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The Multi-Criteria Connectivity Planning Framework: combining multi-criteria analysis and connectivity science to enhance conservation outcomes at regional scale in the Lower Hunter

Report by:

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Landscapes and Policy Hub

General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR): combining multi-criteria analysis and connectivity science to enhance conservation outcomes at regional scale in the Lower Hunter

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Purpose of Report

This report describes the development of a pilot GIS-based decision support framework in the Lower Hunter, the General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) Framework. The report is an output of the Landscapes and Policy Research Hub.

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About the Authors

Dr Alex Lechner from the University of Tasmania is a landscape ecologist experienced in applying spatial analyses to solving ecological problems.

Professor Ted Lefroy from the University of Tasmania is the director of the Landscapes and Policy Hub.

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This independent research is contributing to regional sustainability planning in the Lower Hunter Region, jointly undertaken by the Australian Government and the Government of NSW. The research was funded by the Australian Government through the Sustainable Regional Development Program and the National Environmental Research Program (NERP), which supports science that informs environmental policy and decision making. The report is an output from the Landscapes and Policy Research Hub.

Executive Summary

Habitat fragmentation as a result of human activity is a key threat to natural systems, resulting in landscapes that support smaller, more isolated populations of native species. A consequence is reduced population viability and increased extinction risk. Mitigation efforts often focus on identifying, conserving and restoring habitat patches to maintain connectivity through wildlife corridors or scattered trees that function as stepping-stones for dispersal.

This study set out to develop a decision support framework, the General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) framework, to facilitate participatory planning and implementation of biodiversity connectivity networks at regional and local scales. The intention of this project was to produce and build a transferable GIS framework that could potentially be used across Australia for connectivity planning and draws on best practice ecological science. This report describes the development of the prototype framework in the Lower Hunter Region of New South Wales.

GAP CLoSR was developed by combining multi-criteria decision analysis with connectivity modelling in order to consider the ecological determinants of biodiversity conservation, such as habitat requirements and dispersal behaviour of target species and communities, within a collaborative, whole-of-landscape approach. The framework enables the assessment of a range of land use scenarios that reflect different ecological, social and economic interests within a spatially explicit GIS system. It has been designed to use commonly available spatial data in a scientifically rigorous way and be readily applied by consultants, NRM managers, NGOs or government agencies. The application of the method is flexible so that a range of interests may be included depending on the datasets available and the issues that need to be addressed in a particular region.

GAP CLoSR consists of two major components and a GIS tool: i) a connectivity model, ii) the multi-criteria analysis framework and iii) a GIS tool to automate preparation of spatial datasets for use in the models.

Key features of the connectivity model

It uses a nested, multi-scale approach. High spatial resolution data is processed to provide a realistic representation of the environments encountered by species that use fine-scale landscape features such as scattered trees and wildlife corridors to move through the landscape over short distances. This processed data is then used to model connectivity at the regional scale, and then at the local scale, once particular areas of interest such as critical gaps in the habitat network have been identified.

- It can be used for particular species where data is available, or used on a default setting based on published ecological data that characterises the connectivity requirements of a suite of Australian animals.

- Four key parameters are used to describe the movement of species through a landscape. The default values are shown in brackets, taken from a review of Australian ecological research:
    - Minimum patch size (10 ha)
    - Gap crossing threshold distance (106 m)
    - Inter-patch dispersal threshold (1100 m)
    - Dispersal costs for multiple land cover types (increased dispersal cost due to urban features, roads and rail and hydrological features).
- This is the first time to our knowledge that a gap-crossing threshold (the maximum distance species will cross open ground) has been included in a regional scale connectivity model.

Incorporating social and economic interests into connectivity planning

The following scenarios were explored to test the ability of GAP CLoSR to compare the impact of a range of social and economic interests on connectivity in the Lower Hunter Region in the form of alternative regional futures:

Default scenario: The current state of connectivity in the Lower Hunter Region

Scenario 1.	With development contained in Local Environmental Plans
Scenario 2.	With development contained in Local Environmental Plans PLUS selected developments proposed by state and local governments
Scenario 3.	With the Hunter Expressway completed
Scenario 4.	With areas mapped as having high agricultural value excluded from the regional conservation network.
Scenario 5.	Scenarios 2 to 5 combined
Scenario 6.	With development of all mineral and coal titles and applications
Scenario 7.	With only protected areas forming the regional conservation network

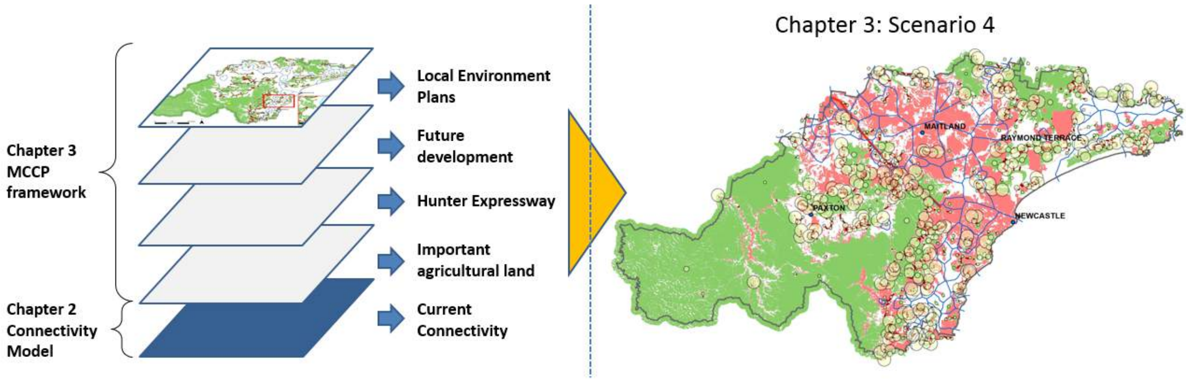
Key features of GAP CLoSR

- Identifies the most important patches and appropriate locations for wildlife connectivity based on the habitat and dispersal requirements of target species, communities and other important landscape elements.
- Compares the outcomes of a range of land use scenarios and assess trade-offs between ecological, social and economic interests.
- Runs on commonly available spatial data on a regular desktop computer using readily available GIS software with an intermediate level of GIS expertise.

GAP CLoSR utilises local and regional scale connectivity models to quantify the impact of a range of scenarios related to connectivity planning such as the guiding principles of the

National Wildlife Corridors Plan (see below). Each of the scenarios represents a range of stakeholder interests. In the report, we describe the connectivity model (Chapter 2) and provide an example of how the connectivity model is used within GAP CLoSR (Chapter 3). This example tests the impact of multiple potential future land uses (red) on connectivity, where each of these impacts is represented by a GIS layer.

Conceptual diagram of GAP CLoSR used to quantify the impact of a range of scenarios.



Key findings from the application of this framework in the Lower Hunter Region

- The majority of woody native vegetation in the region exists in two areas isolated from each other, one large area in the west and a smaller area of interlinked connected patches in the north-east.
- GAP CLoSR quantified the extent to which potential future development scenarios are likely to cause further reduction in connectivity. Future development scenarios were based on spatial data derived from local environmental plans and future development plans identified by the state and local governments.
- The map opposite illustrates the form of output from the model. The map indicates the relative importance of patches for connectivity at regional and local (inset) scales. Model outputs are based on the key ecological parameters of minimum patch size, gap crossing threshold, inter-patch dispersal threshold and dispersal resistance, drawn from a comprehensive review of published habitat requirements and dispersal behaviour (see Doerr et al. 2010). The inset shows how fine-scale analysis can be used to identify bottlenecks in the connectivity network and multiple alternative pathways for restoring connectivity.
- The framework has been demonstrated to staff from state agencies, regional catchment management groups, local government authorities and consultants and is available to quantitatively assess the impact of a range of planning scenarios, such as the Lower Hunter Regional Growth Plan, on connectivity at local and regional scales.

The Guiding Principles from the National Wildlife Corridors Plan

Principle 1. Building wildlife corridors across Australian landscapes is a cooperative endeavour.

Principle 2. Corridors should be designed and implemented in ways that benefit local communities.

Principle 3. Healthy, functioning landscapes require connectivity at a variety of scales.

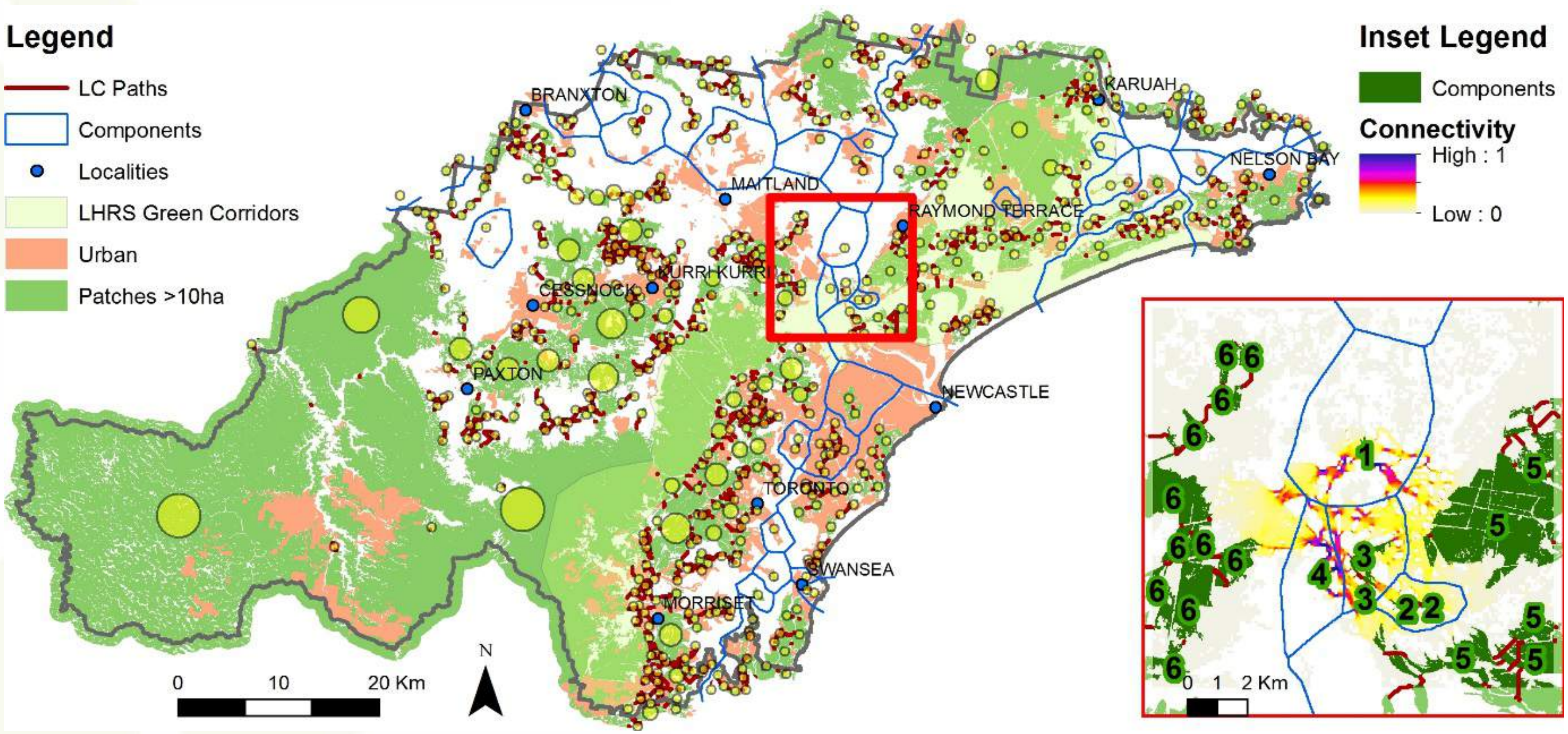
Principle 4. Effective corridors connect the landscape across a mosaic of land tenures and land uses without affecting property rights.

Principle 5. The design and location of corridors should be based on the best available information derived from scientific research, traditional Indigenous knowledge and practitioner experience.

Principle 6. Corridors should be designed to assist native species' adaptation to the impacts of climate change.

Principle 7. Corridor design recognises and manages for potential risks such as those posed by invasive species and fire.

Regional and Local-Scale Connectivity.



Regional scale connectivity in the Lower Hunter region of New South Wales calculated using Graphab graph-network and least-cost (LC) path software. Graduated symbols located at the centre of patches represent their relative importance for maintaining connectivity. Inset: Local scale connectivity between six clusters of isolated remnants calculated using Circuitscape software. Links identified using Graphab software are identified by red lines.

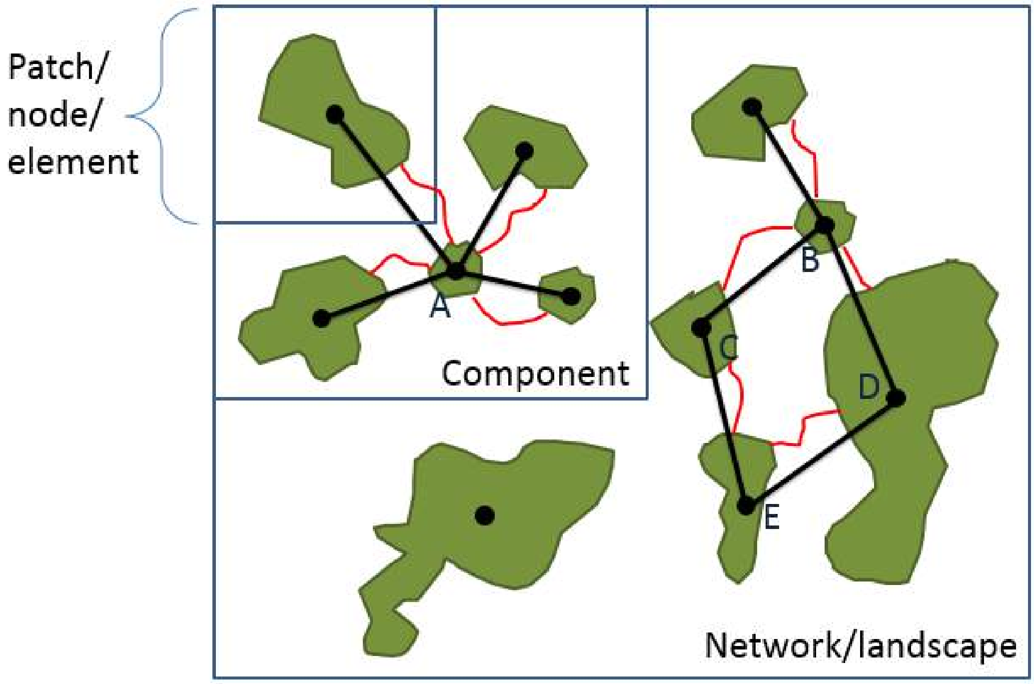
Contents

Glossary of Terms

Throughout the report, certain commonly used terms are used in a very specific sense to describe aspects of connectivity and its mathematical representation in the landscape. The glossary is divided into these commonly used terms and other terms used.

Commonly Used Modelling Terms	
Component	A group of nodes or patches that are linked to each other but isolated from other components, also made of groups of patches (landscape or network>component> node or patch).
Dispersal-cost	A value assigned to each land cover type in a landscape that reflects the ecological costs for individuals to move through it.
Dispersal-cost surface	A raster surface where each pixel's value represents dispersal cost. Also sometimes referred to as a resistance-cost surface.
Graph	A set of linked nodes/patches. Applied to landscape ecology a graph is a set of patches within a landscape linked by movement pathways.
Graph theory	The graph theoretic perspective applied to landscape ecology represents landscapes as a graph. Graph theory uses mathematical structures to describe pairwise relations between nodes.
Graph metrics	Metrics used to describe connectivity at the landscape (= network) scale, component scale, or patch (=node) scale.
Landscape-scale graph metric	A graph metric that describe a connectivity network with a single value for the entire landscape.
Least-cost path	The shortest pathway between two patches as a function of land cover resistance.
Local-scale model	This specifically refers to the use of the Circuitscape analysis for modelling connectivity for a subset of the Lower Hunter region.
Link	An element of a network/graph that connects nodes.
Network/Graph	A graph theory term describing a collection of nodes connected by links. In landscape ecology, nodes and links represent patches and pathways within a landscape.
Node	An element of a network/graph that is represented by patches in landscape ecology.
Patch	A relatively homogeneous area, often habitat, which differs from its surroundings. In this study, patches are defined as an area of woody vegetation greater with a minimum patch size between 10 and 20ha, depending on the scenario.
Patch-scale graph metric	A graph metric value calculated for each patch.
Raster	A rectangular grid of pixels commonly used in a GIS to represent land cover.
Resistance	A value assigned to each land cover type in a landscape that reflects the ecological costs for individuals to move through it. Also sometimes referred to as dispersal-cost. High resistance means high dispersal costs.
Regional-scale Model	This specifically refers to modelling connectivity with the Graphab software for the entire Lower Hunter region.

Graph based schematic representation of connectivity network



Schematic representation of the different levels of analysis within a connectivity network in which patches (green) are connected by multiple links (black lines) represented by least-cost-pathways (red lines) that incorporate information about the matrix (white area). Graph metrics can be considered at three levels: patch-scale, component or landscape-scale. Using the language of graph theory, these patches are considered as nodes (black dots) linked within a graph (or graph-network) (black lines).

Other Terms	
Circuit theory	Electronic circuit theory based on voltage, current and resistance. Applied to ecology it characterises landscapes as a graph where each cell of a raster grid is considered as a node (see McRae et al. 2008).
Circuitscape	Connectivity modelling software that uses circuit theory (see McRae et al. 2008).
Connectivity	The degree to which the landscape facilitates or impedes the movement of individuals between habitat patches. Maximising connectivity is often an objective of conservation planning.
Connectivity model	A modelling method for assessing dispersal.
Connectivity network	A network of habitat patches at the landscape-scale or regional-scale.
Gap crossing threshold	Maximum (average) distance an individual will move between two structural connectivity elements.
Graphab	A software for modelling ecological networks using landscape graphs and least-cost paths (see Foltête et al. 2012)
Inter-patch dispersal distance threshold	The maximum distance that individuals would move between patches provided there is some kind of structural connectivity element such as stepping-stones (for example, scattered paddock trees) or corridors.
Multi-criteria decision analyses	A method for explicitly considering the multiple criteria associated with decision-making.
General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR)	The name coined to the framework developed in this report that integrates Multi-Criteria Decision Analysis with connectivity modelling at local and regional scales.
Structural connectivity elements	Landscape features, which do not provide habitat in themselves, but can be used for dispersal. It includes wildlife corridors (linear links between patches), disconnected linear elements and stepping-stones (paddock trees, shrubs, rocky outcrops or small clusters of these features).
Wildlife Corridor	At the regional scale this term commonly refers to connectivity between isolated patches of habitat supporting the dispersal of species along major ecological gradients (for example, latitudinal, mountains to ocean). It is analogous to connectivity network. At the landscape or site-scale it is used to refer to a specific type of linear structural connectivity element. To avoid confusion we have only use this term in the former case.

Frequently Used Abbreviations

DSEWPaC*	Department of Sustainability, Environment, Water, Population and Communities
ED Hub	Environment Decisions Hub (NERP)
ERIN	Environmental Resources Information Network
GAP CLoSR	General Approach to Planning Connectivity from Local Scales to Regional
GIS	Geographic Information system
GIS-MCDA	Geographic Information System based Multi-criteria Decision Analysis
IAL	Important Agricultural Lands
IIC	Index of Connectivity
LEP	Local Environmental Plan
LEP Dev	Local Environmental Plan (*development scenario*)
LHF Dev	Lower Hunter Future (*development scenario*)
LULC	Land cover/land use
MCAS-S	Multi-Criteria Analysis Shell for Spatial Decision Support
MCDA	Multi-Criteria Decision Analysis
MNES	Matters of National Environmental Significance
NERP	National Environmental Research Program
NGO	Non-Government Organisations
PC	Personal Computer
PCA	Principal Component Analysis
SPOT	Satellite for observation of the earth (French - *Satellite Pour l'Observation de la Terre*)

* On 18 September 2013, the Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) became the Department of the Environment.

