfors, 2010). The scale of impact assessment for land use planning ranges from regional assessments that identify critical wildlife corridors linking a region to local scale assessments such as for an environmental impact assessment that identify whether remnant vegetation found as paddock trees are critical for connecting two habitat patches.

Land use decisions are frequently made in the absence of data or using coarse resolution modelling across large extents, describing connectivity at resolutions inappropriate for answering the questions being asked by these land use planners. In most cases there is little or no capacity to update mapping outputs and assess land use scenarios (Bergsten & Zetterberg, 2013; Whitten et al., 2011). Therefore where existing connectivity mapping is used land use scenario assessments can't be made quantitatively. However, connectivity needs to be assessed as a system, modelling the emergent property of the patches and the network of linkages. Impacts are best assessed through modelling these linkages in response to a scenario. For example, conserving half a threatened species habitat is likely to provide positive conservation outcomes, however, conserving half a corridor is ineffectual. A common approach with static connectivity maps is to overlay impacts of land use change with connectivity pathways. This may be useful where the impacts are simple such as on a single linkage or patch. However, when complexity increases and multiple areas of habitat and linkages may be lost or gained, these methods may not adequately assess impacts at a landscape scale.

In this study we describe a dynamic connectivity modelling framework targeted at land use planners. The dynamic framework is based on an existing fine-scaled connectivity modelling framework (Lechner, Doerr, Harris, Doerr, & Lefroy, 2015) which uses graph-theory with least-cost paths for modelling connectivity at the regional scale (J. C. Foltête, Clauzel, & Vuidel, 2012), and Circuit theory for modelling connectivity at the local scale (McRae, Dickson, Keitt, & Shah, 2008). In the methods section we describe the components of the framework: i) fine-scale connectivity modelling methods, ii) land use scenarios simulation, and iii) methods for assessing connectivity modelling scenarios outputs. We demonstrate the framework's utility for assessing the impact of different land use scenarios on connectivity networks using the Lower Hunter region (NSW, Australia) as a case study. This paper provides an example for how land use planners can operationalise connectivity outputs from existing graph-metric and Circuitscape modelling software. The emphasis of this paper is on providing a simple and robust framework for the rapid assessment of connectivity for land use planners who don't have the time or expertise for the complex analyses that are commonly described in the academic literature.

Methods

Fine-scale connectivity modelling methods

In this paper we utilise the General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) framework originally described by Lechner and Lefroy (2014). The GAP CLoSR framework describes how local and regional scale connectivity models can be used and interpreted to support land use planning through scenario analysis. The framework characterises connectivity based on fine-scale dispersal behaviour and includes : i) a workflow that starts with identification of key ecological connectivity parameters; ii) pre-processing spatial data based on these parameters; and iii) a method for running these spatial data within existing connectivity modelling software. A critical component of this framework is the ability to rapidly re-process data for running multiple scenarios.

The regional scale model is based on Graphab (J. C. Foltête et al., 2012), a graph-network connectivity model that uses least-cost paths, though modified to account for threshold dynamics in dispersal behaviour. Graphab is used to characterise connectivity between patches based on a threshold distance between adjacent patches. Where connectivity exists between patches a single optimal least-cost path is identified between patches.

In contrast Circuitscape characterises connectivity for all pixels in the area of interest between all dispersal sources (patches or groups of patches) but does not allow dispersal thresholds to be used. Circuitscape models the landscape as analogous to an electrical circuit, characterising movement across a resistance surface as current flowing through a circuit. Maps of current density flow are created by modelling electrical current from multiple individual pairs of sources (patches or groups of patches) to highlight alternative pathways and “pinch points” of high current density, where loss of a small area could disproportionately compromise connectivity (McRae et al., 2008). Due to the computational restrictions resulting from the greater complexity of the Circuitscape model, the extent of analysis must be smaller than when using Graphab and thus Circuitscape was confined to local scale analysis.

Case study

Connectivity was modelled in the Lower Hunter Region in New South Wales, Australia, approximately 100 km north of Sydney. It covers an area of approximately 430,000 hectares

and includes five local government areas: Cessnock, Lake Macquarie, Maitland, Newcastle and Port Stephens. This region is expected to see increases in population growth, agriculture and mining, increasing pressure on the environment (NSW Department of Planning, 2006).

In the Lower Hunter we modelled connectivity between woody vegetation, which is the dominant natural vegetation cover type in the study area. The model was parameterized based on a review by Doerr et al. (2010), which synthesized all available evidence on the relationship between structural connectivity and landscape scale dispersal of Australian native fauna species. It identified three important parameters which can be used to characterize dispersal. Firstly, a minimum patch size of 10 ha, below which the patch cannot support a population. Secondly, a gap-crossing distance threshold of 106 m between connectivity elements such as scattered trees, and thirdly, a maximum interpatch-crossing distance threshold of 1100 m, above which the animal is unable to disperse. The two thresholds described in the review were based on a systematic review of all empirical studies in Australia (Doerr et al., 2010).

These ecological inputs were used along with three spatial inputs: i) dispersal-cost surface based on land use/land cover (LULC) mapping, ii) a gap-crossing layer derived from the gap-crossing distance threshold and iii) a patch layer (Table 1). The dispersal-cost surface represents dispersal cost as a percentage of interpatch-crossing distance for multiple land cover types, where the value assigned to each land cover type reflects the cumulative cost for species to move through it. For example, a dispersal cost of 200 % in urban areas means a species can only travel 550 m rather than the maximum interpatch-crossing distance threshold of 1,100 m. The dispersal costs were primarily based on a report from the Port Stephens area by Eco Logical Australia (2012). A unique feature of this modelling method is the inclusion of a gap-crossing layer which identifies pixels where the distances between structural connectivity elements is greater than the 106 m threshold and are treated as barriers to connectivity. This is achieved through buffering fine-scale (2.5 m) vegetation data (Siggins, Opie, Culvenor, Sims, & Newnham, 2006) by half the gap-crossing distance threshold. Areas where the buffers do not touch or overlap become dispersal barriers. Further details of the fine-scale connectivity modelling method can be found in Lechner and Lefroy (2014) and Lechner et al. (2015b).

Land use scenarios

Five scenarios representing different stakeholder interests were modelled and compared to current connectivity. These scenarios ranged from planned future urban development to revegetation of key areas identified in a strategic assessment of the Lower Hunter (Table 2). The scenarios were developed through discussions with stakeholders in the Lower Hunter including local council, NGOs and state government and were based on publically available planning and biophysical spatial data.

The impact of land use scenarios on connectivity was simulated by modifying the spatial data inputs to the connectivity model (Fig. 1). Negative scenarios were simulated through the removal of vegetation that contribute to structural connectivity elements and habitat patches, while positive scenarios were simulated through the addition of vegetation.

The processing of land use scenarios is automated in a freely available software tool which can be accessed from a graphical user interface or directly using the Python programming language with the ArcGIS 10.1 Python libraries (see www.github.com/GAP-CLoSR). Change areas are identified with an ArcGIS vector shapefile and spatial data inputs for current scenarios are automatically updated.

Connectivity modelling scenario assessment methods

There are several classes of model output, varying in complexity and uncertainty, that can be used to assess connectivity for conservation planning (Fig. 3). At the regional or landscape scale, these are, in increasing order of complexity: component analysis, patch-scale graph metrics, and landscape scale graph metrics. At the local scale, these include analyses of patches and links, patch-scale graph metrics, and Circuitscape analysis, again increasing in complexity.

The simplest approach, often used at the first stage of an analysis, is to identify the extent to which habitat components, or patches, are isolated or linked. ‘Components’ are groups of interconnected patches that are isolated from other components due to distance and costs of movement through intervening land uses (Fig. 3a). The component boundaries described by Graphab are drawn at the midpoint between patches from different components and are for visualisation purposes only. At the local scale linkages or the absence of a linkage and their location can be identified between patches (Fig. 3d).

Connectivity is most valuable for biodiversity when it functions to link many habitat areas in a landscape-scale network. At this level connectivity patterns may be complex, involving contributions of both patches and individual links between them to the functioning of the broader network. Assessments of such complex connectivity patterns can be made using graph metrics (Fig. 3b,c,e). These metrics summarise complex patterns resulting from the patch locations and the links between multiple patches across the landscape. These measures can be used to summarise patterns of connectivity across a whole landscape (Fig. 3b,c) or component (examples not given in this paper), or calculated for each patch (Fig. 3b,e).

In this paper we used four different landscape-level graph metrics to reflect a range of connectivity characteristics (Fig. 3c) (Table 3). The magnitude and percentage difference between these metrics can be used to assess the sensitivity of connectivity to the different scenarios (J.-C. Foltête et al., 2014; García-Feced, Saura, & Elena-Rosselló, 2011). For the patch-scale we used the delta Integral index of connectivity (delta IIC), which describes impact of the loss of habitat availability caused by the removal of the focal patch relative to the connectivity network (Pascual-Hortal & Saura 2006; Saura & Pascual-Hortal 2007), and the Clustering coefficient, which describes the level of route redundancy (Minor & Urban 2008; Ricotta et al. 2000). The graph metrics chosen are a subset of the many available graph metrics at the landscape and patch scale (see Minor & Urban 2008; Urban et al. 2009; Rayfield et al. 2010). Table 3 describes each of these graph metrics and their ecological significance.

Least-cost path analysis provides no indication of redundancy or potential alternative routes. However, given our modifications to incorporate dispersal behaviour and landscape thresholds, it does indicate where functional connections exist to help target management of current connectivity assets. In contrast, Circuitscape software (McRae et al. 2008) (Fig. 3d) identifies relative connectivity values of all areas between patches and components, but cannot incorporate maximum dispersal distance thresholds. Thus, it cannot distinguish between areas that currently do or do not provide functional connections, but pathway redundancy and potential bottlenecks can be visualised and it can be useful for identifying areas for future restoration. We used Circuitscape to complement and augment the graph-metric based analyses within a subset of the region, because computational limitations prevent it being run at the same pixel size and extent as the regional-scale analysis.

The order in which outputs are interpreted and whether all classes of output will be used depend on the conservation objectives, the context and the scale (local vs. regional). Generally, an analysis will start by using outputs that have a low complexity of interpretation (Fig. 3). These simple outputs have a straightforward interpretation and explicit relationships to the ecological parameters used in the model. For example, it is simple to relate component boundaries to distance thresholds and land cover between patches. In contrast, more complex outputs from landscape-scale graph metrics represent emergent properties of the graph network and tend to be more contextual and dependent on the research or planning question being asked and its scale. Thus, the first step will often be a visual assessment of the extent and configuration of the components.

The evaluation process described above should be conducted iteratively through discussions with stakeholders by the decision making agencies. For simplicity, we present a subset of the outputs that represent a combination of connectivity modelling techniques characterised by Fig. 3. We focus our analysis on the component configuration (Fig. 3a), some patch-scale metrics (Fig. 3b), the landscape-scale graph metrics outline in Table 3 (Fig. 3c) and present a single example of the Circuitscape analysis (Fig. 3f), in combination with the patch and link analysis (Fig. 3d).

Results

Current connectivity

The current scenario represents current connectivity within the Lower Hunter. This scenario identified two large components (isolated group of interlinked patches) in the west and the east (Fig. 4, Component 1 and 2) representing 91% of the total patch area. This component analysis provides a broad overview of regional patterns of connectivity. The two largest components are divided by a highly fragmented area in the centre of the region, which has a number of small components. Fig. 4 shows the distribution of the two patch-scale graph metrics spatially useful for regional and local-scale analysis. The clustering coefficient highlights patches with low path redundancy, as shown by the inset Fig. 4a, where central patches that link numerous patches have low redundancy value. In contrast most patches in the landscape had similar delta IIC values. Delta IIC is a good overall index for population viability as it characterises patches based on the potential to facilitate dispersal and total area. Only a few patches had high values for delta IIC due to the disproportionately high

contribution to connectivity in the landscape. For example, the large patch in the middle south of the Lower Hunter has the highest value of delta IIC as it contains 30% of total patch area and has links to 72 of the 574 patches.

Scenario 1: Currently planned and future urbanisation [URBAN]

Scenario 1 describes the impact of development on connectivity if all areas currently marked for future urban development were subjected to the removal of all vegetation and conversion to urban land cover (Table 4, Fig. 5b). The impact of this scenario on connectivity was as much a property of the location of the development as the size of development. For example, development in a specific area to the east of the Lower Hunter (north of Newcastle (Fig. 5b – B) resulted in the division of the second largest component in the current scenario (Fig. 4 component 2). Overall there was a reduction in most landscape scale metrics measures (Table 4).

Scenario 2: Impact of expressway [EXP]

This scenario quantified the extent to which the Hunter Expressway would pose a barrier to connectivity. Multiple new components were created as a result of the barrier posed by the expressway (Fig. 5c). The high impact on connectivity of this scenario was the result of the expressway located near the centre of the Lower Hunter, which effectively isolated many parts to its east and west. In this scenario the intensity of the impact (e.g. dispersal barrier) and the location of the impact (centre of the Lower Hunter) was as important as the total area affected.