Chapter 1
Introduction

1.0 Summary

This project was established to deliver a robust decision framework for regional biodiversity connectivity planning and implementation that is aligned with the National Wildlife Corridors Plan and draws on best practice science. The Lower Hunter and Tasmanian Midlands regions are being used to respectively develop and test the decision framework. The decision framework incorporates the outputs of a range of management tools and policy options to explore regional environmental outcomes. It incorporates economic and social factors where possible, such as the impact of planned development on biodiversity conservation and wildlife dispersal.

This report describes the development of a pilot GIS-based decision support framework in the Lower Hunter, the General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) Framework. The framework includes a purpose-built connectivity model that analyses dispersal behaviour of target species and communities at the fine scale, and incorporates this in landscape and regional-scale analyses of a range of social and economic values such as regional land use plans and community capacity for conservation. In this way, the framework enables the user to assess the trade-offs between a range of environmental, social and economic interests within a spatially explicit GIS system that maintains at its core the criteria necessary to maintain ecological and evolutionary processes at regional scale.

1.1. Aim

To ensure that connectivity planning associated with the Sustainable Regional Development (SRD) program utilises best practice science and modelling techniques and addresses social and economic interests associated with connectivity planning such as the principles outlined in the National Wildlife Corridors Plan.

1.2. Regional Sustainability Planning

Regional sustainability planning is a collaborative process involving all levels of government working together to foster economic prosperity, livable communities and environmental sustainability. In the Lower Hunter, the regional sustainability planning process has two main stages. First, the Australian and NSW governments are working together to identify key knowledge gaps and scientific research to inform sustainability planning for the Lower Hunter region. This work will complement and inform the NSW Government review of the NSW Lower Hunter Regional Strategy and Lower Hunter Regional Conservation Plan. Once this review is complete, the second stage will be to undertake a strategic assessment of proposed urban development and related infrastructure corridors. The Lower Hunter strategic assessment will assess broad environmental, social and economic sustainability aspects within the local government areas of Newcastle, Maitland, Cessnock, Lake Macquarie and Port Stephens. The strategic assessment incorporates urban development areas and associated infrastructure

corridors, with a focus on matters of national environmental significance protected under national environmental law (*Environment Protection and Biodiversity Conservation Act 1999*). The purpose of the strategic assessment, once endorsed and approved under this law, is to streamline environmental regulation and provide greater certainty for business and local communities.

1.3. Importance of connectivity

A significant consequence of increased human activities such as agriculture, mining and urbanisation is the loss and fragmentation of habitat, whereby the original natural contiguous landscapes become subdivided into a mosaic of remnant patches resulting in a creation of barriers to dispersal such as roads and backyards (Hudson 1993). This leads to increases in the probability of extinction due to demographic and genetic factors associated with a reduction in dispersal between patches of remnant vegetation (Hanski 1999; Hedrick 2005). The identification and conservation of habitat that allow for dispersal such as wildlife-corridors is recognised as an important component of biodiversity conservation and conservation planning (Gilbert-Norton et al. 2010).

The most common conservation practice used to address the impacts of habitat fragmentation is to increase habitat area or increase connectivity between remnant habitat patches through wildlife corridors (Beier & Gregory 2012). However, in urban environments it is often impossible to increase the size of habitats, as there is rarely the sufficient funding or political will to restore urban areas to habitat. Increasing and preserving connectivity is usually the only option for reducing biodiversity loss in these environments. In Australia and internationally, there is significant investment in maximising connectivity (Figure 1).

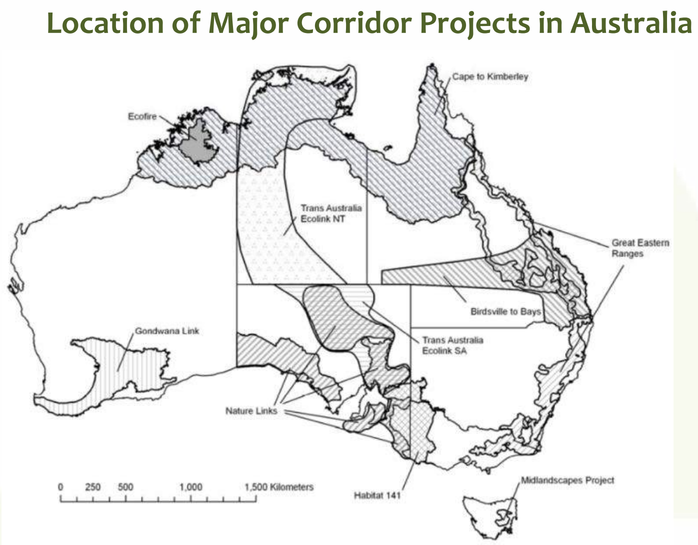


Figure 1 Location of nine major corridor projects in Australia (from Whitten et al. 2011).

Connectivity can be defined as the extent to which a landscape facilitates the movements of organisms and their genes (Rudnick et al. 2012). Wildlife corridors are constructed to maximise what is known as 'functional connectivity'. This describes the degree to which organisms move through the landscape between patches and successfully breed and thereby contribute to

gene flow, increasing species persistence (Belisle 2005; Doerr et al. 2010). Landscape elements, such as wildlife corridors, stepping-stones and riparian connections, facilitate connectivity through providing agreeable habitat or environmental conditions that allow for movement between patches that support permanent or semi-permanent populations (Figure 2).

Conceptual Diagram Describing the Range of Landscape Elements that Link Patches within Fragmented Landscapes

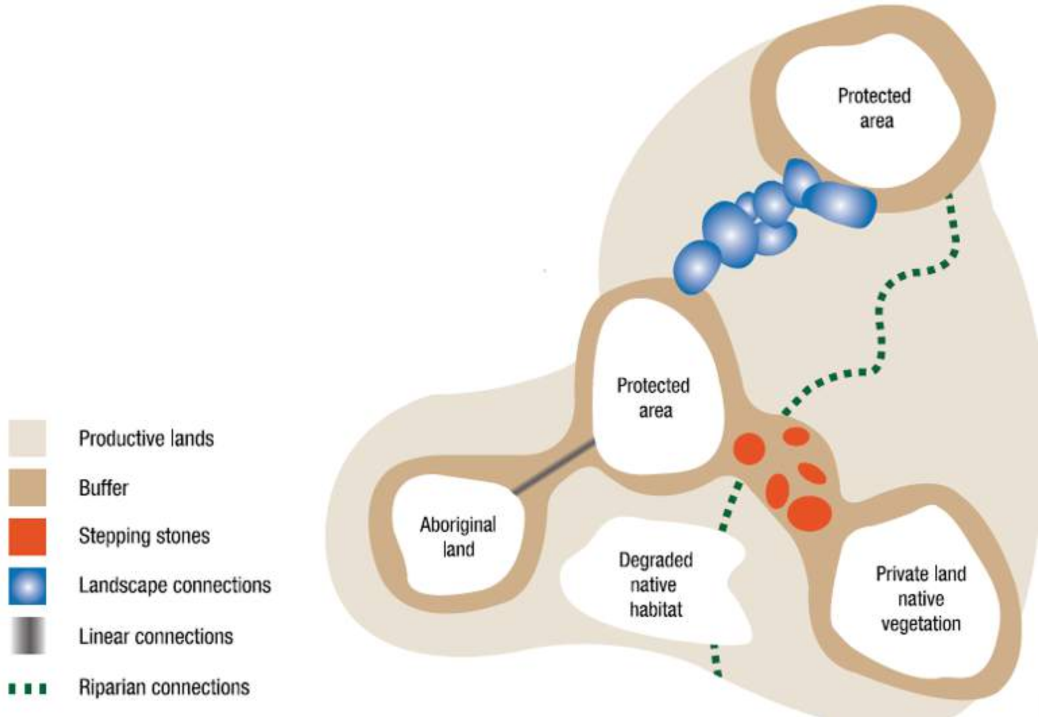


Figure 2 **Connectivity is important for linking patches within fragmented landscapes. These patches include protected areas and native vegetation found on private land. There are a range of landscape elements that can provide connectivity between patches, which range from stepping-stones to linear corridors (from DSEWPaC 2012).**

1.4. National Wildlife Corridors Plan

The objectives of the National Wildlife Corridors Plan are to provide a:

> *'…long-term strategy designed to retain and restore ecological connectivity and facilitate connectivity conservation. Existing and new corridor initiatives at continental, regional and local scales will all contribute to a network of wildlife corridors. Some of these initiatives might also be designated as National Wildlife Corridors' (DSEWPaC 2012).*

These objectives are underpinned by the guiding principles of the national wildlife corridor that:

> *'…guide and support individuals, private landholders and managers, community groups, policy makers, planners and natural resource managers develop and manager corridor initiatives' (DSEWPaC 2012).*

There are seven guiding principles of the National Wildlife Corridors Plan. In order to support the practical implementation of the National Wildlife Corridors Plan, we have interpreted the principles to represent a range of interests and issues that need to be considered when developing wildlife connectivity networks. Each of these principles can be represented by one or more land use scenario(s) described by a GIS layer within a multi-criteria analysis. However, it may be challenging to represent all of these spatially, and in some cases, it may not be sensible to do so. Additionally, not all of these interests may be considered relevant for a specific location. The set of interests selected for a particular region, and the importance of each interest for any regional sustainable planning activity, should be guided by stakeholder engagement and will be specific to a particular area.

The Guiding Principles from the National Wildlife Corridors Plan

Principle 1. Building wildlife corridors across Australian landscapes is a cooperative endeavour.

Principle 2. Corridors should be designed and implemented in ways that benefit local communities.

Principle 3. Healthy, functioning landscapes require connectivity at a variety of scales.

Principle 4. Effective corridors connect the landscape across a mosaic of land tenures and land uses without affecting property rights.

Principle 5. The design and location of corridors should be based on the best available information derived from scientific research, traditional Indigenous knowledge and practitioner experience.

Principle 6. Corridors should be designed to assist native species' adaptation to the impacts of climate change.

Principle 7. Corridor design recognises and manages for potential risks such as those posed by invasive species and fire.

The guiding principles from the National Wildlife Corridors Plan are very general and the method described in this report has been developed for use in any connectivity network planning process where a whole of landscape approach can be used to incorporate environmental, social and economic factors.

Guiding Principle 3 (Connectivity at a variety of scales) and Principle 5 (Corridor design based on best available science, traditional knowledge and local experience) underpin the development of the connectivity model described in Chapter 2.

Guiding Principle 2 (Corridors should be designed and implemented in ways that benefit local communities) and Principle 4 (Connecting across tenures without affecting property rights) were incorporated in a multi-criteria assessment described in Chapter 3.

Guiding Principles 1, 6 and 7 required social processes or scientific data that could not be included in the development phase of this study.

1.5. Stakeholder and expert engagement

A particular emphasis of this project was to develop a framework that utilises the best available science, yet is simple enough to be used without highly specialised GIS expertise and ecological knowledge. To do this a range of stakeholders where engaged who represented potential end-users from the commonwealth, state governments and environmental non-government organisations (NGO). The intention of this project was to produce and build a transferable GIS framework that could potentially be used across Australia for connectivity planning. The framework is a balance between ecological complexity, model robustness and simplicity.

Individuals and Groups Engaged*

Department of the Environment

- Regional Sustainability Planning team (Paul Keighley, Naomi O'Brien, Ross Rowe)
- Environmental Resource Information Network (ERIN) (Randal Storey, Dave Osborn)
- National Wildlife Corridors Planning Team (Jane Campbell, Dominic Ransan-Cooper)

State Government Sector

- Office of Environment and Heritage, New South Wales (Michael Drielsma, Tom Barrett and Jamie Love)
- Department of Primary Industries, Parks, Water and Environment Tasmania (Oberon Carter and Louise Gilfedder)

Non-Government Organisations Sector

- Hunter & Central Coast Regional Environmental Management Strategy group (Meredith Laing)
- Lake Macquarie Council (Robbie Economos)
- Tasmanian Land Conservancy (Daniel Sprod)
- Greening Australia (Nick Fitzgerald)
- Greater Eastern Ranges (Gabriel Anderson, Gary Howling)

University Sector

- Landscapes and Policy NERP Hub (Sue Gould, Brendan Mackey, Chris Raymond)
- Environment Decisions NERP Hub (Amy Whitehead, Heini Kujala)
- CSIRO (Veronica Doerr)

* This report represents the viewpoint of the report authors only and not those of the stakeholders or experts engaged.

1.6. Report outline

This report outlines the development of a modelling framework with an embedded connectivity model and demonstrates its use for assessing a range of land use planning scenarios. These scenarios were evaluated for their impacts on the quality of the connectivity network in the Lower Hunter. The method developed for this project can be considered as a form of multi-criteria analysis within the broader framework of connectivity modelling. It is proposed that the framework would assist implementation of the conservation planning, which considers ecological connectivity within a cooperative and whole-of-landscape approach to biodiversity conservation. We have coined the term General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) to describe this approach, based on a combination of Multi-Criteria Decision Analysis (MCDA) and connectivity modelling at local and regional scales.

This report describes the development of two components of GAP CLoSR, a connectivity model (Chapter 2) and a multi-criteria decision framework (Chapter 3). These chapters will be modified for submission to refereed journals to communicate the development of this approach to the scientific community and subject these two components to peer review.

Chapter 2 describes the development of a connectivity model that operates in conjunction with freely available ArcGIS software at regional and local scales.

Chapter 3 presents the completed MCCP Framework along with an assessment of a range of land use scenarios associated with different ecological, social and economic interests related to the guiding principles.

Chapter 4 provides a synthesis of the previous two chapters and describes future research directions for this project and connectivity modelling and conservation planning in general. As Chapters 2 and 3 are standalone documents to be published separately, there is some overlap in their content.

Conceptual Diagram of MCCP Framework

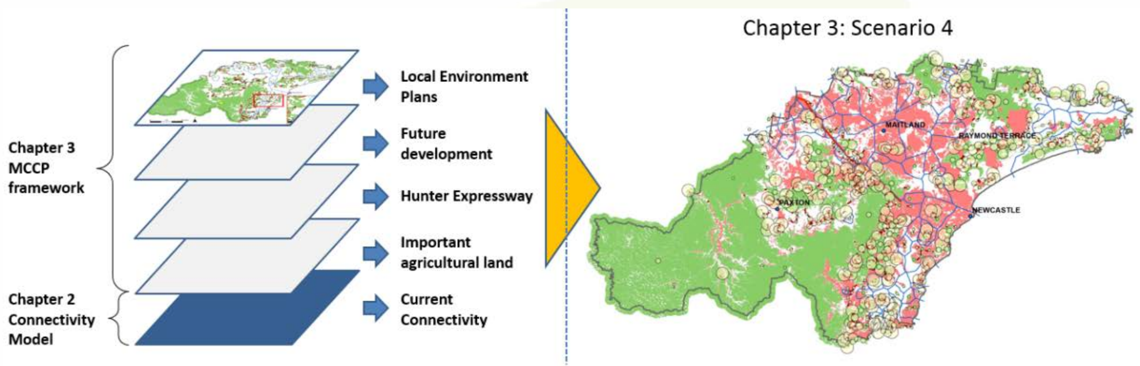


Figure 3 **Conceptual Diagram of the General Approach to Planning Connectivity from Local Scales to Regional used to quantify the impact of a range of scenarios.**

Chapter 2
A connectivity analysis model for characterising fine-scale dispersal behaviour for conservation planning at local and regional-scales

2.0 Abstract

Habitat fragmentation results in landscapes that support smaller, more isolated populations of native species with reduced population viability and increased extinction risk. Conservation efforts often focus on addressing the impacts of habitat fragmentation through the identification and conservation of landscape features that are thought to be critical for connectivity such as wildlife corridors and scattered trees used as stepping-stones for dispersal. This study presents a connectivity model and freely available ArcGIS-based tool for parameterising and pre-processing spatial data to assess local-scale connectivity using circuit theory and regional-scale connectivity using graph theory. The model addresses scale issues associated with characterising connectivity at fine spatial resolutions over large spatial extents while addressing the computational limitations of common modelling software and desktop computer platforms on which they run. These limitations are addressed for both local and regional scale connectivity methods by aggregating fine spatial resolution data in a way that preserves the data's ecological integrity. The fine-scale resolution provides a realistic representation of the environment encountered by species that move over short distances and depend on ecologically significant but small or linear landscape elements such as scattered trees and wildlife corridors. The regional-scale analysis characterises connectivity between patches by identifying a single optimal pathway between patches, while the local-scale model characterises connectivity for every pixel in the area of interest as opposed to a single optimal pathway. Using a combination of these methods, information can be provided at an appropriate scale for management. For example, management to address factors that limit dispersal such as roads commonly operates at fine scales, whereas overall connectivity and the importance of a single patch or group of patches is only evident over large spatial extents.

We demonstrate the application of the connectivity model using the Lower Hunter Region, New South Wales, Australia, as a case study area. The Circuitscape software (McRae et al. 2008) is used to model connectivity at the local scale and Graphab graph-network software (Foltête et al. 2012) is used to model connectivity at the regional scale. We demonstrate the method using a generalised native woody vegetation versus non-vegetation connectivity model. This assumes that our model characterises habitat and dispersal for the majority of the native fauna species that utilise woody native vegetation and the plant species that depend on these fauna for dispersal. The software automates the processing of fine resolution data (2.5 m) that describes dispersal cost between patches of remnant woody vegetation and does so in a way that preserves dispersal costs regardless of pixel size. Different rule sets need to be used to integrate barriers and dispersal costs within coarser resolution pixels (25 m) in an ecologically realistic way. This method also includes a novel approach to incorporating gap-crossing behaviour into connectivity models that is not

computationally intensive. This is the first time that gap-crossing behaviour has been included in a connectivity model. Automating this process enables efficient sensitivity testing of the degree of uncertainty in the connectivity model. Connectivity modelling and its parameterisation require trade-offs between multiple constraints, including optimising spatial resolution within computational limitations, while characterising multi-scaled ecological complexity. The model represents the practical application of this trade-off based on commonly available spatial data and connectivity modelling software. It is targeted at intermediate level GIS users within government agencies, catchment management organisations and NGOs involved in conservation planning with the expectation that it is used as part of a conservation management process, rather than providing a single static map on which to base decisions.

2.1. Introduction

Human modification of landscapes typically result in fragmentation and isolation of populations of native species. Habitat loss and fragmentation are among the key causes of population decline. Once populations are small and dispersal is limited they face a higher risk of extinction due to demographic and environmental stochasticity (Brook et al. 2008; Caughley 1994; Lindenmayer & Fischer 2007). Identifying, conserving or restoring vegetation in locations thought to be critical for supporting population connectivity is a key focus of conservation efforts (Lindenmayer & Fischer 2007). This requires spatially explicit analyses of landscape connectivity combined with knowledge of species movement behaviour.

Landscape connectivity can be analysed using graph-networks or circuit theory in conjunction with methods for quantifying faunal resistance to dispersal between habitat patches. Using these methods, landscape connectivity is characterised as mosaics of patches or nodes made up of suitable habitat versus non-habitat that limit dispersal. Non-habitat is parameterised using dispersal costs, which represent the energetic costs, difficulty or mortality risk of moving across these areas (Adriaensen et al. 2003; Sawyer et al. 2011). Dispersal cost is typically determined by land cover characteristics, such as levels of urbanisation combined with species-specific dispersal probability and distance thresholds. Using cost-weighted distance analysis, least-cost pathways between patches of suitable habitat can be calculated. The least-cost pathway is not necessarily simple Euclidean distance (that is, a straight line) as the pathway may seek to avoid land cover with high resistance such as roads. Assessing the significance of patches within a connectivity network can be quantified using the graph theoretic approach through the calculation of network measures (Minor & Urban 2008; Rayfield et al. 2011; Urban et al. 2009). Complex patterns resulting from location and links between multiple patches across a landscape can be condensed and summarised using graph-network measures such as the role of a patch as a stepping stone.