Scenario 3: Agricultural intensification [AGRI.]

In this scenario the contribution of important agricultural land (IAL) to connectivity was tested. As IALs are concentrated to the north of the Lower Hunter, the major impact was the creation of new components in this area, notably around Braxton and Maitland (Fig. 5d). As with scenario 2, the differences in patch-scale graph metrics compared to the current scenario were concentrated around a specific area of impact. This is in contrast to scenarios 1 and 2, where the impacts were spread across the region. Patch area decreased substantially more from scenario 3 than from scenario 2 (74 km^2 compared to 3 km^2), but there were similar decreases in the percentage differences in landscape-scale graph-metrics (Table 4d).

Landscape metrics can be useful in highlighting changes in habitat or land cover (such as in scenario 3 [EXP.]) that have disproportionately high impacts relative to area.

Scenario 4: All scenarios combined– [ALL]

In this scenario all previous scenarios were included. This scenario results in the most fragmented landscape with the number of components increasing from 42 in the current scenario to 73 (Table 4). While these impacts are much more uniform across most of the region in comparison to scenario 3 and 4, the majority of the impacts are found in the central region of the Lower Hunter in a band extending from Braxton in the north, to Maitland then New Castle and finally to Port Macquarie (Fig. 5e). Graph metric values for all landscape levels were lower than those in all previous scenarios with percentage decreases ranging from 12 – 50%.

Scenario 5: Revegetation of green corridors [CORRIDOR]

Scenario 5 shows the impact of the creation of the green corridor identified in Lower Hunter regional strategies, which would connect the western and eastern components. This would result in the majority of vegetation being located within a single component, which would connect 95% of the total patch area and reduce the number of components from 42 in the current scenario to 33. Landscape scale graph metric values also show much higher values than all other scenarios indicating an increase in habitat connectivity.

Local scale analysis using Circuitscape – [Current versus ALL]

A local scale connectivity analysis using Circuitscape was conducted for the area within the centre of the Lower Hunter for scenario 4 (ALL) compared to the current scenario (Fig. 6a,b). This area was composed of highly fragmented small remnant patches that fail to connect the two large components to the east and west of the region. The area is part of the ‘green corridor’ identified in the Lower Hunter Regional Strategy (NSW Department of Planning 2006) (Fig. 6c) and the ‘high priority corridors’ identified in the Lower Hunter Conservation Strategy (DECCW 2009) (not depicted in Fig. 5f, but has a similar footprint as the green corridor). The Circuitscape analysis showed that the connectivity potential across the region of interest was constrained to small narrow corridors in scenario 4, with multiple bottlenecks represented by high current density values along these pathways. These areas represent

locations where options for movement are likely to be restricted and thus good areas to target for conservation.

Discussion

GAP CLoSR provides land managers with a systematic framework for assessing the impact of future land uses on connectivity. The framework can be used to guide management decisions by assessing impacts at a range of scales both regionally and locally, and assess the efficacy of a range of conservation planning instruments such as protected areas, offsets and covenants. It can also be used to assess the contribution of a range of conservation planning instruments such as in protected areas, offsets and covenants through testing and assessing connectivity between only these areas within a scenario (i.e. remove all habitat apart from in reserves). The approach addresses the need for systematic conservation planning products that are dynamic, user-friendly and useful for decision makers (Bergsten & Zetterberg, 2013; Pierce et al., 2005; Whitten et al., 2011).

The strength of the framework lies in its simplicity and its ability to test a range of interests depending on the datasets available and the issues that need to be addressed within limited timeframes. This is particularly important for the questions being asked by land use planners within local and state/provincial governments and catchment management authorities. The scales at which these decision makers operate are typically at the property scale or finer, in some cases assessing the significance of scattered tree or roadside corridors for connectivity. These types of land use decisions may be required on a monthly or annual basis.

Scenario comparison

The analysis of a range of development scenarios showed the extent to which connectivity would be reduced, highlighting the vulnerability of the already fragmented central region within the Lower Hunter to further fragmentation. For some scenarios, notably Scenario 2 [EXP.] and Scenario 4 [AGRI.], the impacts would be concentrated in particular locations rather than spread across the region as a whole. While the regional-scale assessment identified changes to connectivity across the Lower Hunter in response to the different land use scenarios, the local-scale analyses highlighted changes in connectivity not apparent at the larger scale. The regional-scale connectivity assessment for example does not account for a

loss of redundancy in potential connectivity pathways between patches. Based on the scenarios tested here the potential to connect the two large components in the east and west of the region using “high priority corridors” identified in the Lower Hunter Conservation Strategy (DECCW, 2009) or the “green corridor” area in the Lower Hunter Regional Strategy (NSW Department of Planning, 2006) will be reduced. In contrast the revegetation scenario (scenario 5) shows visually and quantitatively the positive impact of the green corridor on the Lower Hunter.

The characterisation of future scenarios represented here assumed homogeneous impacts, where development resulted in the removal of structural connectivity elements and patches, making these areas a barrier to dispersal. In practice, development approval could require vegetation retention or restoration, which would reduce the impacts on connectivity through the provision of structural elements important to connectivity identified by the Circuitscape analysis. For example, open space areas could be required to provide for wildlife corridors as well as recreation in a new housing development. However, along with structural connectivity elements, it is also important to preserve patches of large sizes which are often lost to future developments.

Conservation planning

Incorporating connectivity modelling and scenario planning into conservation planning should be iterative and dynamic (e.g. conservation action planning (The Nature Conservancy 2007)). Figure 7 provides examples of how model outputs can be used in combination with scenarios to assess the potential impacts of proposed developments, or identify the most effective locations for restoration.

A consultative approach needs to be used because the connectivity model outputs do not provide a single value or best answer that can direct conservation management decisions. While component patterns, the location of linkages and Circuitscape outputs are straightforward to interpret, graph metric values provide a greater level of ecological complexity and corresponding uncertainty in their application (Fig 3). The direction of change in the graph-metric values indicates improvements or declines in connectivity at the landscape or patch scale, but interpreting the magnitude of the ecological impact can be difficult. It is also important to use multiple indices, since the sensitivity of different indices will vary depending on the impact and the connectivity property they have been designed to

measure (Baranyi, Saura, Podani, & Jordán, 2011). When using landscape-metric values for the extreme scenarios (eg. scenario 4 [ALL] and scenario 5 [CORRIDOR]), it is easy to distinguish positive and negative impacts using graph metrics. However, where impacts are smaller, such as in scenario 3 [AGRI.], the difference in impact was almost negligible for the IIC. Impacts for these scenarios are likely to be more significant at the local scale and should be analysed in conjunction with expert local knowledge. For example, the expressway (scenario 2 [EXP.]) may fragment a local population of a listed species. Thus the analysis of component boundaries and lost-links may be more critical than changes in landscape-level graph metrics.