The connectivity model described here addresses scale issues associated with characterising connectivity at fine spatial resolution over large spatial extents while addressing computational limitations of common modelling software and desktop PC platforms on which they run. In conservation planning, there is a need for property or local scale data for

management decisions whereas overall connectivity at the regional scale is only evident over large spatial extents. Fine spatial resolution data is important for identifying small and linear features that provide connectivity such as scattered trees and roadside corridors (Bennett 1990; Carruthers et al. 2004; Hilty et al. 2006; Lechner et al. 2009). This fine-scale data needs to be rescaled to a coarser resolution for modelling software while preserving its ecology integrity.

In this study, we present a transparent connectivity model and tool for parameterising and pre-processing spatial data for connectivity models that characterise local and regional scale connectivity using the Lower Hunter, Australia as a case study. The method is based on a general connectivity model in which connectivity between landscape elements represented by large patches of woody vegetation is assessed. This assumes that the model characterises the dispersal characteristics of the majority of the native fauna species within the landscape. Connectivity is parameterised using two thresholds, the inter-patch dispersal and gap crossing distance, based on a review by Doerr et al. (2010) of Australian connectivity studies. We demonstrate the application of this method for regional conservation planning using the Graphab graph-network connectivity model for regional-scale analyses (Foltête et al. 2012) and Circuitscape for local-scale analyses (McRae et al. 2008). The Graphab modelling method describes connectivity based on least-cost-paths where pathways between habitat patches minimise travel distances and exposure to unsuitable habitat. The Circuitscape method complements this approach by considering all possible pathways across a landscape simultaneously. This provides a connectivity surface at local scales only, given that computational limitations prevent large images being processed.

The model and tool described in this chapter have been designed for the use of GIS technical staff within government and NGO organisations with an intermediate level of expertise. The method developed should be used as part of a conservation management process undertaken by these groups rather than providing a single static map on which to base conservation decisions. The method addresses multiple scale issues associated with characterising connectivity for species whose behaviours is determined by features at fine scales over large extents but need to be modelled at coarser spatial resolutions in order to address computational limitations of modelling software and desktop PC platforms on which they run for both regional (Graphab) and local-scale (Circuitscape) models. The method includes a novel technique for incorporating species gap-crossing behaviour in connectivity models that is not computationally intensive.

In this chapter, we outline the connectivity model and provide step-by-step instructions on how to parameterise connectivity models. We then describe the ArcGIS tool developed to automate the pre-processing of spatial data to create dispersal cost surfaces used as connectivity model inputs. Automating the data processing allows the model's sensitivity to uncertainty to be tested using a range of dispersal costs and dispersal distances without time consuming manual processing. Next, we provide an overview of the current regional-scale connectivity network within the Lower Hunter using graph metrics, identifying important patches for preserving connectivity. A local-scale analysis is then presented using Circuitscape

to identify potential areas where rehabilitation may take place to increase connectivity across the region. We conclude by describing the limitations of this method and future directions for research in this area.

2.2. Methods

2.2.1. Study area

The Lower Hunter Region occurs 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. The Lower Hunter includes a range of environments, from highly urbanised areas, farmlands, mountain ranges to the coastal and estuarine environments. This region is expected to see a high level of population growth resulting in increasing pressure on the environment (NSW Department of Planning 2006).

2.2.2. Six-step framework for parameterising connectivity model with empirical ecological data

The processes of parameterising and modelling can be considered as a six-step process (Figure 4). It can be adapted to other regions and particular target species if sufficient empirical ecological data is available on the minimum patch size, and the inter-patch dispersal distance and gap crossing thresholds for those species. A default set of published dispersal characteristics from Australian studies is included in the general connectivity model.

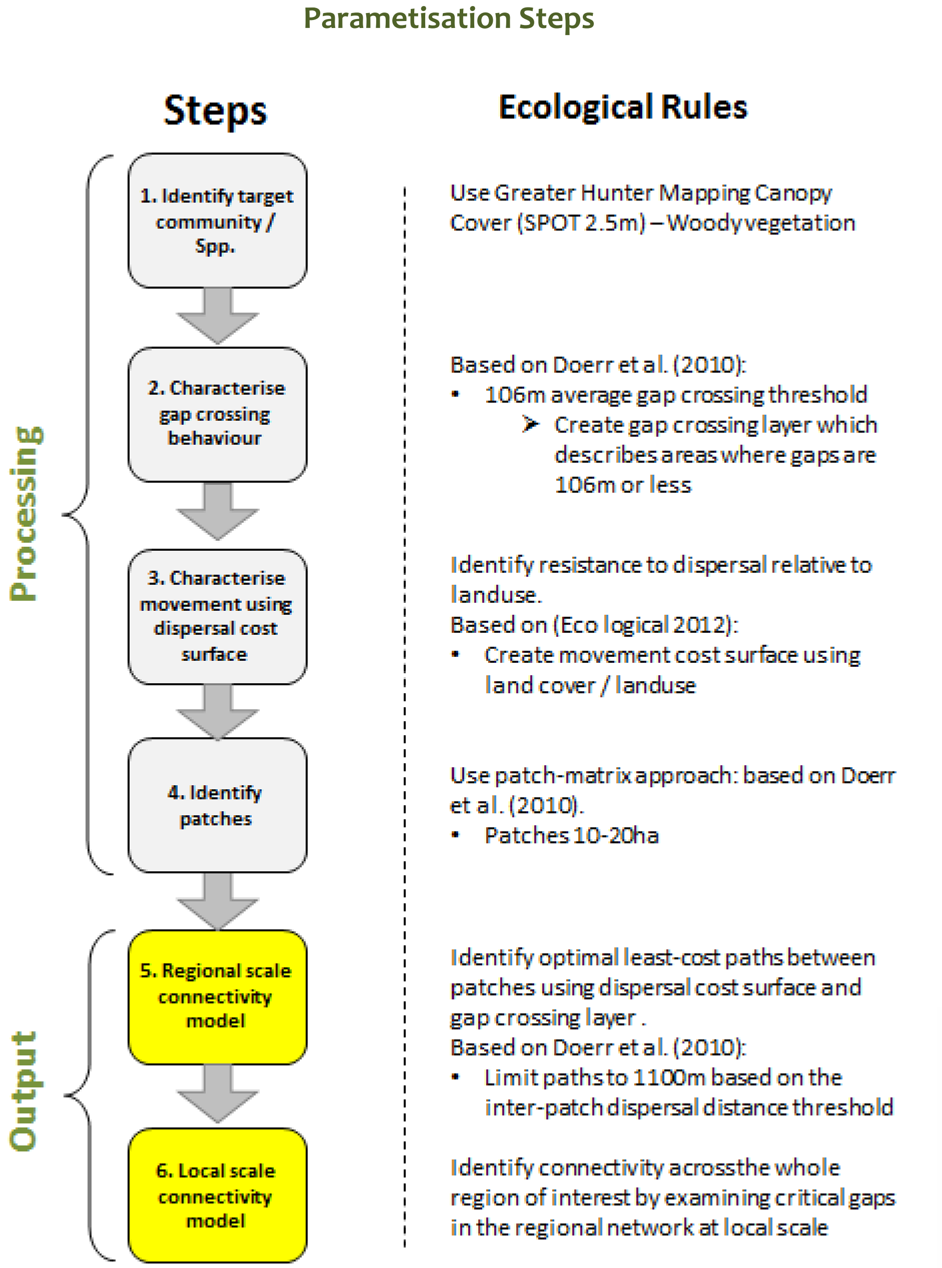


Figure 4 **Flow diagram describing the steps used in parameterising the general connectivity model.**

The dispersal parameters used in our model were primarily based on a review of connectivity by Doerr et al. (2010), which assessed whether structural connectivity facilitates dispersal (Table 1). This review synthesised all available evidence on the relationship between structural connectivity and landscape-scale dispersal of Australian native fauna species. This review of 80 studies (from 98 sources) calculated values for a mean gap-crossing threshold and an inter-patch crossing threshold. Of the studies reviewed, 41 provided data on mammals, 32 provided data on birds, 8 provided data on reptiles and 5 provided data on plants and invertebrates respectively. In the majority of studies, dispersal was inferred from species presence within landscape elements that provide connectivity such as scattered trees and corridors. These values were applicable to our case study region as the majority of the studies

reviewed were in similar woodland and forest dominated ecosystems impacted by fragmentation primarily from agriculture. We assume that our general connectivity model represents functional connectivity between patches of remnant woody vegetation for the majority of faunal native species in the region and plant species that depend on these fauna for dispersal. Limitations of using these data are described in the discussion. However, the same modelling method may also be used for a single species with differing habitat and dispersal characteristics through changing the ecological parameters used in the model. For example, when modelling connectivity for waterfowl, connectivity between wetlands vegetation should be modelled instead of woody vegetation and rivers and streams will benefit dispersal not act as barriers.

Table 1 Parameters used to describe dispersal based on Doerr et al. (2010). Min and max refer to the values used in our sensitivity analyses. Values with * are found in Doerr et al (2010).

	Doerr et al. (2010)	Default Value	Sensitivity Test
Patch size	10 - 20 ha*	10 ha	20 ha
Inter-patch dispersal distance threshold with structural connectivity	1.1 km	1.1 km*	550 m and 2200 m
Mean gap crossing threshold	106 m	106 m*	No threshold

Step 1: Identify target community/species

A general connectivity approach to modelling was used in this study as it reflects a compromise between the uncertainty associated with the complexity of parameterising a multi-species connectivity model and the simplicity of a structural connectivity model that ignores the complexity of species movement between patches. This approach, focusing on connecting landscape features or land-facets instead of species, has been used internationally (Alagador et al. 2012; Brost & Beier 2012).

In this study, the landscape was characterised as either a patch of suitable habitat or non-habitat. This characterisation conforms to the patch-mosaic/patch-matrix paradigm commonly used in landscape ecology (Forman & Godron 1986) and most connectivity studies in Australia (Doerr et al. (2010). A patch was defined as woody vegetation using 2.5 m SPOT satellite Greater Hunter mapping (see Siggins et al. 2006 for relevant metadata and classification accuracy information). Non-habitat included areas of non-woody vegetation and non-native vegetation such as urban or agricultural lands.

In our study, we only defined dispersal thresholds for linking patches in contrast to many other connectivity modelling studies that use a single dispersal distance based on a distance decay function (Hanski 1994) to model the probability of dispersal at various distances (for example, Drielsma et al. 2007). An inter-patch dispersal distance threshold of 1.1 km was identified from

Doerr et al. (2010) as the maximum distance that individuals would move between patches provided there is some kind of structural connectivity element such as stepping-stones (for example, scattered paddock trees) or corridors. Dispersal distances were also based on the mean gap crossing threshold at which species will disperse between components of structural connectivity. This was identified as 106 m from Doerr et al.'s (2010) review.

In order to simulate connectivity based on an inter-patch dispersal distance threshold it was necessary to buffer the study area to ensure that vegetation outside the study area but within the dispersal distance is not excluded. For this study, we used a buffer of 1.2 km to address this issue - slightly larger than the inter-patch dispersal distance threshold.

Step 2: Gap crossing threshold layer

In order for species to move long distances between patches there is a need for landscape features such as corridors to facilitate movement (Doerr et al. 2010; Lindenmayer & Fischer 2007). In general, individuals are less likely to cross long distances of open ground and will tend to move between structural connectivity elements. Doerr et al. (2010) found that the average maximum distance that individuals would cross is 106m.

Structural connectivity elements are important in fragmented habitats as they facilitate the dispersal of many species (Fischer & Lindenmayer 2002a, 2002b; Van Der Ree et al. 2004). These elements include wildlife corridors (linear links between patches) and also a variety of other landscape features that do not directly connect elements such as disconnected linear elements and stepping-stones (Doerr et al. 2010). Stepping-stones include isolated features such as individual paddock trees, shrubs, rocky outcrops or small clusters of these features (Carruthers et al. 2004; Doerr et al. 2010; Gibbons & Boak 2000).

Landscape features that contribute to connectivity range in size and can include clumps of tussock grass, rocky outcrops or coarse woody debris (Doerr et al. 2010). We did not differentiate between linear corridors, disconnected linear features or stepping-stones as Doerr et al. (2010) found that stepping-stones were at least as effective as continuous corridors, if not more so.

Vegetation under a minimum patch size of 10-20 ha was treated as structural connectivity elements and the size and the shape of these features was ignored (for example, whether it was a corridor shape or stepping-stone). To simulate the gap-crossing threshold, rather than modelling connectivity between individual features we created a gap crossing threshold layer. This layer identifies areas in which the distance between structural connectivity elements is less than the threshold (106 m) on average. The reason for creating this layer was to make the task of characterising connectivity less computationally intensive by removing the need to calculate dispersal between structural connectivity elements, while still reflecting real dispersal behavioural characteristics.

This layer is produced by aggregating fine-scale spatial data to a coarser resolution where each course resolution pixel describes the presence or absence of structural connectivity elements at the gap-crossing threshold. Vegetation data at 2.5 m resolution (Siggins et al. 2006) was

used to identify vegetation that may act as structural connectivity elements. The derivation of these ecologically important small and linear features require very high spatial resolution data, otherwise they may be under-represented in the landscape when pixel sizes common to most satellite data is used such as SPOT XS (10 m) and Landsat 30 m) (Lechner et al. 2009).

The first step in this process was to calculate the size of the coarse resolution pixel in which the average distance between two fine resolution pixels occurring in neighbouring coarse resolution pixels is equal to the gap-crossing threshold (Figure 5). This was calculated by simulating the distance between a fine resolution pixel located at random within a coarse resolution pixel and a neighbouring fine resolution pixel thousands of times.

Assessment of the Average Distance for the Gap Crossing Layer

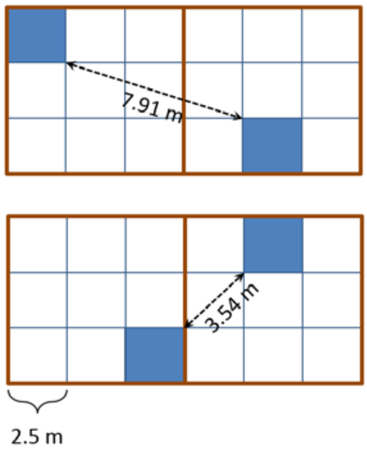


Figure 5 **Simplified example of method used to assess the average distance between two fine resolution pixels within neighbouring coarse resolution pixels. Using this method, the gap-crossing layer was derived (see text for more details).**

The average distance between these pixels at multiple coarse resolution pixel sizes is described by Figure 6. Based on SPOT 2.5 m spatial data, the coarse resolution pixel size with an average distance similar to the gap crossing distance of 106m was 100 m (Figure 6). The average distance is a property of the pixel size of the original data (2.5 m) and the coarse resolution data. This needs to be recalculated for data with different spatial resolutions. We have included R code to automate this processing (see Appendix A).

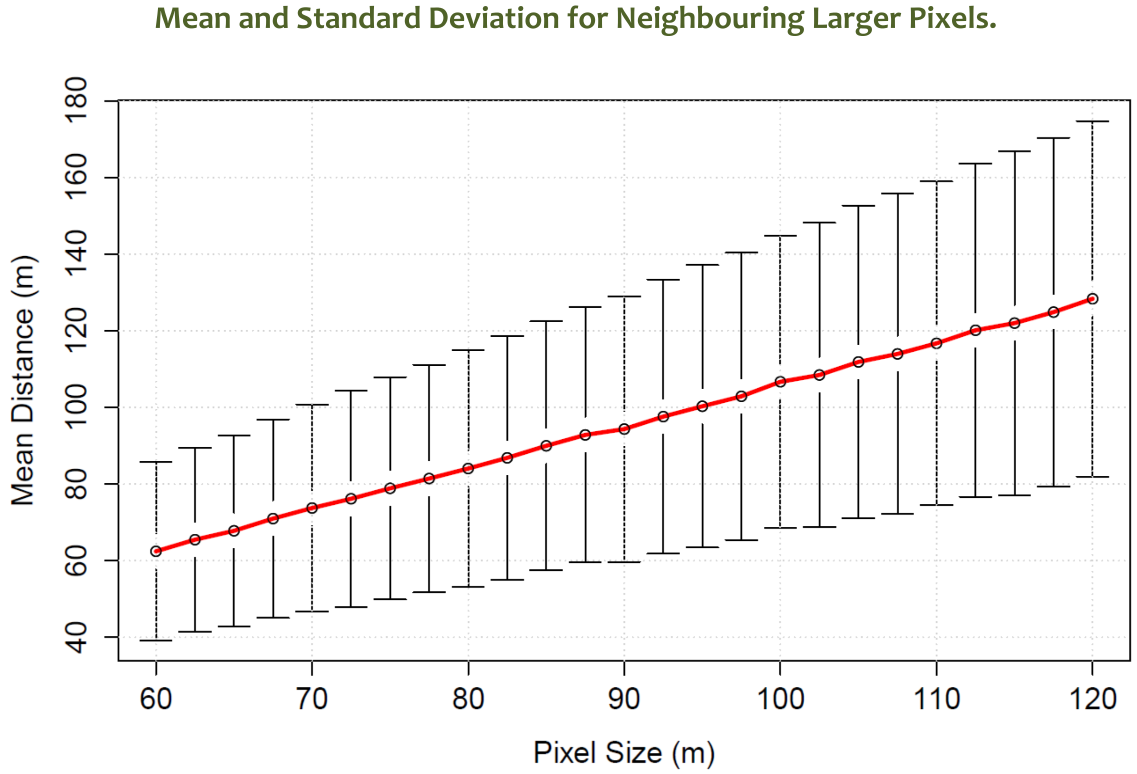


Figure 6 **Mean and standard deviation for the distance between two 2.5m pixels (y axis) found at random within two neighbouring larger pixels (x axis).**

In the next step, we aggregated the 2.5 m vegetation data to 100 m based on the above calculations (Figure 7). Pixels at 100 m that contained at least a single 2.5 m vegetation pixel were classified as having structural connectivity elements. Dispersal is possible only within pixels identified by this layer.

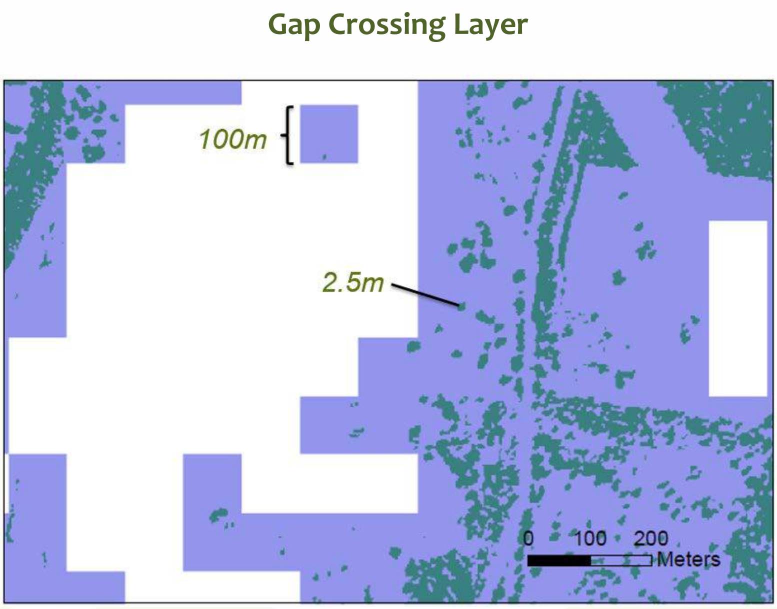


Figure 7 **Gap crossing layer with woody vegetation in green, areas where dispersal is possible in blue and areas where dispersal is not possible in white.**

Step 3: Assign dispersal cost based on land use/land cover and gap crossing layer

Create dispersal cost surface from land use/land cover map

Resistance to dispersal between patches was characterised by increasing the movement costs based on land cover properties. For example, land cover with high dispersal resistance may double the movement cost and thus the inter-patch dispersal distance threshold would be reduced from 1.1 km to 550 m. A wide road or a wide river will be composed of multiple pixels so will have a greater total resistance.