When using patch-scale metrics the importance of patches for connectivity can be assessed by comparing relative difference in graph metric values as in the case of landscape metrics. Zetterberg et al. (2010) suggested that two different perspectives need to be accounted for: the site-centric and system-centric view. The system-centric view identifies areas where improvements (adding more patches) need to be made or areas need to be conserved where there is little redundancy (e.g. based on the clustering coefficient values (see fig 4. Insert). In contrast, the site-centric view assesses areas of conservation importance that could potentially be isolated with the loss of other patches and linkages between patches. This can be done visually by examining the number of linkages for each patch or through utilising other patch-scale metrics such as node degree (not described in this study – see Lechner et al. 2015b). In addition to the site-centric and system-centric view at the landscape scale the most important patches can be identified through patch-scale metrics such as delta IIC that combine both connectivity and area.

The approach we have presented addresses both local and regional scale connectivity. It is at these scales that many conservation priorities are set. However, achieving large scale connectivity at a state or continent scale, which is essential for protecting critical ecological processes under climate change, requires semi-static, big-picture habitat connectivity assessment (e.g. Drielsma, Howling, & Love, 2012). A combination of approaches is therefore required to achieve multi-scale connectivity assessments, since a single methodology is unlikely to successfully cater for all considerations across all scales.

It is also important that connectivity is seen within the context of other ecological values such as species persistence, biological diversity, habitat quality and carrying capacity (Moilanen, 2011). Some studies have suggested that there is a strong relationship between population

viability and graph metrics, and that graph metrics are a good surrogate for more spatially complex, time-consuming, data hungry, meta-population methods such as population viability analysis (Bergsten & Zetterberg, 2013; Emily S Minor & Urban, 2007). A key future research task is to develop methods for assessing uncertainty in the input maps and the parameterisation of scenarios to quantify the trade-off between less complex methods with more ecologically realistic methods that may only be applied by academic researchers rather than land use planners. Our method utilised dispersal thresholds and a patch-matrix view of landscapes following Doerr et al. (2010), however, connectivity operates at a range of spatial and temporal scales, with movement varying between and within species in response to changes occurring on yearly, seasonal and daily basis. Movement may also shift as an adaptation to climate change (Doerr, Barrett, & Doerr, 2011; Zetterberg et al., 2010). While the patch-matrix view of landscapes is simpler computationally and is the most common approach for ecological studies of dispersal (e.g. Doerr et al. 2010), it is best suited for naturally patchy landscapes such as the Lower Hunter and alternative approaches need to be used where this is not the case (e.g. Drielsma et al. 2007).

Alongside these ecological considerations there are several sources of untested uncertainty not specific to the model outlined in this study, but common to connectivity modelling and landscape ecology in general. Uncertainty within the characterisation of land cover and vegetation data using remote sensing can result from uncertainty in the classification scheme being used, the spatial scale and classification error (Lechner, Langford, Bekessy, & Jones, 2012). All of these have the potential to interact, propagate and magnify the uncertainty of the model outputs (Langford, Gergel, Dietterich, & Cohen, 2006; Lechner, Reinke, Wang, & Bastin, 2013). However, it is difficult to see how such complexities would be addressed within the timeframes at which local government planners, natural resource management agencies and community groups operate.

Conclusion

Federal, state and local governments, landowners and businesses are making land use decisions that will impact on the natural environment for years to come. Reliable and easy to use decision support tools can provide a better understanding of the impacts of these decisions on connectivity and help decision makers make more informed choices. Combining connectivity modelling with scenario planning enables environmental, economic and social

considerations to be integrated. When used in conjunction with other planning processes, it can highlight the likely consequences of alternative scenarios for biodiversity, and identify interventions that benefit conservation in the face of other needs and interests.

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Figure Captions

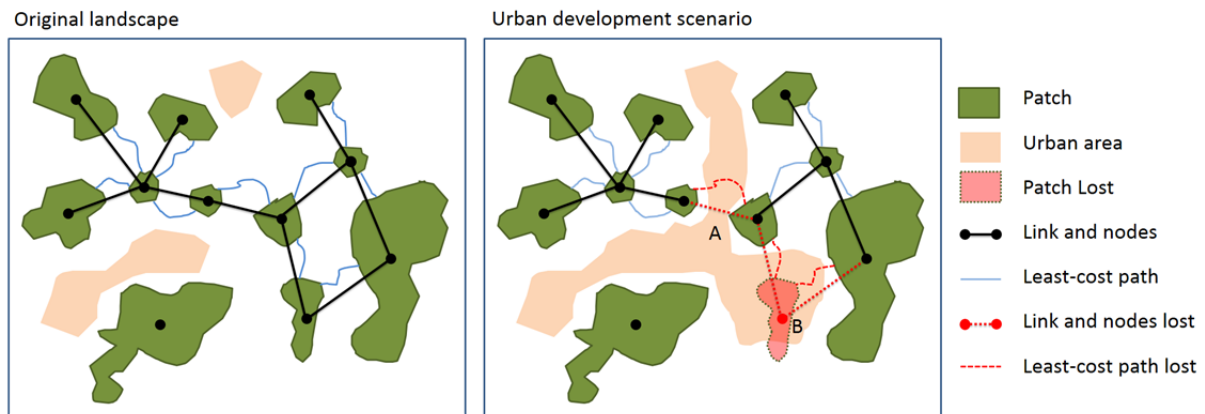


Figure 1: Graph theory is used to represent patches as nodes and connected patches as links. Actual paths between patches can be represented as least-cost paths. Graph metrics are useful for characterising the contribution of individual patches to connectivity and characterising overall connectivity. This diagram presents a development scenario that results in the expansion of urban areas. The impact of this scenario can be described through the lost links and nodes which can be quantified using graph metrics.

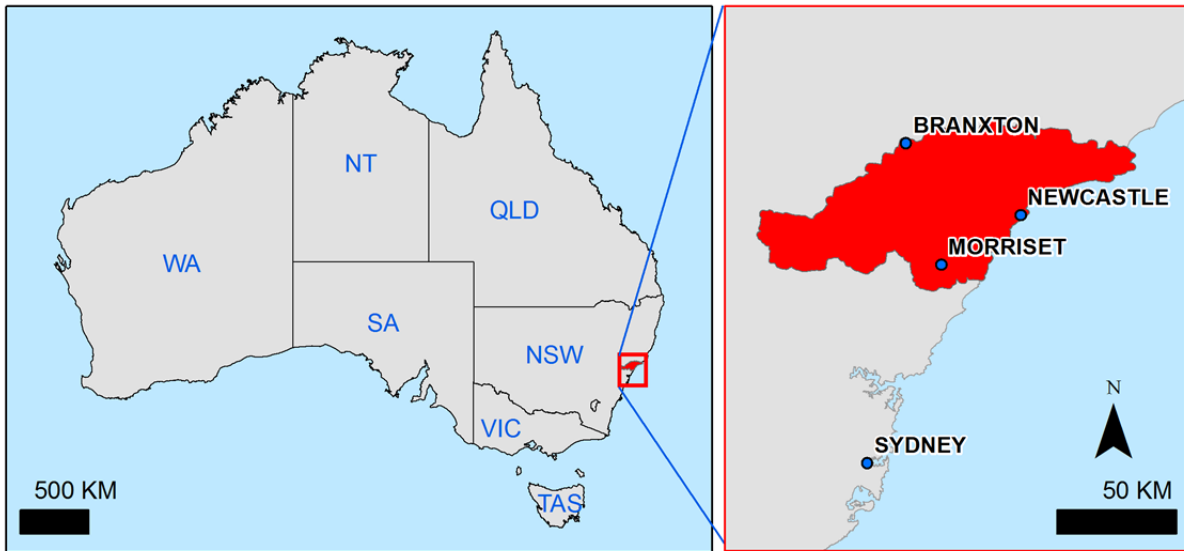


Figure 2. Lower Hunter study area in New South Wales, Australia.

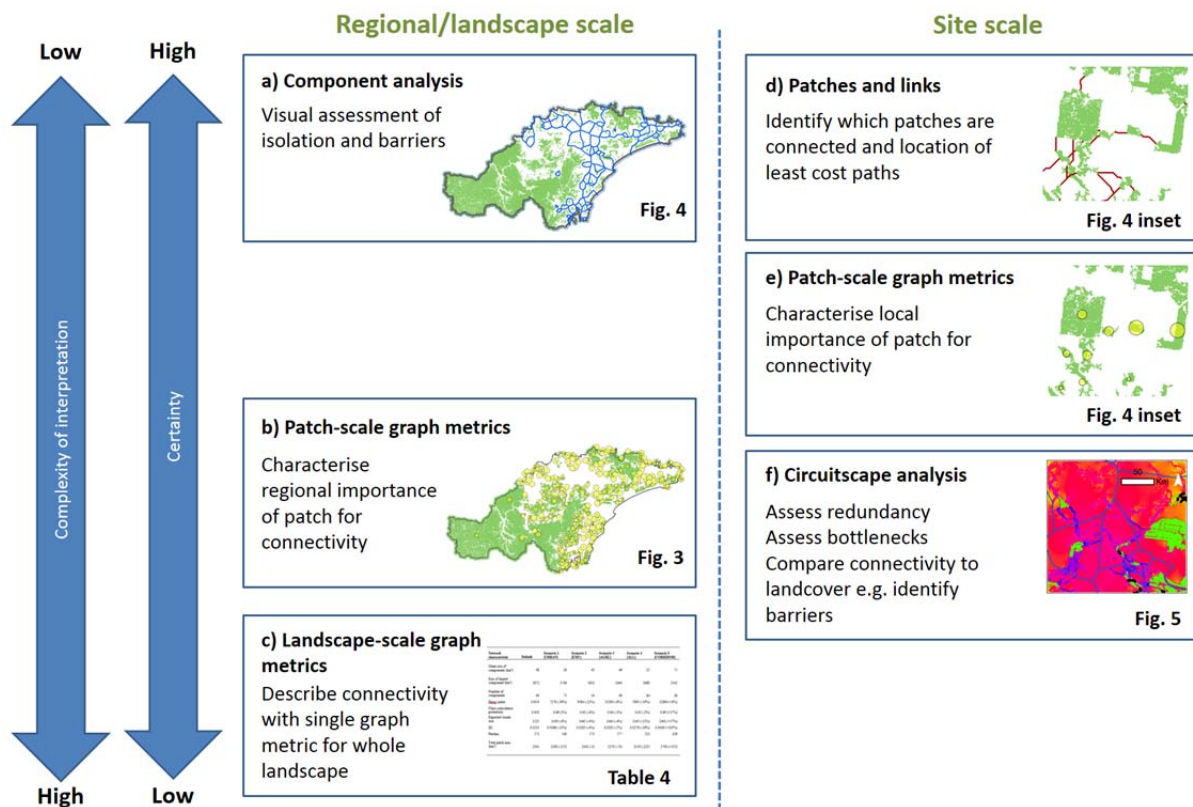


Figure 3. Framework for representing the five classes of model output and their complexity and certainty that can be used for assessing connectivity at the regional and site scale.