A literature review and expert opinion was used to parameterise movement cost. Four different land cover/land use (LULC) classes were identified as important and movement costs calculated as follows: Infrastructure, transportation, hydrological and other (see Table 2 for further description of the land cover cost classes). Following other general connectivity modelling methods (for example, Drielsma et al. 2012) generic land cover classes were used that were not specific to a land cover mapping method and thus suitable outside the study area.

The default land cover dispersal cost values used in this model were derived from a connectivity modelling assessment of the Port Stephens Local Government Area in the Lower Hunter, which included eight species, a bird, two amphibians and six mammals. (Eco Logical Australia 2012). The cost values for most of these species for multiple land covers were the same or very similar in most cases. Thus, the multiple cost values identified in the Port Stephens study were aggregated to the four land cover types used in this study. However, unlike the Port Stephens study, farmland (except for farm infrastructure) was given a low dispersal cost. The inclusion of connectivity elements such as scattered trees allows areas of pasture without scattered trees to be a barrier for dispersal, unlike the study by Eco Logical Australia (2012). To address uncertainty in dispersal costs, sensitivity analyses were conducted (Table 2).

Table 2: **Land cover resistance and dispersal cost in metres for four different land cover classes in areas that have connectivity elements present or absent. In all cases except 'No resistance', areas where landscape connectivity elements are not present are considered barriers to movement (for example, infinite resistance). The impact of differences in resistance values are included in 3 of the 6 sensitivity analyses scenarios (Table 4).**

	Land Use	Default Resist-ance Case	Cost for 25 m pixel	No resistance (Case 1)	Gap crossing only (Case 2)	Case 4: High resistance (Case 3)	Description
Structural connectivity elements absent	**All**	Infinite	Infinite	100%	Infinite	Infinite	Areas without gap crossing features at the gap crossing threshold
Structural connectivity elements present	**Other**	100%	25 m	100%	100%	100%	Other land use – predominantly agricultural or grazing areas.
	Hydrology	300%	25 m	100%	100%	400%	Water bodies such as rivers and lakes
	Transport	200%	50 m	100%	100%	300%	Roads and train lines
	Infrastructure	200%	50 m	100%	100%	Infinite	Urban and industrial areas

These land cover types were derived from the NSW LULC layer based on 1998-2000 air photo interpretation at 1:25000. The original LULC map in the Lower Hunter had 42 classes and was converted to the four new land cover classes related to dispersal costs as described above (Figure 8). A semi-quantitative assessment of thematic accuracy and feature geometric accuracy was conducted to ensure that the aggregation of fine thematic resolution LULC classes was logical and current for 2013. In some cases, land cover polygons were reclassified based on the visual assessment.

Land Cover Map used to derive the Dispersal Cost Surface

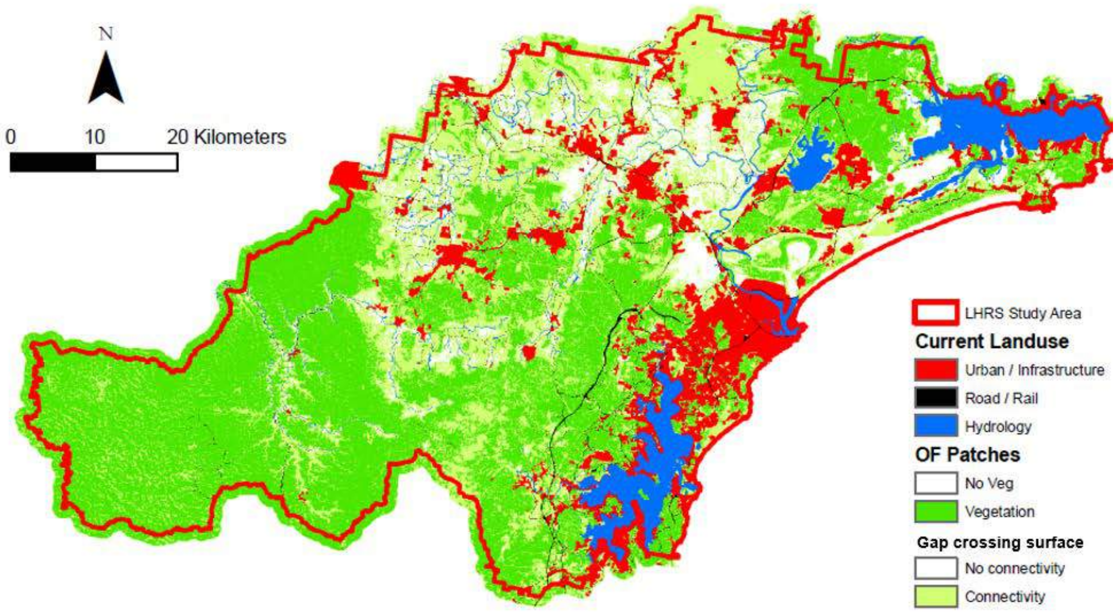


Figure 8 **Land cover map used to derive the dispersal cost surface from the NSW Land Use Land Cover layer at 1:25,000.**

<u>Combining gap crossing layer and dispersal cost surface</u>

The final step in the creation of the dispersal cost surface was combining the gap-crossing layer with the dispersal cost surface. For most connectivity modelling software, the input layer is a raster surface with pixel values describing dispersal cost for each pixel and patches. The dispersal cost value assigned to each pixel is a function of: (a) pixel size (for example, if the pixel size is 30 m and there is no resistance the cost should be 30 m); (b) land cover resistance; and (c) the presence of structural connectivity elements identified with the gap crossing layer.

Using the original fine-resolution pixel size is rarely an option when using connectivity software; a trade-off is required between the spatial extent and the spatial resolution (that is, pixel size). However, important land cover elements that impact on dispersal occur at fine scales, for example, the width of a road, train track, river or stream. To address this limitation the pixel size of the dispersal cost surface was aggregated using a method that preserved dispersal costs in a realistic way. The original pixel size of 12.5 m (1:25,000) for the LULC and 2.5 m for the canopy cover layer were aggregated to 25 m. We found that 25m was the finest pixel size that could be processed by the Graphab connectivity software in a study of this spatial extent (4,300 km^2).

The dispersal cost surface was a property of the presence of structural connectivity elements and the movement cost due to features in the LULC map such as roads, urbanisation and agriculture. Areas in which the gap-crossing layer showed an absence of structural connectivity elements were considered barriers to dispersal regardless of the underlying land cover. A series of raster processing steps were used to identify areas in which dispersal: a) does not occur (for example, infinite cost); b) areas in which there is a cost to dispersal due to land

cover resistance such as roads (average costs); and c) areas where there are no extra cost to dispersal (for example, agricultural landscapes with structural connectivity) (Figure 9). The processing steps outlined in Figure 9 have been automated using the Python programming language with the NumPy and ArcGIS libraries. In the future, this will be packaged as an ArcGIS tool that can be accessed through the ArcGIS toolbox.

Summary of processing rule set:

- Structural connectivity elements take precedence over all other land cover classes, based on the assumption that without the presence of structural connectivity there will be no dispersal.
- Even if land cover occupies a small percentage of the aggregated pixel, the final dispersal cost for the aggregated pixel will be infinite. Using this rule set, barriers can be created regardless of physical size in relation to the aggregated pixel size. Barriers need only be a single pixel wide. This processing step is important to ensure linear features that represent barriers are actually modelled as barriers within the connectivity model.
- The dispersal cost for a single aggregated pixel is calculated as an average of all land covers except if a barrier is present as described above.

Processing Flow Chart Describing the Derivation of A Raster Layer Dispersal Cost Layer

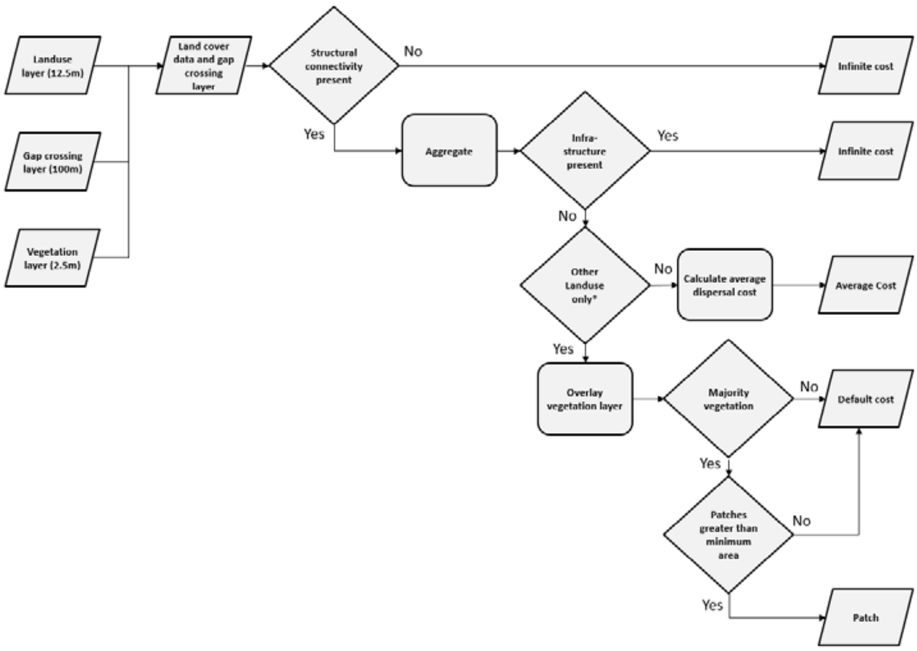


Figure 9 **Processing flow chart describing the derivation of a raster layer for Case 4 (High resistance – where infrastructure has infinite cost) that represents patches of habitat and dispersal costs at a coarser pixel size than the original input data. *Other landuse refers to pixels which contain no roads/rails or hydrology for example, mostly farmland.**

Step 4: Identify minimum patch size

The review by Doerr et al. (2010) suggested that the minimum area of remnant native vegetation that can function as a patch is between 10 ha and 20 ha in size. Areas of native vegetation that were less than 10 ha identified using the SPOT mapping were classified as having structural connectivity elements, that is, allowed for dispersal but did not contribute to habitat. Figure 10 shows the distribution of vegetation greater than 10 ha within the Lower Hunter.

Patches were calculated as part of the previous processing steps using the aggregated pixel values, where vegetation was in the majority and pixels did not contain the land cover classes infrastructure, hydrology or transport. This aggregation process is important, as at a pixel size of 2.5 m, there are likely to be gaps in the canopy typical of woodlands and forests that do not reflect gaps within the habitat. Thus at the coarse resolution (25 m) only 50% of a pixel need to have canopy for it to be considered as habitat.

Remnant Woody Vegetation Patches in the Lower Hunter Greater than 10 ha

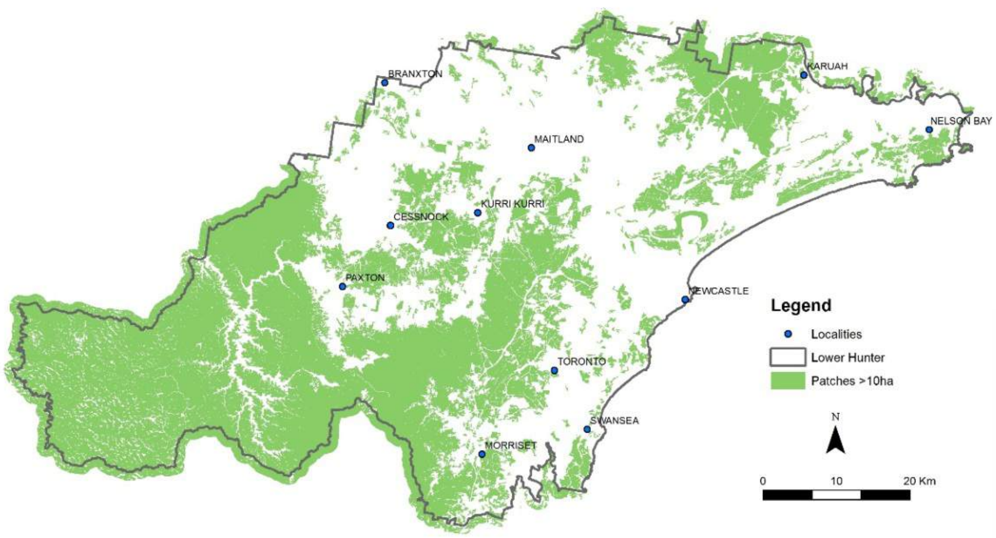


Figure 10 **Remnant woody vegetation patches in the Lower Hunter greater than 10 ha.**

Step 5: Regional connectivity model based on graph theoretic approach using Graphab

Graphab analysis

The graph theoretic perspective can be applied to landscapes to describe ecological fluxes, in particular those associated with meta-populations and dispersal (Minor & Urban 2008; Rayfield et al. 2010; Urban et al. 2009). Applied to landscape ecology, a graph can be used to represent landscapes as a set of nodes and edges where the nodes are patches within a network and the edges represent connectivity between nodes (Figure 11). Graph-networks can be used to identify components that represent isolated groups of interlinked nodes (for example, patches).

Schematic Representation of Connectivity Networks using Graph Theory

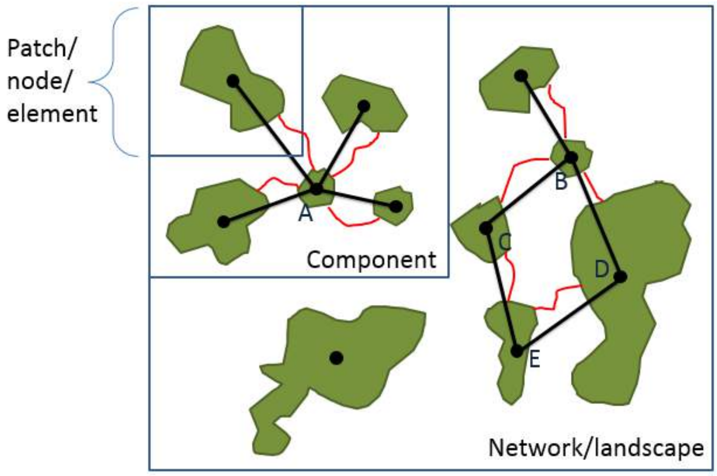


Figure 11 **Schematic representation of the different levels of analysis within a connectivity network in which patches (green) are connected by multiple links (black lines) represented by least-cost-pathways (red lines) that incorporate information about the matrix (white area). Graph metrics can be considered at three levels: patch-scale, component or landscape-scale. Using the language of graph theory, these patches are considered as nodes (black dots) linked within a graph-network (black lines). Graph metrics are useful for characterising the importance of patches in the landscape. For example patch A is a critical stepping stone important for connecting multiple patches, while the pathway between patch B and E is more resilient to patch loss as connectivity can be achieved through patch C or D.**

Using the graph-theoretic approach, least-cost pathways between each node or patch were calculated using a cost-weighted distance analysis as a function of land cover resistance and the inter-patch dispersal distance threshold. The graph-network analysis identified the single most optimal link between patches based on cumulated cost in relation to land cover resistance. Cumulated costs were chosen as they have been identified as the best approach for modelling least-cost paths (Etherington & Penelope Holland 2013).

Graph-networks are useful for characterising connectivity within landscapes by identifying patterns that are ecologically significant and also patterns that may have consequence for conservation planning. These complex patterns resulting from the location and links between multiple nodes across a network can be condensed and summarised using graph-network metrics. A wide variety of graph metrics have been developed to describe these patterns (Rayfield et al. 2010). These measures can be calculated at multiple scales: patch, component and network (Figure 11). Of key importance for conservation planning is identifying patches that are critical for maintaining connectivity across a network (Minor & Urban 2008) and connectivity networks where redundant routes exist between pairs of habitat patches (Rayfield et al. 2010). For example, graph metrics can be used to identify route vulnerability where there is little redundancy and hence prioritise patches for conservation protection.

We selected a subset of the numerous patch-scale graph metrics available that describe the many different aspects of connectivity. Patch-scale graph metrics are calculated for each patch in the landscape. A subset was chosen as many measures are closely related and some nearly redundant (Baranyi et al. 2011). In total we selected five measures (Table 3) to test a broad

range of components of heterogeneity and ensure that every broad category of spatial heterogeneity described in Rayfield et al. (2010) were measured. Rayfield et al. (2010) identified four characteristics of connectivity: route-specific flux, route-redundancy, route vulnerability and connected habitat area. Each graph metric was plotted spatially on a map and in a scatter plot.

Table 3 Patch-scale graph metrics used in the study, indicating their ecological significance, definition and source. These values are calculated for each patch.

Graph metric	Ecological Significance	Definition	Rayfield et al. (2011) Connectivity characteristic	Reference
Node degree	Characterises connectedness of a focal patch and its potential accessibility. For Example, node degree of zero indicate the patch is a dead end in a pathway.	A simple metric describing the number of links associated with a focal patch	Route-specific flux	(Ricotta et al. 2000)
Clustering coefficient	Measures the level of redundancy within a network. High values indicate that alternative paths exist and pathways through the focal patch is not unique.	Average proportion of a focal patches neighbouring patches that are also neighbouring patches with each other	Route-redundancy	(Minor & Urban 2008; Ricotta et al. 2000)
Connectivity correlation	Indicates the degree of compartmentalisation or presence of sub-networks. Important for reducing the spread of cascading disturbances such as fires or invasive species.	Average degree of focal patch relative to the average degree of its neighbours	Route vulnerability	(Minor & Urban 2008)
Delta Integral index of connectivity (IIC)	The loss of habitat availability caused by the removal of the focal patch relative to the connectivity network. High values indicate that the patch is important for connecting habitat or contains a lot of habitat.	Indicate the probability that two randomly located points in habitat are connected	Connected habitat area	(Pascual-Hortal & Saura 2006; Saura & Pascual-Hortal 2007)
Delta Harary Index	Importance of the patch for connecting patches across the landscape. High values indicate that the patch is important for connectivity	One minus the difference between the sum of the inverse of the number of links between all pairs of patches with focal patch removed and without removal.	Route-specific flux	(Ricotta et al. 2000)

Finally, a principal component analysis (PCA) was used to explore the similarity between graph metric values. As the analyses were exploratory and no tests of statistical significance were conducted, the assumption of normality was not required to be observed.

Graphab sensitivity analysis

Six cases were tested to assess the sensitivity of the connectivity model to uncertainty in different aspects of model parameterisation (Table 4). The default case represents the best available ecological knowledge for parameterising the general connectivity model. Sensitivity analyses are useful for quantifying the range and distribution of predictions and identify data, model structure or parameters that require improvement (Crosetto et al. 2000).

Table 4 Default and sensitivity analysis.

Case Name	Description
Default Case	Default parameterisation.
Case 1: No Resistance	No land cover dispersal resistance and gap crossing threshold layer excluded. Dispersal based on Euclidian distance.
Case 2: Gap-Crossing Only	No land cover resistance, but gap crossing threshold used.
Case 3: High Resistance	All land cover types have high resistance.
Case 4: 20 ha Patches	20 ha minimum patch size
Case 5: 550 m inter-patch dispersal distance threshold	Inter-patch dispersal distance threshold 550 m.
Case 6: 2200 m inter-patch dispersal distance threshold	Inter-patch dispersal distance threshold 2200 m.