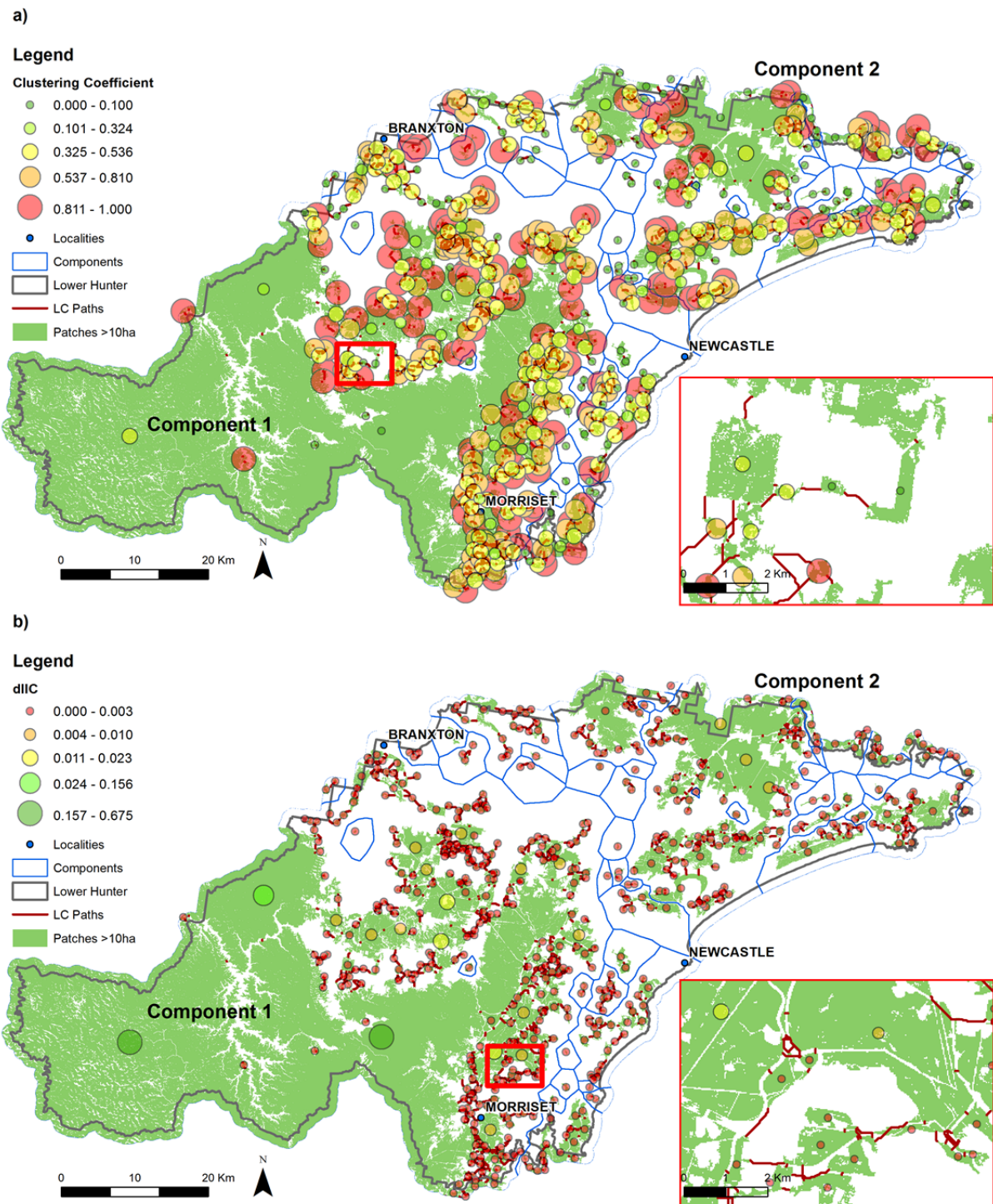


Figure 4: Regional scale connectivity analysis for the current connectivity showing least-cost paths in red for patches greater than 10 ha using Graphab. Circular symbols at the centre of each patch describe: a) Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network and b) delta IIC, a measure of the probability that two dispersers randomly located within patches in the landscape can access each other. The color scale for the circular symbols characterises connectivity; with high values in green and low values in red.

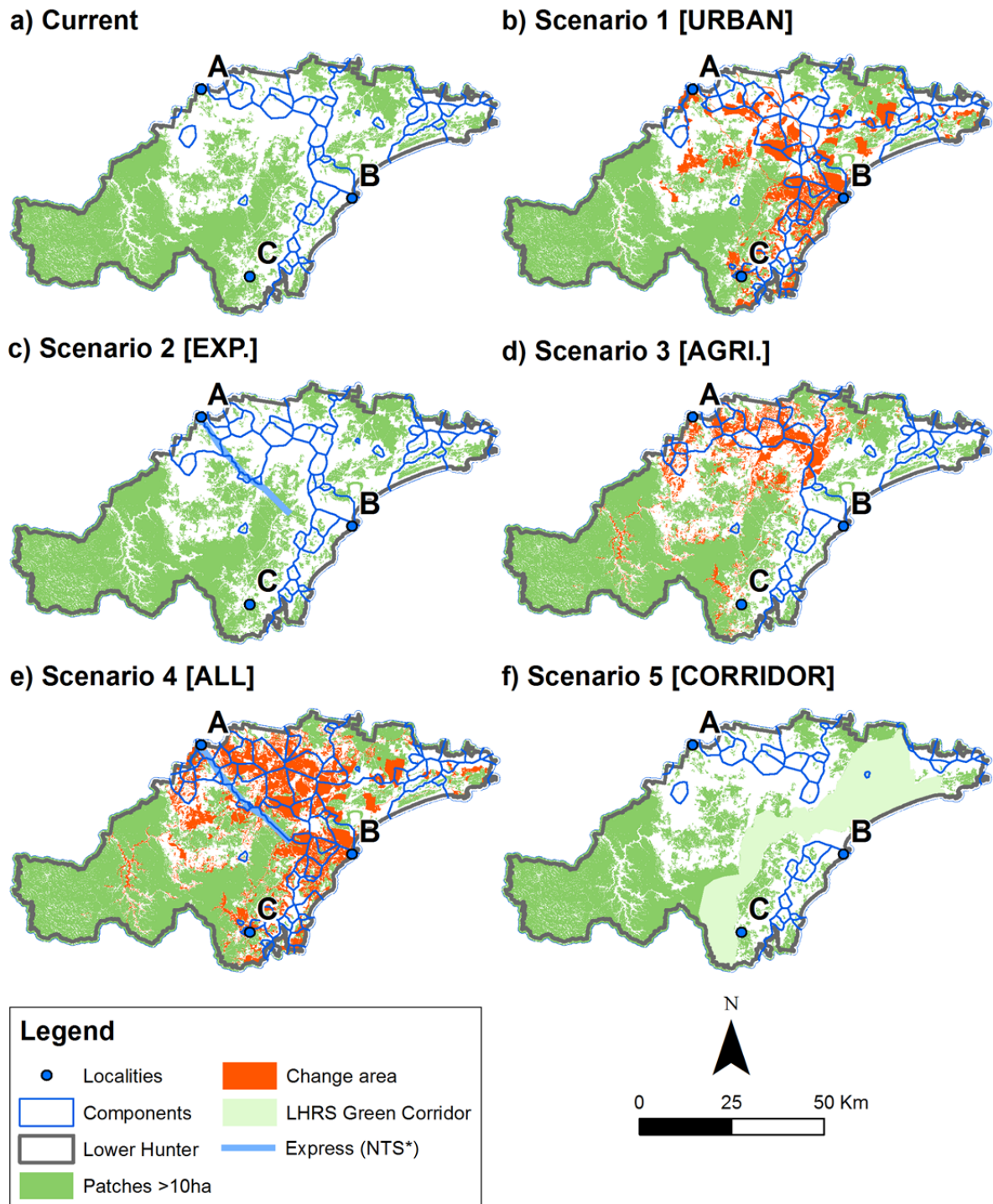


Figure 5: Regional scale connectivity analyses for current connectivity and land use scenarios showing the patterns of components in blue identifying areas that are connected or disconnected. Three localities have been included for orientation purposes: A) Branxton, B) Newcastle and C) Morristet.