A quantitative assessment of the differences in the graph metrics and a qualitative assessment of the differences in least-cost pathways and components were used to evaluate the parameters most sensitive to uncertainty. For each case, a range of landscape-scale graph metrics (as opposed to patch-scale metrics used in the previous step) were calculated, characterising the connectivity for the entire landscape with a single value (Table 5). The magnitude of the difference between the values measured was used to assess the sensitivity to the different cases. These measures were chosen as they represent a range of methods for characterising the pattern of connectivity. We chose a combination of two of the four connectivity properties measured that can be used for graph based analyses identified by Rayfield et al. (2010). The remaining connectivity properties identified by Rayfield et al. (2010) could not be measured using the Graphab software. However, these measures are quite unique and the majority of the graph metrics identified at the network level are represented by these two categories.

Table 5 **The landscape-scale (network) graph metrics used in the study with their ecological significance, definition and source. These metrics describe the connectivity with a single value for the entire landscape.**

Graph metric	Ecological Significance	Definition	Rayfield et al. (2011) Connectivity characteristic	Reference
Mean Size of Components (km^2)	Simple measure that describes the average component area.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Size of Largest Component (km^2)	A simple measure that describes the area of the largest component.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Number of Components	Simple measure that describes the number of isolated areas in the landscape. High number of components to total number of patches indicate that the landscape is highly fragmented.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Harary Index	The number of patches that contribute to linking patches across the landscape. High value indicate a highly connected landscape.	Sum of the inverse of the number of links between all pairs of patches.	Route-specific flux	(Ricotta et a l. 2000)
Class Coincidence Probability	Measure of dispersal relative to component isolation. High value indicate that the landscape is connected.	Probability that two randomly located points are found in the same component.	Connected habitat area	(Pascual-Hortal & Saura 2006)
Expected Cluster Size (km^2)	Indicate the mean area that a disperser has access to. Larger the value the greater the available area.	Area-weighted mean number of nodes within each component.	Connected habitat area	(O'Brien et al. 2006)
Integral index of connectivity (IIC)	Probability that two dispersers randomly located in the landscape within a patch can access each other. Higher value indicate greater connectivity.	Probability of two individuals being connected weighted by area.	Connected habitat area	(Pascual-Hortal & Saura 2006)

Step 6: Local-scale connectivity model based on Circuitscape

Local-scale analyses using Circuitscape were conducted for a specific area in the Lower Hunter based on a semi-quantitative assessment of the best possible rehabilitation sites for increasing connectivity across the study area. This assessment was directed by the Graphab regional-scale outputs, local knowledge and previous conservation assessments. In practice, this step should be conducted in response to potential management actions such as a proposed development.

The previous connectivity modelling method based on Graphab identified the single most optimal link between patches, while Circuitscape was used to assess connectivity for all pixels within the target area at the local scale. High connectivity values calculated with Circuitscape are analogous to a high probability that plants or animal will disperse. However, the connectivity values described by Circuitscape may not represent actual dispersal, as Circuitscape does not allow for inclusion of thresholds such as the inter-patch dispersal distance threshold (as in Graphab). Thus, we consider this analysis as a way of identifying areas of high connectivity for future rehabilitation or potential connectivity.

Two types of analyses were conducted with Circuitscape: (a) an assessment of potential areas for rehabilitation and (b) an assessment of path redundancy. In the first analysis, we assessed connectivity between components where all patches within a component were treated as a single node. Connectivity was then calculated using all pairs as focal nodes. In the second method, dispersal between patches based on the optimal paths identified by Graphab was compared to the Circuitscape analyses. In this case, each patch was considered as a focal node. Using this method, we could assess whether there was redundancy or potential bottlenecks to connectivity between patches. In both analyses, we used pairwise analysis with eight neighbourhood connections.

2.3. Results

2.3.1. Regional connectivity model based on Graphab – default case

The Graphab least-cost path graph-network connectivity modelling, based on the default case, identified two large components (isolated group of interlinked patches) in the west and the east (Figure 12, Component 1 and 2). The patches within the component to the west (Figure 12, Component 1) contain 80% of the patch area in the Lower Hunter and contain the three largest patches that include 65% of the total patch area (Figure 12, A-C). The centre of the Lower Hunter from Branxton, to Newcastle and Morisset in Lake Macquarie is highly fragmented consisting of small components made up of one or a few small patches isolating the two largest components in the east and west. A total of 574 patches were identified greater than 10 ha, existing within 42 separate components (Table 6).

Regional-Scale Connectivity Model with Patch Area Described

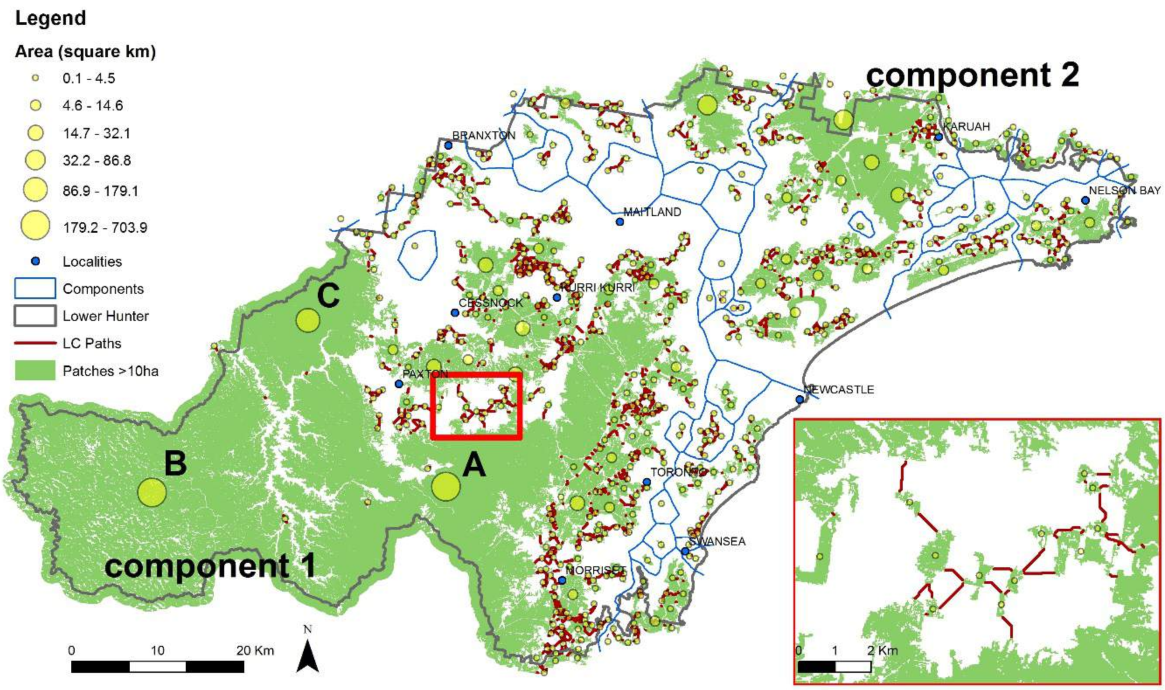
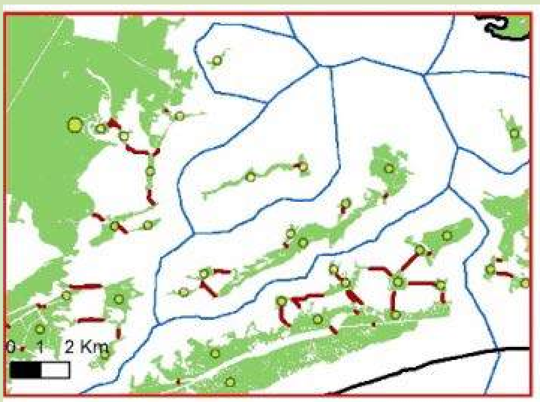


Figure 12 **Regional-scale connectivity analysis using least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols describing patch area are located at the centre of each patch. Least coast (LC) paths between patches are shown in red. The letters (A-C) denote the three largest patches in the landscape. Components 1 and 2 contain 91% of the total patch area in the region.**



Interpreting blue component location lines.

The blue lines are used to identify which patch are part of the same component. The location of the lines are for visualisation purposes only. The lines are found at the midpoint between patches from different components.

Table 6 **Network characteristics for the default case.**

Network characteristic	Default Value
Mean Size of Components (km^2)	56
Size of Largest Component (km^2)	1885
Number of Components	42
Number of Patches	575

The graph metric analysis found that the largest patch (Figure 12, A) was by far the most important in terms of connectivity at the regional scale and total patch area (Figure 12). All graph metrics apart from Clustering Coefficient characterised Patch A as having the highest value. The graph metric Integral index of connectivity (IIC) is area weighted and consequently was correlated with patch area. Along with IIC, Connectivity Correlation and Node degree were correlated with patch area (Figure 12). Large patches within the Lower Hunter are important for connectivity as they provide links (for example, high Node Degree) to many patches throughout the landscape due to their physical size. However, not all large patches had high graph metric values as shown by patches B and C. As a result, of their position near the boundary, their values for a range of graph metrics were similar to the average yet they were the second and third largest patches. The Clustering Coefficient was the only graph metric in which Patch C did not have a very high value. This graph metric describes the level of patch redundancy and thus Patch C's low values are due to its central position and the large number of links it provides across the landscape. Patches with low Clustering Coefficient represent patches that are irreplaceable with a connectivity network.

Plots of Patch Area Versus Five Graph Metrics Showing the Spearman's R Correlation and Cumulative Patch Area

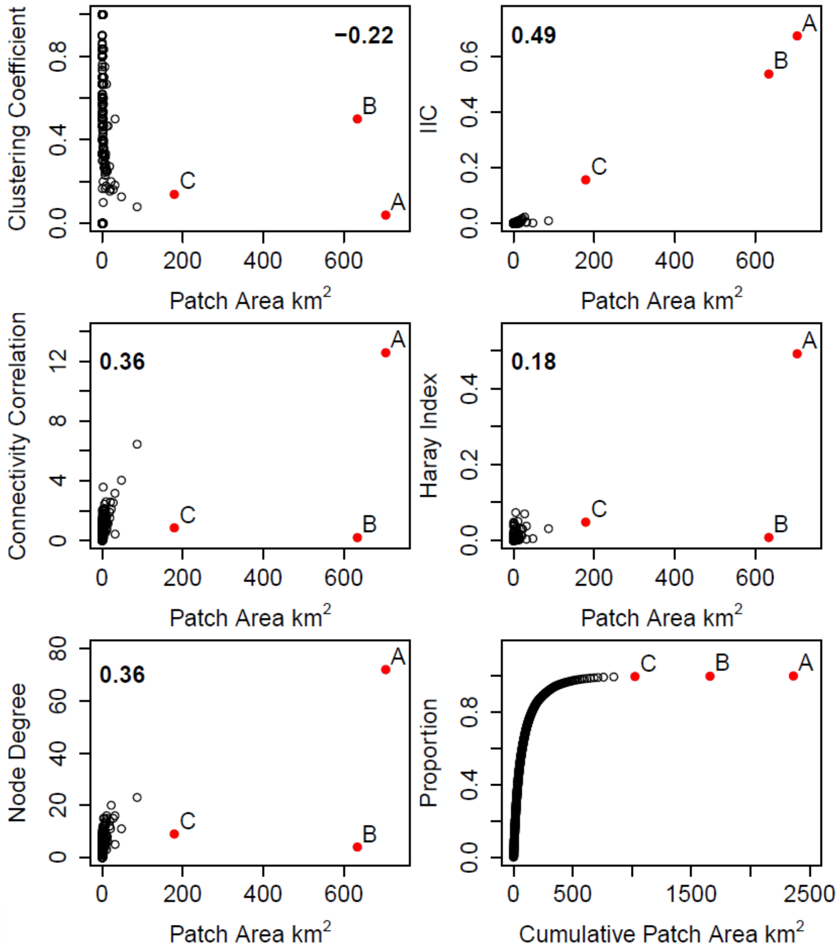


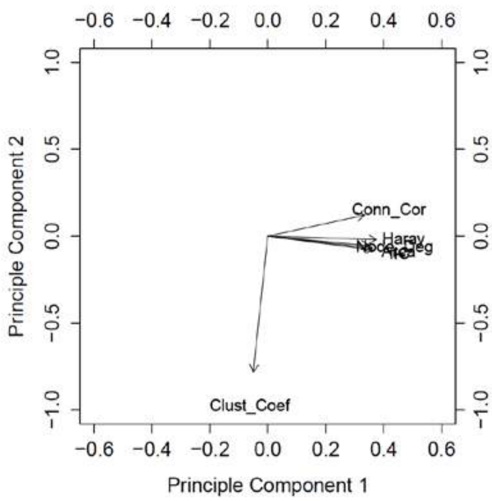
Figure 13 **Plots of patch area versus five graph metrics showing the Spearman's R correlation. The sixth plot (bottom right) shows the proportion of total number of patches plotted against the cumulative patch area, with the three largest patches identified as A, B and C where A is the largest and C is the smallest (see Figure 12).**

The ordination plot from principal components analysis shows that the graph metrics Harary index, Node Degree, IIC, Connectivity Correlation and area are highly correlated (Figure 14a). The ordination plot was based on a principle component analysis (PCA) of the graph metrics and area. It showed that the first two components, 1 and 2, describe 80% of their total variability (Table 7). While the graph metric Clustering Coefficient had a uniquely different response to the other metrics. However, this analysis was highly influenced by large patches with high graph metric values skewing the distributions (Figure 12). An ordination plot with the 15 largest patches removed showed a very different pattern with less correlation between graph metric values (Figure 14b) demonstrating the influence of large patches on the interpretation of the graph metrics.

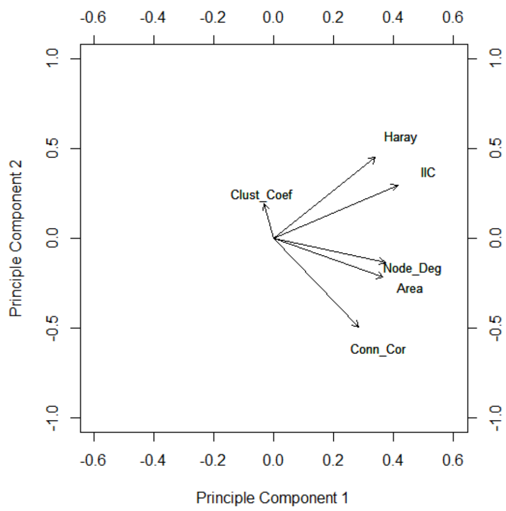
Table 7 **Principle component analyses of the relationship between graph metrics and area.**

Principle Component	1	2	3	4	5	6
Standard deviation	1.95	1.01	0.90	0.49	0.38	0.06
Proportion of variance	0.63	0.17	0.14	0.04	0.02	0.00
Cumulative proportion	0.63	0.80	0.94	0.98	1.00	1.00

Ordination Plot (PCA) of the Five Graph Metrics and Area



a)



b)

Figure 14 **Ordination plot from a principal components analysis (PCA) of the five graph metrics and area in the plane of Principal Component 1 and Principle Component 2. a) PCA of all patch values where principle components 1 and 2 describe 80% of the total variation. b) PCA with 15 largest patches removed where principle components 1 and 2 describe 69% of the total variation.**

Maps that show the distribution of graph metrics are useful for interpreting spatial priorities (Figure 15 - Figure 18). The graph metrics were mapped using graduated circles that vary in size in proportion to the particular graph metric value. The spatial distribution of these values mirrors the interpretation above, whereby differences between patches that were small in area were unobservable at the regional scale.

The Clustering Coefficient graph metrics, which describes patch redundancy, appears to be high throughout the Lower Hunter Region except for specific patches that provide important links. Figure 15 inset shows that patches that hold a central place within the connectivity network are important stepping-stones for connectivity and tend to have low redundancy.

Clustering Coefficient (number of alternative possible connections) for the Regional Connectivity Model

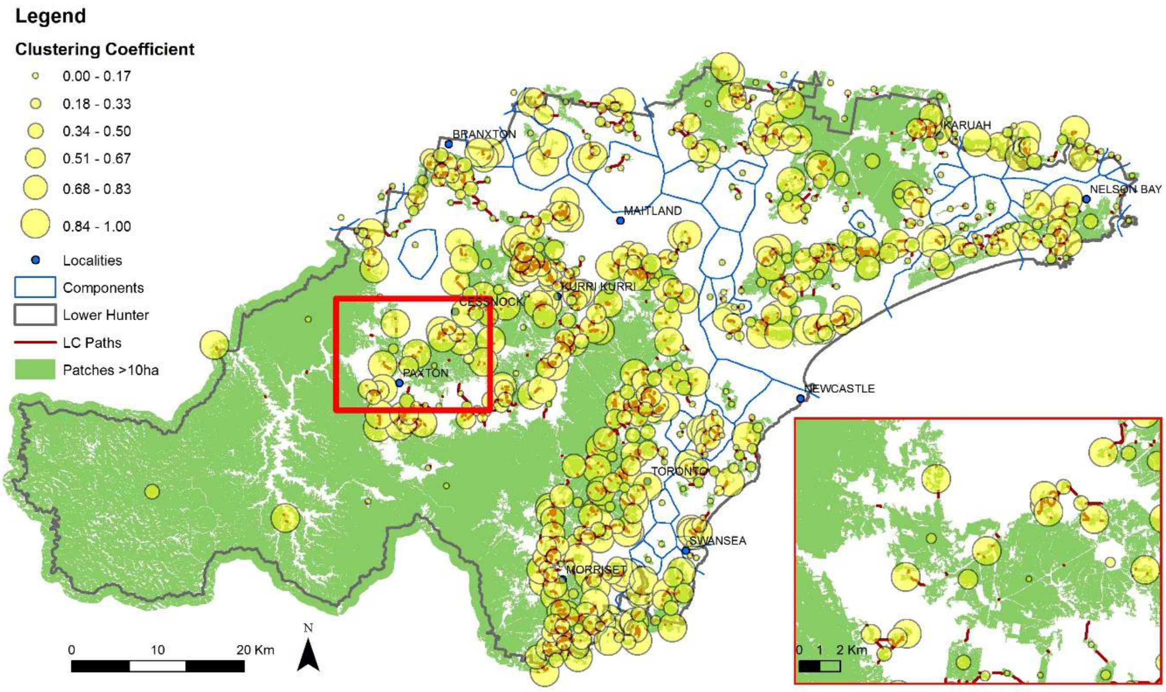


Figure 15 **Regional-scale connectivity analyses based on least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols located at the centre of patches describe the Clustering Co-efficient, which is a measure of patch redundancy in a connectivity network.**

The graph metrics Connectivity Correlation (Figure 16), Node degree (Figure 17) and the Harary Index (Figure 18) appear to show similar spatial distributions of values. The largest patch (A) has a much larger value than all other patches within the landscape, indicating it is particularly important for connectivity within the landscape.

Connectivity Correlation (degree of compartmentalisation) for the Regional Connectivity Model

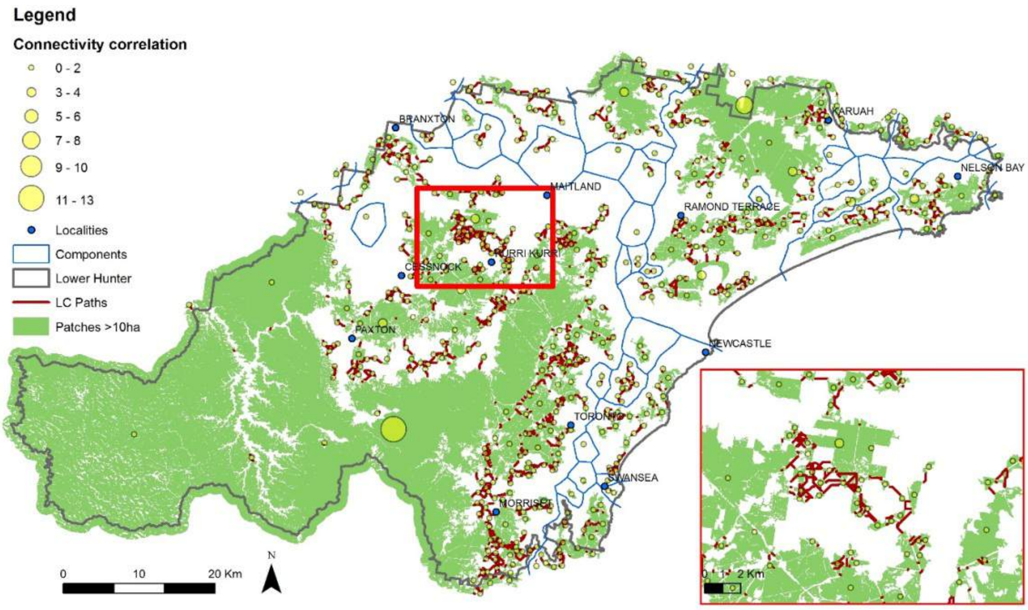


Figure 16 **Regional-scale connectivity analyses based on least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols located at the centre of patches describe the Connectivity Correlation, which is an indicator of the degree of compartmentalisation or presence of sub-networks.**

Node Degree (number of patches to which a focal patch is connected) for the Regional Connectivity Model

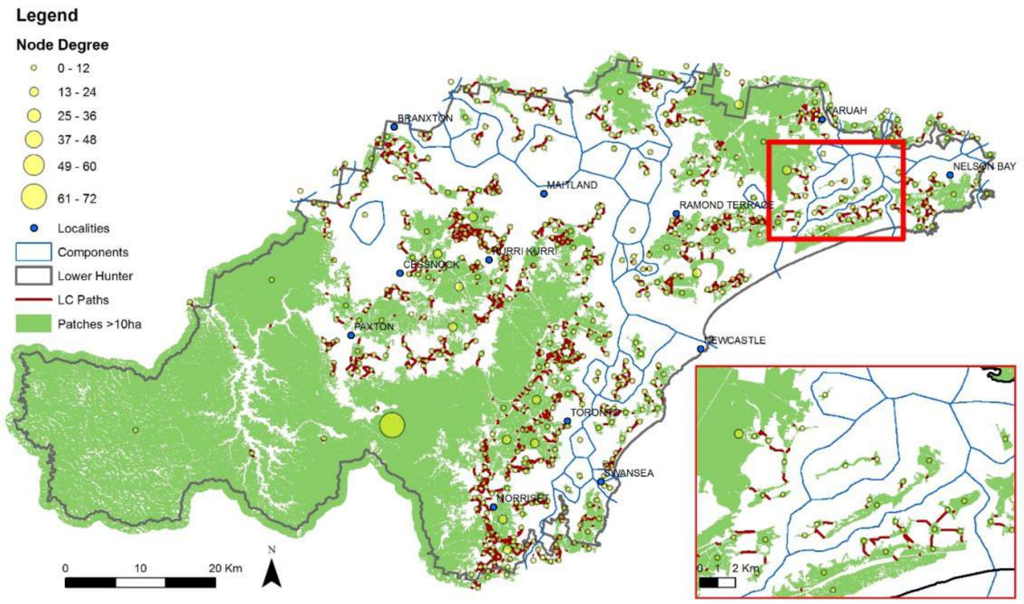


Figure 17 **Regional-scale connectivity analyses based on least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols at the centre of patches describe the Node Degree, a measure of the number of patches to which a focal patch is connected.**

Harary Index (connectedness of a patch within a network) for the Regional Connectivity Model

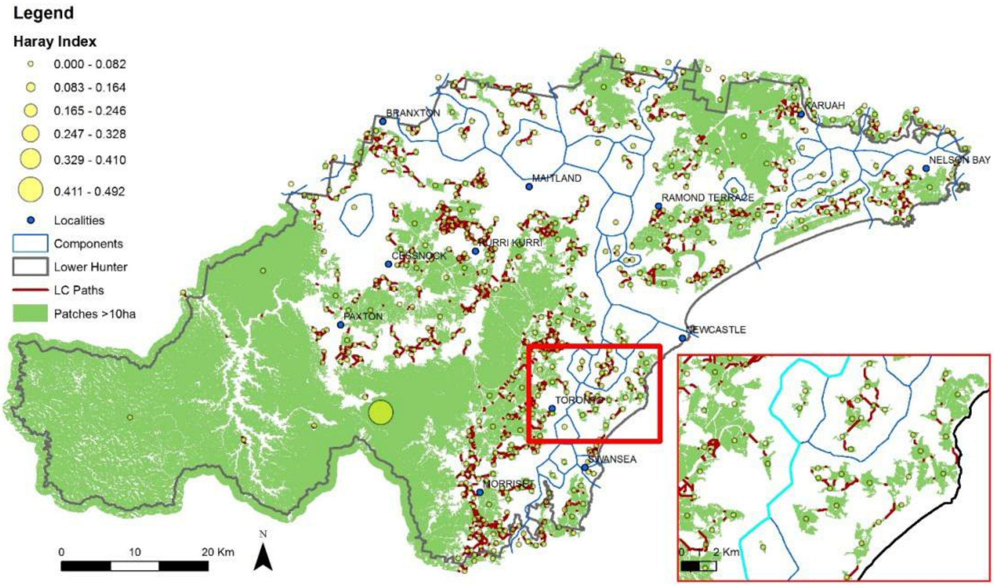


Figure 18 Regional-scale connectivity analyses based on least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols at the centre of patches indicate the Harary Index, indicating the connectedness of focal patch to other patches in the network.

Integral Index of Connectivity (measure of habitat patch connectedness, weighted by patch area) for the Regional Connectivity Model

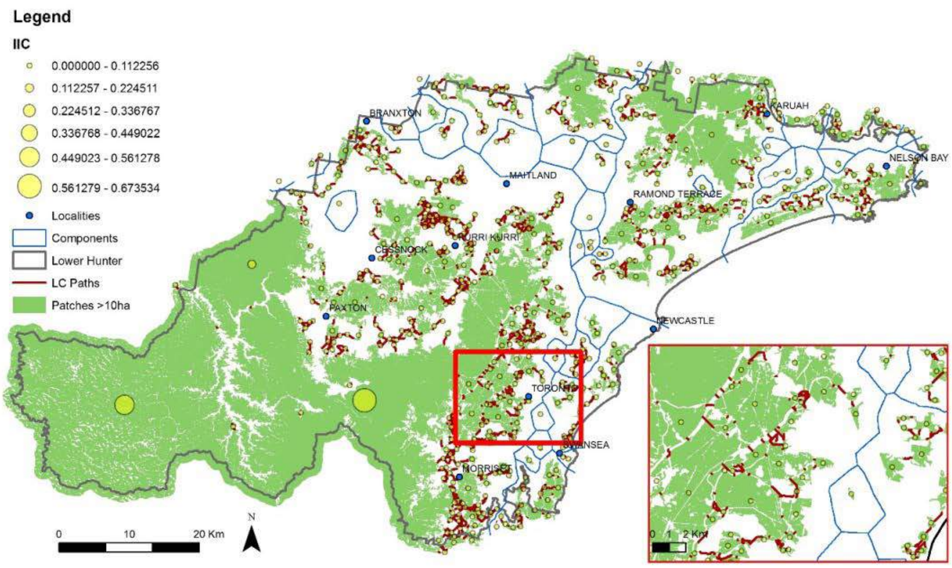


Figure 19 Regional-scale connectivity analyses based on least–cost paths for patches greater than 10 ha using Graphab. Circular graduated symbols at the centre of patches describe the IIC index, a measure of the probability that two dispersers randomly located in the landscape within a patch can access each other.

The IIC graph metric is an area-weighted index that assesses the probability that two dispersers randomly located in the landscape within a patch can access each other (Figure 19). In the Lower Hunter, this index is highly correlated with patch area. Similar patterns are seen in non-area weighted graph metrics. This is likely to be due to large patches having a greater role in connecting patches (for example, high Node Degree) across the landscape due to their physical extents.

2.3.2. Regional connectivity model based on Graphab – sensitivity analyses

The results of the sensitivity analysis of the model parameters using graph metrics are presented in Table 8. The connectivity network, including the location of components and least-cost paths for a qualitative assessment, is described in Figure 20 to Figure 25. The modelled connectivity network appeared to be relatively insensitive to different parameterisations except for the Harary index. The two largest components (Figure 12, Components 1 and 2) contain of the majority of the patch area in the Lower Hunter in the east and west and appear to be connected regardless of the parameterisation. Furthermore, the total patch area of the largest component (Component 1) was very similar regardless of the parameterisation (Table 8, Size of Largest Component). The number of components and mean size of components fluctuated depending on the case. However, a visual inspection of the connectivity network (Figure 20 to Figure 25) shows this is largely to do with smaller patches that make very little contribution to total patch area, but become isolated or connected due to different parameterisations. Other graph metrics such as Harary Index, Class Coincidence Probability and Expected Cluster Size appear relatively stable. Additionally, the IIC was nearly the same for all cases.

Table 8 Sensitivity analyses network characteristics.

Network characteristic	Default Case	Case 1: No resistance	Case 2: Gap crossing only	Case 3: High resistance case	Case 4: 20 ha Patches	Case 5: Min dispersal 550 m	Case 6: Max dispersal 2200 m
Mean Size of Components (km^2)	56	139	56	32	61	25	169
Size of Largest Component (km^2)	1885	1938	1885	1857	1871	1854	1913
Number of Components	42	17	42	74	38	93	14
Harary Index	11954	15512	10830	9858	5318	8069	18146
Class Coincidence Probability	0.65	0.70	0.65	0.63	0.66	0.63	0.68
Expected Cluster Size (km^2)	1538	1657	1538	1491	1532	1538	1614
IIC	0.02	0.02	0.02	0.02	0.02	0.02	0.02

The greatest differences in the connectivity network appear to stem from using the no resistance (Figure 20) and high (Figure 25) or low inter-patch dispersal distance thresholds (Figure 24) cases. Differences in the parameterisation of the dispersal cost surface for the high resistance case did not appear to change the connectivity network greatly except in an area in the north, near Branxton that appeared to be more fragmented. A similar pattern of fragmentation was seen in the minimum dispersal case. This pattern may be the result of urban land cover, given infinite resistance posing a barrier to connectivity. For patches that make up the majority of the total habitat area in the regional, the connectivity network appeared stable for most cases. However, at finer scales differences within the modelled least-cost paths could be identified (see insets for Figure 20 to Figure 25).

Sensitivity Analyses for Case 1
(*no land cover resistance or gap crossing layer*)

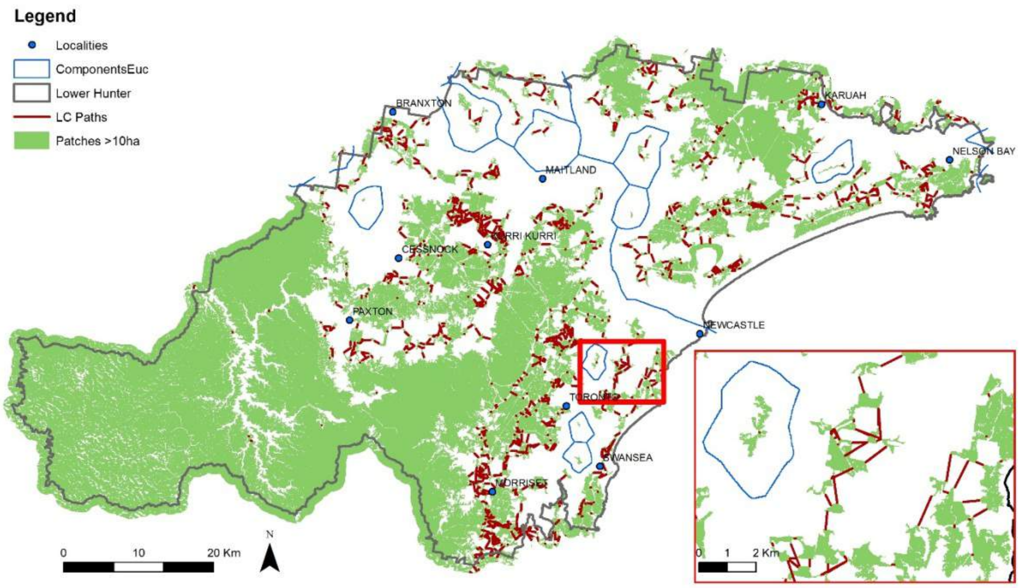


Figure 20 Regional-scale connectivity analyses using Graphab. Case 1 – least-cost paths between patches greater than 10 ha were calculated with no land cover resistance or gap-crossing layer. The inset highlights the output from the least-cost path algorithm.

Sensitivity Analyses for Case 2
(*gap crossing threshold layer, but no land cover resistance*)

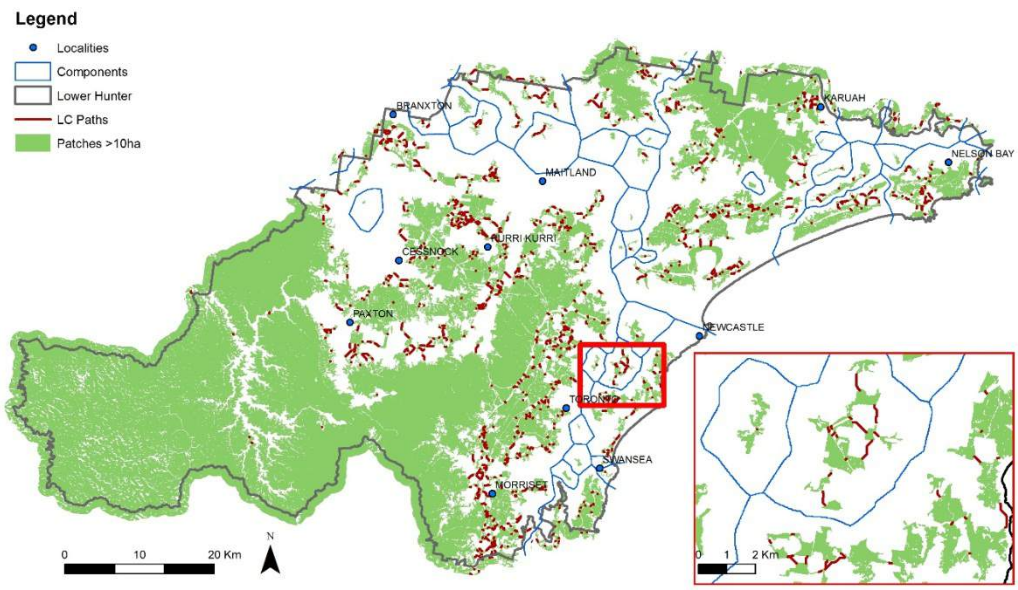


Figure 21 Regional-scale connectivity analyses using Graphab. Case 2 - least-cost paths between patches greater than 10 ha were calculated using the gap crossing threshold layer only but no land cover resistance. The inset highlights the output from the least-cost path algorithm.

Sensitivity Analyses for Case 3
(*high dispersal costs*)

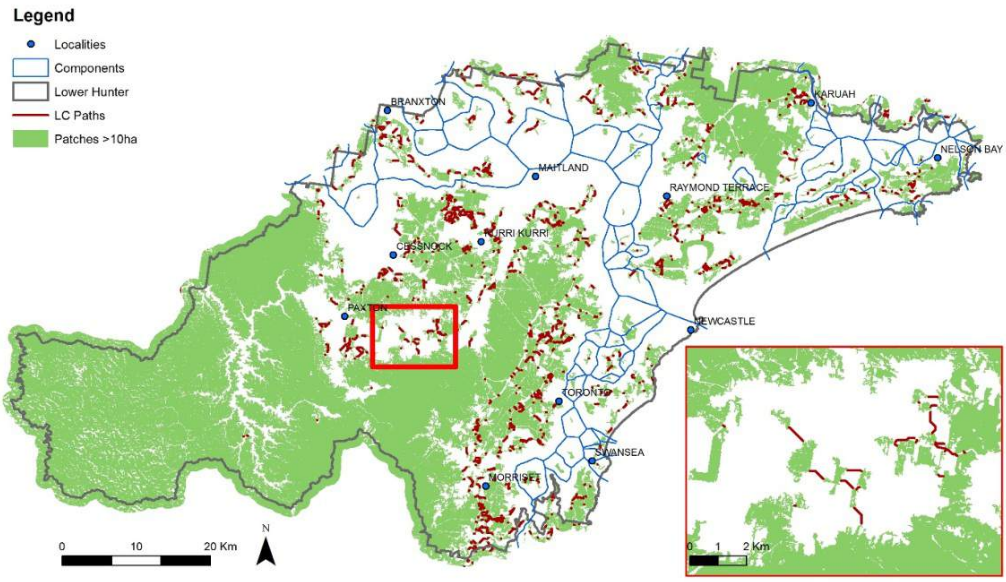


Figure 22 **Regional-scale connectivity analyses using Graphab. Case 3 - least-cost paths between patches greater than 10 ha are identified using high dispersal costs. The inset highlights the output from the least-cost path algorithm.**

Sensitivity Analyses for Case 4
(*patches greater than 20 ha*)

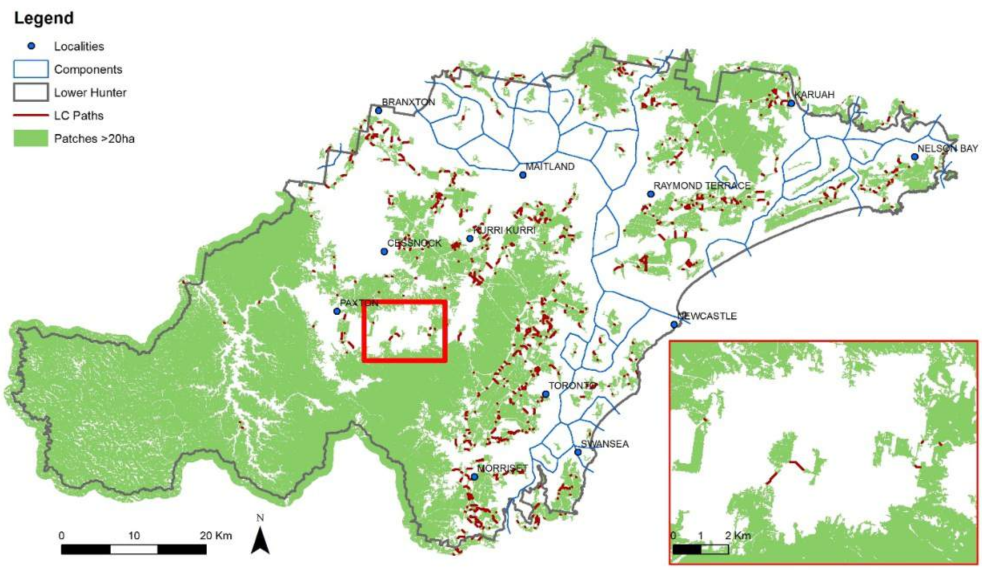


Figure 23 **Regional-scale connectivity analyses using Graphab. Case 4 - least-cost paths between patches greater than 20 ha are identified. The inset highlights the output from the least-cost path algorithm.**

Sensitivity Analyses for Case 5
(*inter-patch dispersal distance threshold of 550 m*)