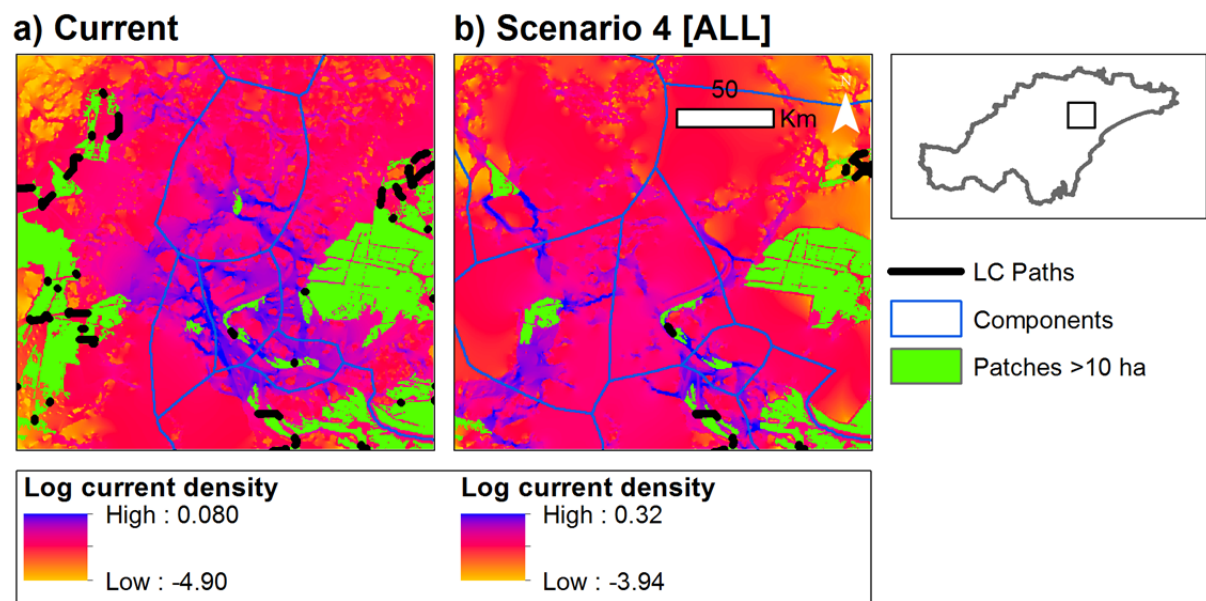
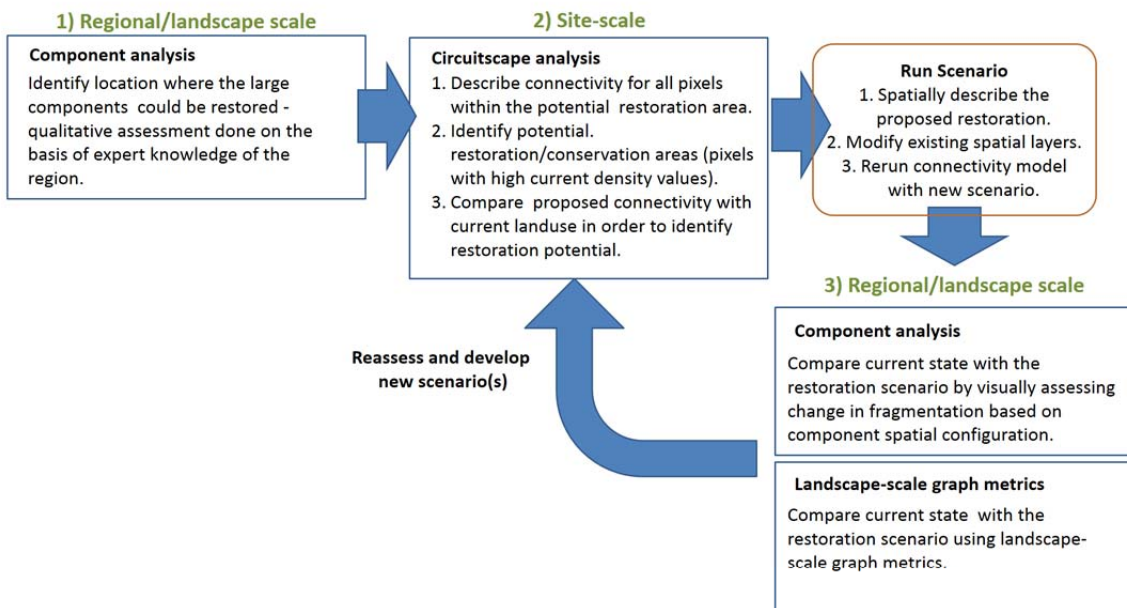


Figure 6: Local-scale connectivity calculated with Circuitscape software between groups of patches in seven components for a) “current” and b) “Scenario 4: [ALL]. Least-cost paths (LC Paths) and component boundaries identified with Graphab software. Areas where gap-crossing distance > 106 m (i.e. no scattered trees) given high resistance.