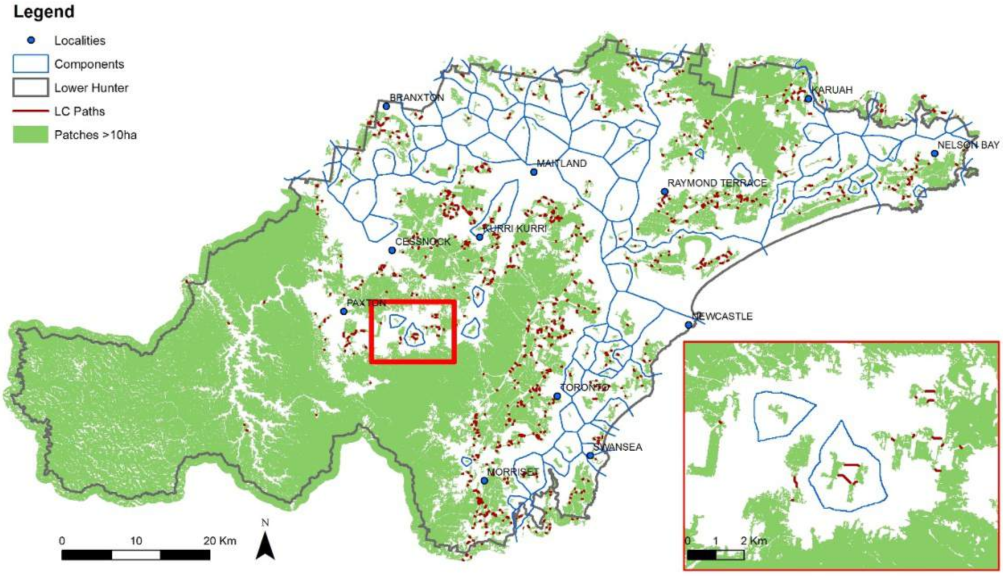


Figure 24 **Regional-scale connectivity analyses using Graphab. Case 5 - least-cost paths between patches greater than 10 ha are identified with as inter-patch dispersal distance threshold of 550 m. The inset highlights the output from the least-cost path algorithm.**

Sensitivity Analyses for Case 6
(*inter-patch dispersal distance threshold of 2200 m*)

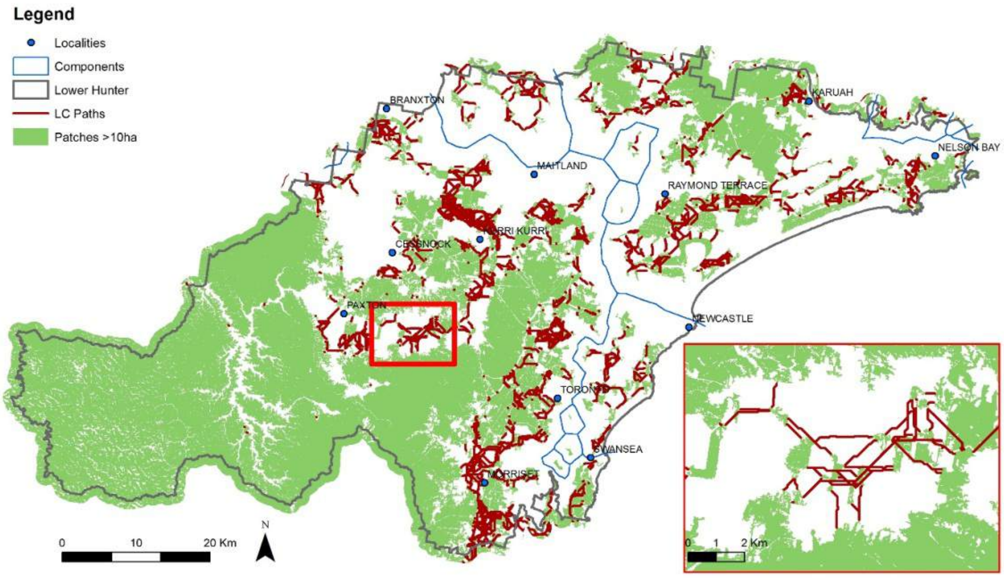


Figure 25 **Regional-scale connectivity analyses using Graphab. Case 6 - least-cost paths between patches greater than 10 ha are identified with an inter-patch dispersal distance threshold of 2200 m. The inset highlights the output from the least-cost path algorithm.**

2.3.3. Local-scale connectivity model based on Circuitscape

Identifying future connectivity potential

The centre of the Lower Hunter is composed of highly fragmented small remnant patches that fail to connect the two large components in the east and west of the region. It is in this location that a local-scale analyses was conducted using the Circuitscape software. This region is also part of the Green Corridor in the Lower Hunter Regional Strategy and contains the majority of the unconnected habitat within the corridor (Figure 26). We only included the northern half of this corridor within our analyses as the vegetation within the southern portion is composed predominantly of wetland vegetation dissimilar to the woody vegetation classified as patch in the general connectivity model (Figure 27). The pre-1750s mapping show that woody vegetation communities, except for the freshwater wetland complex vegetation community, dominate the local-scale connectivity analysis study area. The freshwater wetland complex vegetation community is also likely to contain scattered trees. Within this area, we identified four components that are currently isolated from each other.

Area of Interest for Local-Scale analyses using Circuitscape

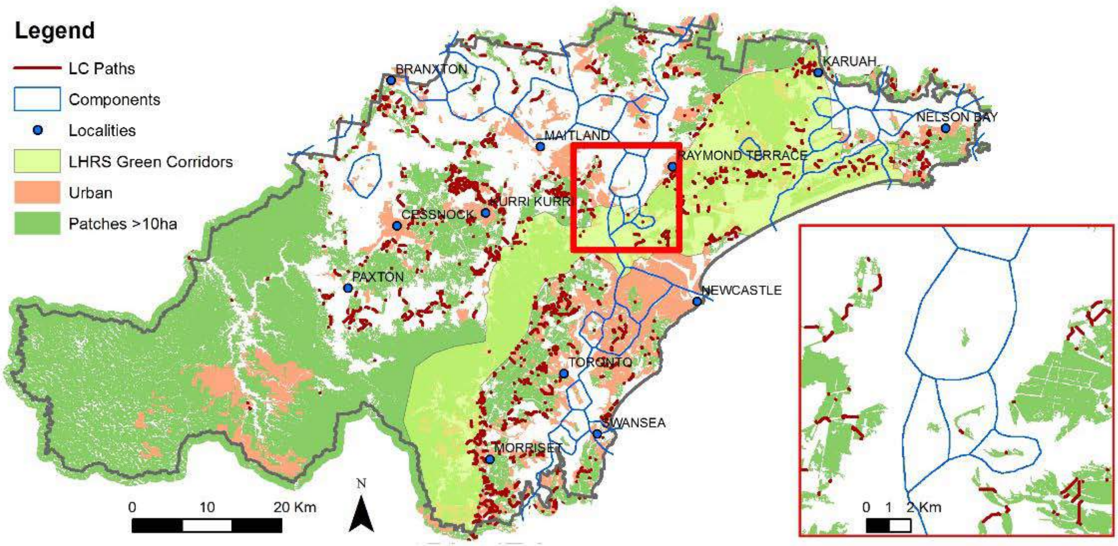


Figure 26 **Identification of area of interest for local-scale analyses using Circuitscape (inset) in relation to Lower Hunter Regional Strategy Green Corridors. Links identified at regional scale using the Graphab software are shown as red lines.**

Pre-1750 Vegetation Cover within Area of Interest for Local-Scale Analysis

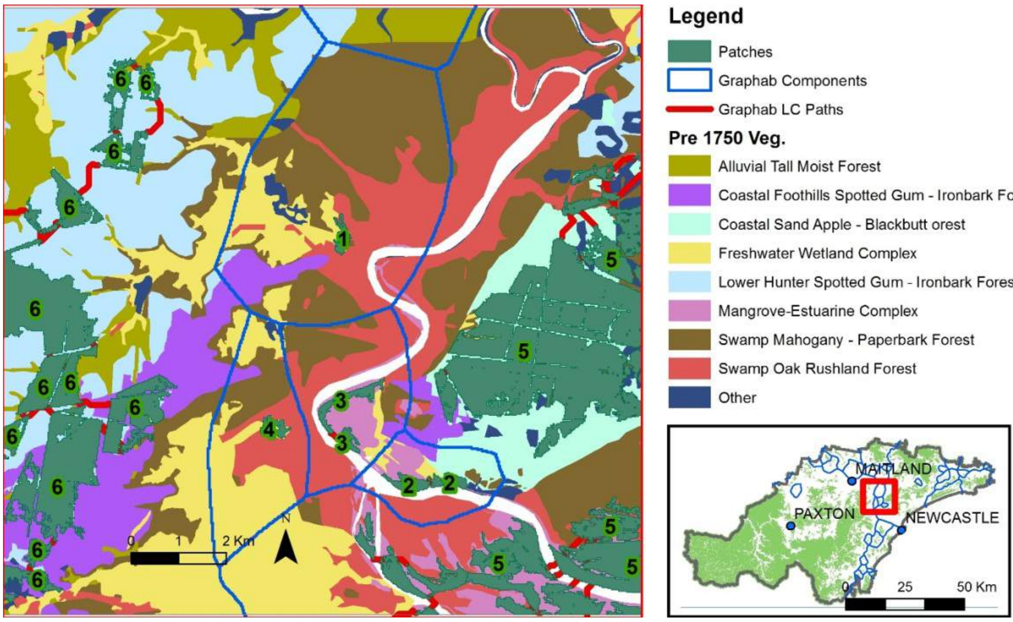


Figure 27 **Pre-1750 vegetation cover within area of interest for Circuitscape analysis of connectivity between six key components (groups of isolated patches) in the centre of the region. Links identified at regional scale using the Graphab software are shown as s red lines. Pre-1750 vegetation mapping was used to ensure that any future restoration is not proposed in areas that would not support woodland and forest communities modelled using the general connectivity model.**

The Circuitscape analyses found high connectivity values near focal nodes (patch locations), where dispersal costs were low, along pathways that have short distances between remnants and at pinch points where there were few options for dispersal (Figure 28). Connectivity pathways from the east to west appear to have high redundancy (identified by low connectivity values). In contrast, options for connecting the western component (Component 6) may be limited as demonstrated by two pinch points of high connectivity values. Finally, the middle section has the highest connectivity values, partly due to its importance for connecting multiple components, its high land cover costs and the presence of areas with no connectivity due to a lack of structural connectivity elements, resulting in bottlenecks.

Characterising Potential Future Connectivity with Local-Scale Analysis

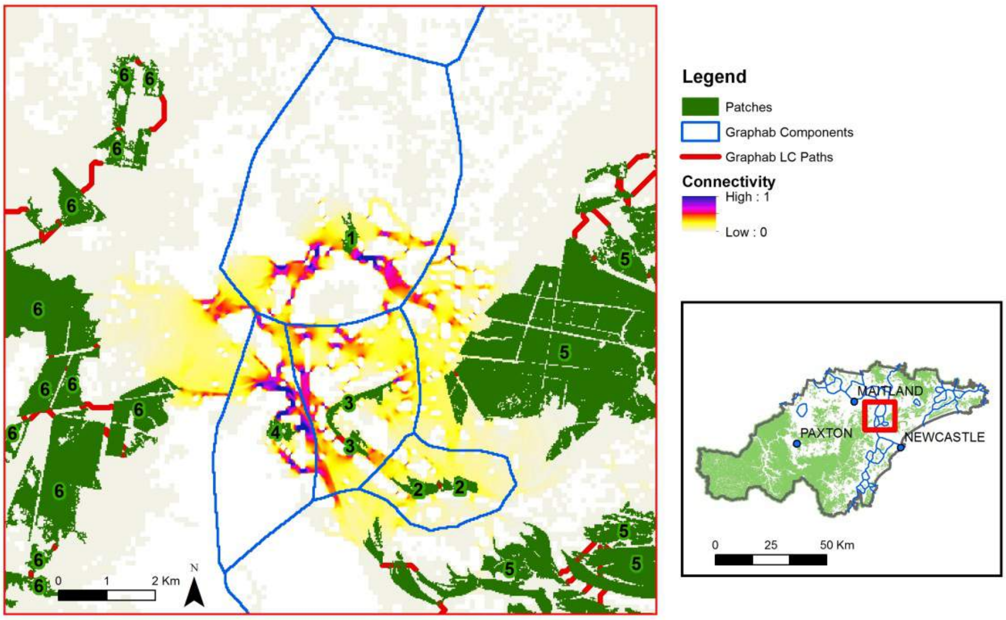


Figure 28 Connectivity between six key components (groups of isolated patches) in the centre of the region calculated using the Circuitscape software. Links identified at regional scale using the Graphab software shown as red lines.

Identifying current pathway redundancy

The Graphab connectivity analyses identifies the single most optimal least-cost path between two patches but does not indicate if there is path redundancy, that is, the presence of multiple possible routes between patches. Using Circuitscape, we selected an area at random to demonstrate its application for this type of analysis (Figure 29). The Circuitscape analysis shows that connectivity values are relatively homogenous across most of the fragmented area in the middle. The area is predominantly grazing with scattered trees that provide structural connectivity and allow for dispersal. Pinch points to the north-east represented by high connectivity values are largely the result of human activity. The satellite data shows the presence of a farmstead and a private horse-training racetrack and fewer scattered trees.

Characterising Redundancy Using Local-Scale Analysis

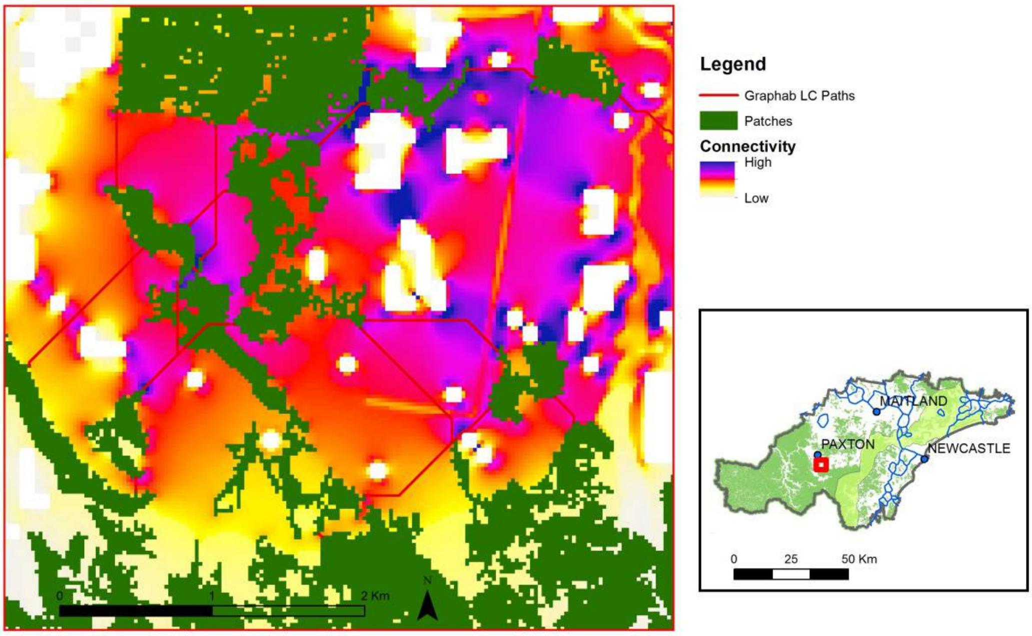


Figure 29 **Example of using Circuitscape to characterise redundancy or multiple options for connectivity in the form of least-cost paths previously identified using Graphab. Connectivity was modelled between eleven patches. White pixels represent zero connectivity.**

2.4. Discussion

2.4.1. Overview

The regional-scale, graph-network connectivity analysis found that the large vegetation patches to the west of the Hunter dominate the graph metrics, emphasising the importance of these patches for connectivity. These areas are important ecologically as the majority of vegetation within the region is contained within these patches, and due to their large extents, they link many of the smaller patches. The three largest patches found in this component contain 65% of the patch area in the Lower Hunter (Figure 12, A, B and C). The analyses also found that these patches to the west were part of a component that was relatively well connected at the regional scale. This component includes 80% of the patch area in the Lower Hunter (Figure 12, Component 1 and 2). However, the remaining vegetation in the Lower Hunter appears to be highly fragmented especially within the centre of the region from the north in Branxton to Morisset in Lake Macquarie. This area is composed of small isolated interlinked patched that form a barrier to connectivity between the component to the west and the second largest component in the east that accounts for 11% of the total patch area in the region. These fragmented areas in the centre of the Lower Hunter are also where the majority of agriculture and urbanisation is located and where future development is expected to take place, and therefore of interest for conservation. This area includes the Lake Macquarie LGA (near Toronto, Morisset and Swansea), which is more susceptible to fragmentation due to the presence of the Lake in the centre forming a natural barrier to dispersal.

For conservation planning, the importance of a specific patch can be assessed at the regional scale relative to other patches in the landscape using graph-network metrics such as the Clustering Coefficient, which describes the level of patch redundancy. However, conservation priorities should be assessed within the spatial context of a management action such as a proposed development. This is especially true for the Lower Hunter, where large patches dominate the graph metrics making the relative differences between patches with small areas very minor. In such cases, further analyses are necessary at the component or sub-network scales within a component to assess the relative importance of small patches for specific management actions.

Analyses at the local scale need to account for regional-scale connectivity. The Circuitscape software can be used to complement least-cost paths analyses conducted at the regional scale by identifying path redundancy or bottlenecks between connected patches (McRae et al. 2008). This finer scale analysis is important for assessing whether there is need to preserve vegetation that contribute to connectivity, such as scattered trees, or prevent land use changes that increase dispersal costs. As demonstrated here, Circuitscape is also useful for identifying potential areas for future restoration as it identifies connectivity values beyond the inter-patch dispersal distance threshold.

2.4.2. Application to conservation planning

The methods developed in this study should be considered as part of a conservation planning process, particularly the use of Circuitscape. Where possible, both the input data and the modelled connectivity pathways should be validated in the field. It is with this in mind that connectivity has been modelled; to enable local government authorities and natural resource managers to analyse connectivity using a relatively simple but ecologically robust method. The connectivity model can be considered an instruction manual for connectivity planning, particularly in the Australian context where data such as that in the review by Doerr et al. (2010) can be used as a source of default values for the essential parameters of gap-crossing threshold, patch size and inter-patch distance threshold. While generalised methods are open to misuse in the absence of cautious interpretation of the results, connectivity planning is underway across Australia at small and large scales, often without adequate spatial planning (Whitten et al. 2011). The model described here provides a robust scientific basis for connectivity planning, based on an understanding of the behaviour and habitat needs of a range of species that can be readily applied at landscape and regional scales.

In a review of existing and planned Australian wildlife corridor projects and initiatives, Whitten et al. (2011) identified the challenges of moving from site-scale to landscape-scale conservation based on the operational experience of one particular wildlife corridor, the Slopes to Summit component of the Greater Eastern Ranges Initiative (see www.greateasternranges.org.au). One of the challenges identified in that example was that the skills and ability to characterise connectivity within a geographic information system (GIS) resided outside the organisation, preventing the exploration of GIS data at finer scales in

response to changing circumstances. The method developed here specifically set out to overcome this lack of capacity within organisations on the ground to perform their own connectivity assessments.

2.4.3. Incorporating fine-scale ecological connections for regional and local- scale assessments

The approach described here accommodates fine-scale dispersal behaviour within a regional-scale analysis, unlike most previous studies where dispersal behaviour is characterised at coarser spatial resolutions. This allows for the incorporation of landscape connectivity elements such as scattered trees that have been identified as critical for dispersal (Carruthers et al. 2004; Doerr et al. 2010; Gibbons & Boak 2000), but are only identifiable in fine-scaled spatial data (Lechner et al. 2009). GAP CLoSR can be potentially used to assess: i) the impact of the removal of a group of trees, patch or area of vegetation; ii) the relative significance of a group of trees, patches or areas of native vegetation within a connectivity network; iii) identify where funds are best spent to improve connectivity; and iv) integrate connectivity on a regional and local scale to form a network (as either in isolation is much less effective and may not work).

The inclusion of structural connectivity elements in GAP CLoSR allows for the assessment of lower quality habitat that are often unprotected such as those made up of scattered trees in grazing lands. These habitats may be otherwise excluded from conservation assessments due to the difficulty in assessing their contribution to biodiversity. Furthermore, the ability to quantify the contribution of these elements at fine scales using graph metrics allows them to be targeted through management actions. In addition, fine-scale identification allows these landscape features to be included in development approval processes that usually operate at the local or property scale, often under the jurisdiction of local government authorities.