a) Identifying potential locations for restoring regional scale connectivity



b) Identifying the impact of proposed developments at site-scale

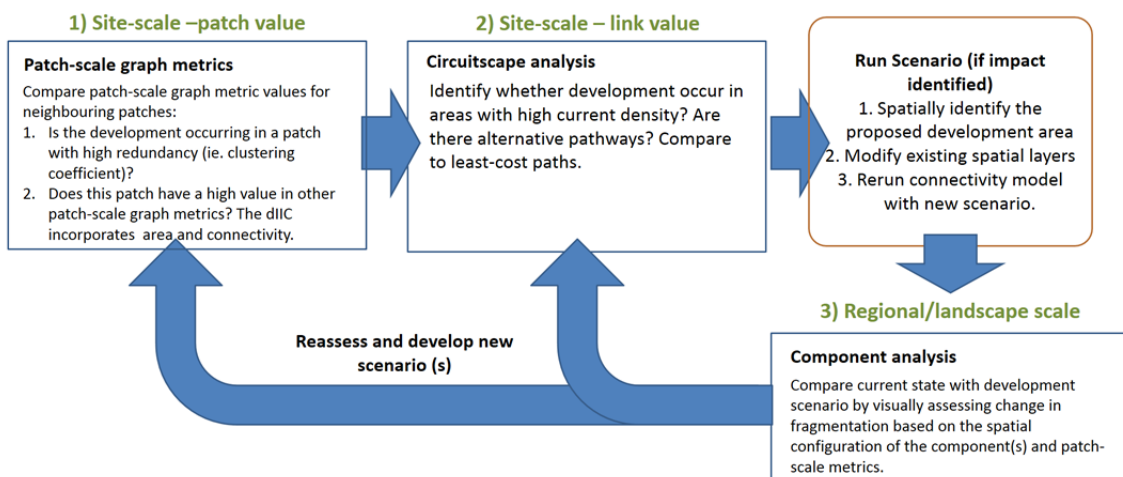


Figure 7. a) An example of how GAP CLoSR outputs may be used to identify potential locations for restoring regional scale connectivity. b) An example of how GAP CLoSR outputs may be used to identify the impact of proposed developments at site-scale

Tables

Table 1: Ecological parameters and input layers used in the connectivity model (Lechner and Lefroy 2014, Lechner et al. 2015a).

Description	Value	Source
Dispersal distance		
Minimum patch size	10 hectares	Doerr et al., 2010
Interpatch-crossing distance threshold	1.1 km	Doerr et al., 2010
Gap-crossing distance threshold	106 m	Doerr et al., 2010
Dispersal-cost surface		
Connectivity elements (e.g. paddock trees) absent	Infinite	Doerr et al., 2010
Other (predominantly farmland)	100%	Eco Logical Australia, 2012
Hydrology	300%	Eco Logical Australia, 2012
Transport	200%	Eco Logical Australia, 2012
Infrastructure	200%	Eco Logical Australia, 2012
Geoprocessing		
Land use/land cover layer	1:25000 / ~12.5 m	NSW LULC layer based on 1998-2000 air photo interpretation
Vegetation layer	2.5 m	SPOT satellite Greater Hunter mapping (Siggins et al., 2006).
Processing pixel size	25 m	Based on smallest pixel size that could be processed

Table 2: Land use scenarios tested in the Lower Hunter and the spatial data processing used to represent them. Scenarios 1-4 represent futures in which vegetation is removed and scenario 5 represent the consequence of revegetation.

Scenario	Description	Processing
Scenario 1: Currently Planned and future Urbanisation [URBAN]	The impact of urbanisation that results in the removal of all vegetation within urban areas identified from local government areas' (LGA) local environmental plans (LEPs) and future growth. Assumption: all areas zoned for development in LEPs and future plans will result in complete removal of all vegetation.	Removal of vegetation and change in land use value except in areas of pre-existing transport, hydrology and Infrastructure.
Scenario 2: Impact of Expressway [EXP.]	New multi-lane expressway. This scenario tests the impact of the expressway posing a barrier to connectivity.	Creation of 100 m movement barrier based on express way centreline with infinite dispersal costs.
Scenario 3: Agricultural intensification [AGRI.]	Areas of high agricultural value were identified from the Important Agricultural Lands (IAL) mapping and avoided. IAL identifies "land that is capable of sustained use for agricultural activity, with appropriate management practices, and which has the potential to contribute substantially to the ongoing productivity and adaptability of agriculture in the region". Assumption: land mapped as IAL will experience removal of vegetation and change to intensive land use.	Removal of vegetation and change in land use value except in areas of pre-existing transport, hydrology and Infrastructure.
Scenario 4: All Scenarios [ALL]	All the above scenarios were incorporated into a single scenario.	See above
Scenario 5: Revegetation of the Green corridor [CORRIDOR]	Lower Hunter Regional Strategy 'green corridor' (NSW Department of Planning 2006) is revegetated. An area recognized as the most significant high priority conservation area (DECCW, 2009).	Add vegetation in the area of the Green Corridor where water bodies don't exist.

Table 3: Selection of landscape-scale (network) graph metrics used in the study with their definition and ecological significance (adapted from Lechner, Doerr, Harris, Doerr, & Lefroy, 2015).

Graph metric	Ecological Description	Reference
Landscape-scale metrics		
Mean size of components (km ²)	Describes the level of isolation between groups of landscape patches	Urban and Keitt, 2001
Size of largest component (km ²)	Describes the level of isolation between groups of landscape patches	Urban and Keitt, 2001
Number of components	Simple measure that describes the number of isolated areas in the landscape	Urban and Keitt, 2001
Harary index	Measure of dispersal relative to component isolation based on the probability that two randomly located points are found in the same component	Ricotta et al. 2000
Expected cluster Size (km ²)	The mean area that a disperser has access to	O'Brien et al., 2006
Integral Index of connectivity (IIC)	Probability that two dispersers randomly located in the landscape can access each other	Pascual-Hortal and Saura, 2006
Patch-scale metrics		
Delta Integral index of connectivity (dIIC)	The loss of habitat availability caused by the removal of the focal patch relative to the connectivity network	Pascual-Hortal and Saura, 2006
Clustering coefficient	The level of redundancy for the patch within a network	Minor and Urban, 2008; Ricotta et al., 2000

Table 4: Landscape-scale (network) graph-metrics and the number of patches for the scenarios tested. Values in brackets refer to percentage difference compared to the current connectivity, for all metrics apart from total patch area which describes change in area.

Network characteristic	Current	Scenario 1 [URBAN]	Scenario 2 [EXP.]	Scenario 3 [AGRI.]	Scenario 4 [ALL]	Scenario 5 [CORRIDOR]
Mean size of components (km ²)	48	29	43	46	25	75
Size of largest component (km ²)	1872	1766	1833	1464	1680	2545
Number of components	49	75	54	49	84	36
Haray index	11954	7278 (-39%)	9384 (-22%)	11294 (-6%)	5961 (-50%)	12884 (+8%)
Expected cluster size	1525	1439 (-6%)	1465 (-4%)	1464 (-4%)	1345 (-12%)	2401 (+57%)
IIC	0.0213	0.0186 (-13%)	0.0205 (-4%)	0.0203 (-5%)	0.0176 (-18%)	0.0436 (+105%)
Patches	572	540	573	577	523	458
Total patch area (km ²)	2345	2190 (-155)	2342 (-3)	2270 (-74)	2119 (-225)	2700 (+355)