2.4.4. Complementing least-cost path analyses with circuit theory

Circuitscape provides a method for assessing connectivity over the whole landscape. This would appear to be more useful than the Graphab least-cost path method, which only characterises a single optimal path. The main drawback of the finer-scaled Circuitscape approach is the higher demand for computational resources, which limits the number pixels and the number of patches that can be processed. Additionally, Circuitscape does not allow for the assessment of thresholds based on the inter-patch dispersal distance threshold, which are critically important for assessing the adequacy of conservation networks parameterised using Doerr et al.'s (2010) study.

2.4.5. General connectivity approach

The development of a general connectivity model linking landscape features or land-facets as used in this study addresses the uncertainty associated with the complexity of parameterising a multi-species connectivity model. It follows similar general approaches that have been used in previous studies in Australia (for example, Drielsma et al. 2012). Species connectivity models commonly investigate one or a handful of species, whereas conservation planning commonly

takes a whole of ecosystem approach (for example, DSEWPaC 2012). The general connectivity approach focusing on land-facets for connectivity conservation as opposed to species has been used internationally (Alagador et al. 2012; Brost & Beier 2012) and demonstrated to be more robust for characterising species than multi-species approach elsewhere (Beier & Brost 2010).

This approach taken in this study can be used where the purpose is to identify connectivity networks that are suitable for conserving the majority of species. It is for this reason that the model was parameterised using average dispersal values. This method will not identify connectivity for species with shorter inter-patch dispersal distances, however, these species are often smaller in body size and may be less affected by fragmentation as smaller patches can provide habitat for these species to remain viable. Furthermore, as Doerr et al. (2010)'s review focused on fauna, specifically mammals and birds the connectivity assessment is likely to favour those species. The general approach outlined in this study needs to be complemented with single species models in order to assess connectivity for species of particular conservation concern, such as those listed as matters of national environmental significance under federal environmental law. This approach could also be complemented by modelling of functional dispersal groups if data is available, for example, location method, range size etc.

The general connectivity approach used here is based on default parameterisation based on empirical evidence from Australian woodland and forest ecosystems summarised by Doerr et al. (2010). The alternative would be to develop multiple single-species models to represent the majority of species. This requires either empirical data that is often unavailable (Doerr et al. 2010; Rudnick et al. 2012) or expert opinion that in some cases can be highly uncertain (Zeller et al. 2012). Furthermore, the construction of complete single species models can require many years of research making it unfeasible for a large number of species (Rudnick et al. 2012) and impossible within the timeframes required for conservation planning such as strategic assessments.

Finally, this approach has the potential to accommodate the results of other connectivity modelling carried out at larger extents, such as those developed in Australia by the NSW Office of Environment and Heritage (Drielsma et al. 2012) and the federal Department of the Environment (DSEWPaC 2013).

2.4.6. Sensitivity analyses

In the Lower Hunter Region, the assessment of sensitivity demonstrated that the connectivity network identified at the regional scale was relatively robust to uncertainty in model parameterisation, especially for patches that account for most of the patch area within the region. The greatest differences occurred where inter-patch dispersal distances were changed or the gap-crossing layer was not used. Fortunately, the parameterisation of these more sensitive cases is supported by the empirical research of Doerr et al. (2010). Differences between the dispersal cost for the default case, gap-crossing layer only case, and high

dispersal cost case were minor by comparison. The parameterisation of resistance had less empirical support and was based on expert opinion for a small number of species.

At the local scale, differences in the connectivity between smaller patches were apparent, which introduces some doubt into local-scale decision making. The source of these differences varied with the different sensitivity cases. These sources of variability can be minimised by using Circuitscape and field validation at the local scale, and carrying out quality assurance on the input spatial data layers.

2.4.7. Other limitations and sources of uncertainty

There are several sources of untested uncertainty that need to be addressed in future use of this connectivity model. The mapping outputs are only in draft form and will be updated as feedback is received from end users toward the end of 2014. For example, the canopy cover mapping in Lake Macquarie has been identified as having greater classification error than other parts of the Lower Hunter. The impact of those errors on modelling outcomes need to be tested through incorporating additional fine-scale vegetation data or conducting mapping specifically for these areas.

There are many sources of 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. All of these have the potential to interact, propagate and magnify the uncertainty of the model outputs (Langford et al. 2006; Lechner et al. 2012b; Lechner et al. 2013). Sources of uncertainty specific to connectivity modelling includes least-cost path weighting (Parks et al. 2013; Rayfield et al. 2010), methods for characterising alternative paths (Sawyer et al. 2011) and the need to validate model outputs with biological data.

The ecological parameters used in this study were based on the best available science identified by Doerr et al. (2010). However, further research is needed to assess: a) its general application to different ecosystems, b) applicability to species with a range of dispersal behaviour and c) application to dispersal of plants. Furthermore, the connectivity model assumed dispersal is unidirectional and did not incorporate source-sink dynamics and migration was not dependent on genetic or demographic factors. Uncertainty in characterising connectivity using the patch-matrix and least-cost path assumptions is also an important area for future research. Other authors have suggested using a life-cycle based approach that defines patches and links with respect to a resource used within a specific part of a species life-cycle such as breeding and migration (Zetterberg et al. 2010). Alternative approaches to the patch-matrix paradigm for characterising landscapes include the variegated approach, which has also been used for connectivity modelling (Drielsma et al. 2007). In many instances, there will be great difficulty in utilising these other methods due to the lack of available empirical data.

The model developed in this study should be viewed as one of the many decision support tools for conservation planners. It is important to recognise that the method described here only

models connectivity, and if species persistence is the goal of conservation planning, other methods that reflect the maintenance of processes in addition to connectivity need to be used to complement this approach such as population viability assessment (for example, Akcakaya 2002; Southwell et al. 2008).

2.5. Conclusions

This connectivity model was developed through engagement with stakeholders in multiple levels of government and non-government organisations engaged in connectivity planning. The result of this consultation was the development of an approach to connectivity modelling that attempts to balance ecological complexity and robustness with usability and computational efficiency. The method presented here provides a nested approach to assessing connectivity at regional and local scales that preserves the ecological integrity of dispersal behaviour that is determined at fine spatial scales. Connectivity planning should be seen as part of an ongoing process rather than a single static map identifying priority locations for maintaining and restoring connectivity. Connectivity planning needs to be considered as part of a broader conservation planning process that incorporates ecological, societal and economic drivers of conservation.

Chapter 3
Multi-criteria connectivity planning: Combining multi-criteria analysis and connectivity science to enhance conservation outcomes at the regional scale

3.0 Abstract

Habitat fragmentation from human activities is a key threat to natural systems resulting in landscapes that support smaller, more isolated populations of native species with reduced population viability and increased extinction risk. Mitigation efforts often focus on the identification and conservation of habitat for structural connectivity such as wildlife corridors and scattered trees used as stepping-stones for dispersal. This study presents a robust decision making framework for engaging in regional biodiversity connectivity planning and implementation using the Lower Hunter, Australia as a case study. The method developed allows for the assessment of a range of scenarios associated with land use practices related to ecological, social and economic interests. The framework is a spatially explicit GIS system - a connectivity model within a multi-criteria decision analysis framework. Such tools are required for connectivity planning which consider ecological connectivity within a whole-of-landscape and cooperative approach to biodiversity conservation.

The application of the method is flexible so that a range of interests may be included depending on the datasets available and the issues that need to be addressed. A range of scenarios was tested with a focus on the impact of future development on connectivity in the Lower Hunter (see box below).

The Land Use Scenarios Examined Using the Connectivity Model

Default Scenario:	The current state of connectivity in the Lower Hunter Region
Scenario 1.	With development contained in Local Environmental Plans
Scenario 2.	With development contained in Local Environmental Plans PLUS selected developments proposed by state and local governments
Scenario 3.	With the Hunter Expressway completed
Scenario 4.	With areas mapped as having high agricultural value excluded from the regional conservation network.
Scenario 5.	Scenarios 2 to 5 combined
Scenario 6.	With development of all mineral and coal titles and applications
Scenario 7.	With only protected areas forming the regional conservation network

These scenarios were related to Guiding Principle 2 (Corridors should be designed and implemented in ways that benefit local communities) and Guiding Principle 4 (Cross tenure without affecting property rights). The results of this analysis indicated that proposed future development is likely to affect connectivity within the Lower Hunter, resulting in greater fragmentation within the central and Lake Macquarie regions of the study area. The analyses also showed that vegetation outside currently protected areas would need to be conserved to provide connectivity between largely intact areas to the east and west of the Lower Hunter Region. The framework developed and the results of the analyses need to be cautiously interpreted due to uncertainty associated with data quality, future scenarios and our ecological understanding of connectivity. However, the impacts of development scenarios on patterns and graph metrics quantifying connectivity were greater than differences between scenarios associated with uncertainty, as measured using sensitivity analysis (Chapter 2). The framework and the results could potentially be incorporated as part of future planning for development in the Lower Hunter. The method was developed so that it could be readily applied by consultants or government agencies as development plans, data and ecological knowledge change over time and connectivity models will need to be constantly updated.

3.1. Introduction

Fragmentation of natural areas through human activities due to changes in land use patterns result in the creation of a mosaic of patches containing isolated populations of native species with reduced population viability and greater extinction risk (Brook et al. 2008; Caughley 1994; Lindenmayer & Fischer 2007). Depending on the land cover found between these patches, species connectivity may be reduced or prevented. Highly disturbed non-natural areas such as housing developments can reduce dispersal due to avoidance behaviour or increased mortality (Sawyer et al. 2011). The management of patterns and the type of land cover are thus important for reducing the impact of fragmentation on connectivity.

The impact of fragmentation can be modelled using connectivity analysis based on graph-networks (Minor & Urban 2008; Rayfield et al. 2011; Urban et al. 2009) or circuit theory in conjunction with methods that quantify resistance to dispersal between habitat patches (Adriaensen et al. 2003; Sawyer et al. 2011). Connectivity models based on graph theory consider the landscape as a series of patches or nodes made up of suitable habitat versus non-habitat that limit dispersal (Figure 11). Resistance to dispersal within non-habitat is reflected by increasing energetic costs, difficulty or mortality risk of moving across a non-habitat (Adriaensen et al. 2003; Sawyer et al. 2011). Resistance is typically determined by the characteristics of land cover such as the degree of urbanisation. Least-cost pathways are calculated between each node as a function of land-cover resistance. Least-cost pathways seek to avoid land cover with high resistance such as roads.

Schematic Representation of Connectivity Networks using Graph Theory and Assessment of Changes

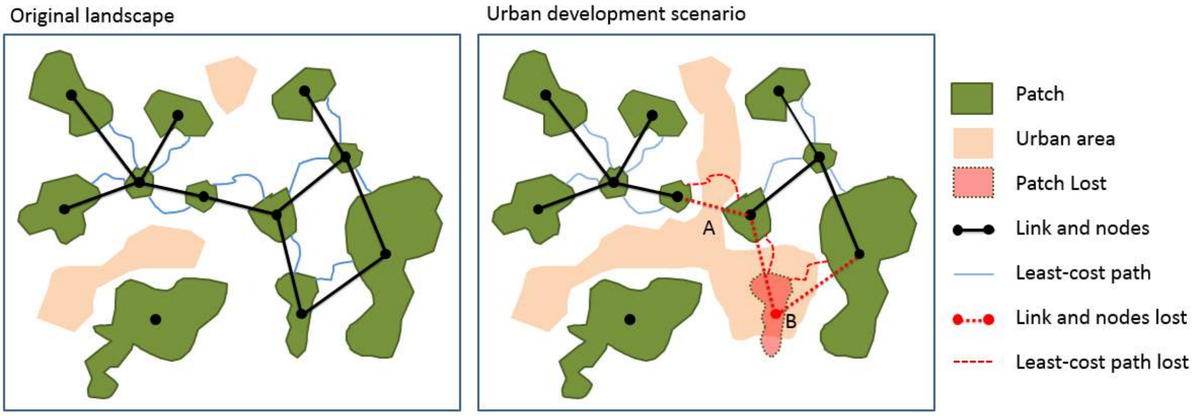


Figure 30 **Graph theory is used to represent patches as nodes and connected patches as links. Actual paths between patches can be represented as least-cost paths. Graph metrics are useful for characterising the contribution of individual patches to connectivity and characterising overall connectivity. 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.**

The objective of a connectivity network for conservation is to maximise connectivity across a region or area of interest. However, competing land uses such as the development of a road network or agricultural intensification may reduce overall connectivity. This chapter focuses on developing a framework that utilises the connectivity model developed in Chapter 2 to evaluate the impacts of different land use scenarios on the quality of a connectivity network. We have coined the term General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) to describe this approach. This is a combination of Multi-Criteria Decision Analysis (MCDA) and connectivity modelling. MCDA methods are used for structuring complex problems in order to explicitly consider multiple criteria used in the decision making process. A key focus of MCDA methods is to quantify the consequences associated with trade-offs between alternative interests and combinations (Lesslie 2012; Linkov 2012; Malczewski 2010). Such tools are required for implementing land use planning and policy, such as the National Wildlife Corridors Plan, which consider ecological connectivity within a collaborative, whole-of-landscape approach to biodiversity conservation.

The aim of this chapter is to test the GAP CLoSR approach in the Lower Hunter, Australia, by assessing a range of land use scenarios. The connectivity model was based on graph-theory with least-cost paths for connectivity at the regional-scale and Circuitscape at the local-scale. This approach is outlined in Chapter 2. An important aspect of the framework design was the creation of a geo-processing workflow that allows for additional data describing land use scenarios to be processed without significant manual effort. This chapter focuses on the development of a method that could examine a range of land use scenarios. These scenarios were tested that result in a reduction of patch area and/or increases dispersal costs through changing land use. The analysis quantified these changes at the regional scale using Graphab (Foltête et al. 2012). A single local-scale example is also provided using Circuitscape software to

illustrate how the impacts of alternative scenarios can be quantified at finer scales (McRae et al. 2008).

3.2. Methods

3.2.1. Background

GAP CLoSR is made up of the connectivity model described in Chapter 2 and a GIS that creates multiple land use scenarios representing stakeholder interests. The MCDA used in this project conforms to the GIS-MCDA approach (typified by Lesslie 2012) that focuses on providing spatially explicit output to facilitate collaborative decision-making. Using the GIS-MCDA approach, we interpreted the guiding principles of the National Wildlife Corridors Plan as reflecting a range of stakeholder interests. These principles range from 'the design and location of corridors should be based on best available scientific knowledge' to 'corridors should be designed in a way that benefit local communities' (DSEWPaC 2012). For each principle, there are one or more interests that can be considered. Some principles, however, do not lend themselves to being modelled in this way as they reflect planning processes as opposed to a stakeholder interest. In practice, these interests should be represented through stakeholder engagement as part of a participatory modelling approach (for example, Mendoza & Prabhu 2005; Voinov & Bousquet 2010).

3.2.2. Connectivity model

The regional-scale connectivity model outlined in Chapter 2 was used to characterise connectivity where habitat was defined as patches of woody vegetation greater than 10 ha in size. The regional-scale model was based on Graphab (Foltête et al. 2012), the graph-network connectivity model, using least-cost paths. The model addresses multiple scale issues associated with characterising connectivity for species that act at fine scales and large extents, yet need to be modelled at coarser spatial resolutions to accommodate the computational limitations of common modelling software and the computers on which they run. The local-scale model was based on Circuitscape, which uses circuit theory to characterise connectivity for all pixels within the region of interest (McRae et al. 2008).

The connectivity networks identified using the model are the products of three spatial data inputs, plus the ecological parameterisation of dispersal characteristics. The inputs are a) dispersal-cost surface based on land use/land cover (LULC) mapping, b) a gap-crossing layer and c) a patch layer (Table 9). The dispersal costs were primarily based on a review by Doerr et al. (2010) and a report from the Port Stephens area by Eco Logical Australia (2012) (see Chapter 2).

Table 9 Ecological parameters and input layers used in the connectivity model (see Chapter 2 for further information).

Description	Value	Source
DISPERSAL DISTANCE		
Patch size	10 ha	(Doerr et al. 2010)
Inter-patch dispersal distance threshold with structural connectivity elements present	1.1 km	(Doerr et al. 2010)
Mean gap crossing threshold	106 m	(Doerr et al. 2010)
DISPERSAL COST SURFACE		
Connectivity elements absent	Infinite	(Doerr et al. 2010)
Other	100%	(Eco Logical Australia 2012)
Hydrology	300%	(Eco Logical Australia 2012)
Transport	200%	(Eco Logical Australia 2012)
Infrastructure	200%	(Eco Logical Australia 2012)
GEOPROCESSING		
LULC 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)
Pixel size for connectivity model	25 m	Based on smallest pixel size that could be processed

3.2.3. Modelling land use scenarios

The impact of land use scenarios, representing different stakeholder interests, on connectivity were simulated by modifying the spatial data inputs to the connectivity model (Figure 31).

Land use change can have a negative influence on connectivity through:

- Decreasing patch size or the removal of patches;
- Increasing dispersal costs by changing the resistance of land cover types from low to high, such as by converting grazing land to urban;
- Removing elements important to structural connectivity, such as scattered trees that allow for dispersal.

While this was not tested in this study, land use change can have a positive influence on connectivity through:

- Increasing patch size or the creation of new patches;
- Decreasing dispersal costs by changing land cover type, such as removing urbanisation and conversion intensive agricultural land use to grazing;
- Adding structural connectivity elements (such as scattered tress) that allow for dispersal.

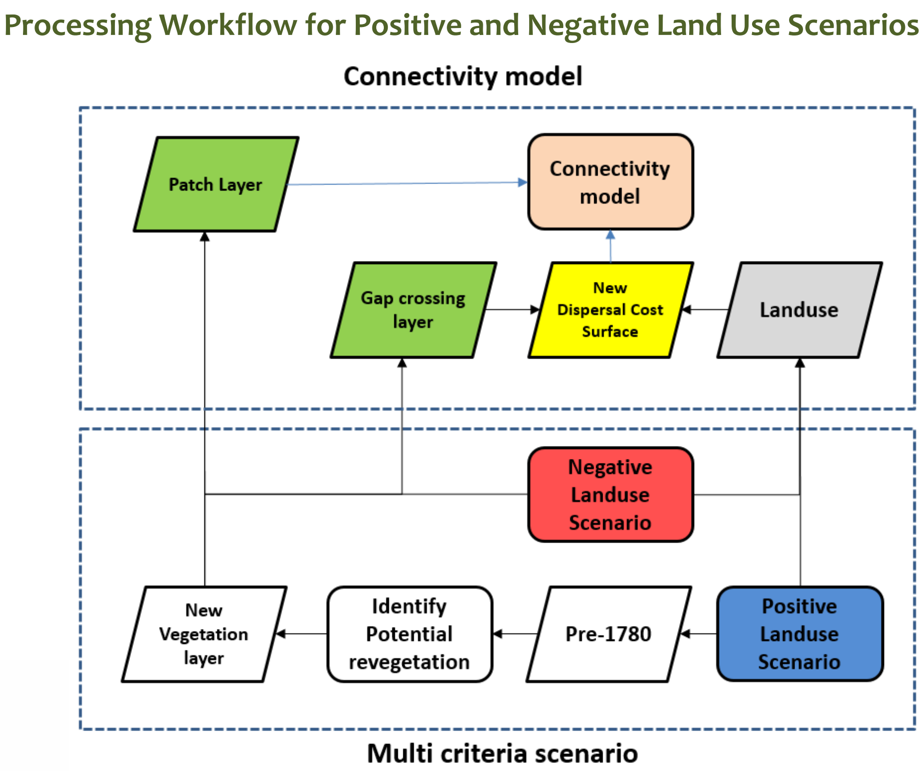


Figure 31 **Processing workflow outlining the relationship between positive and negative land use scenarios and the spatial data inputs to the connectivity model. Positive land use scenarios were not tested in this study.**

3.2.4. Land use scenarios

A range of scenarios were tested by quantifying the change in connectivity resulting from simulating negative changes to land cover and comparing the outcome with existing measures of connectivity (Figure 32). These scenarios provide an example of how GAP CLoSR may be used in response to stakeholder interests.

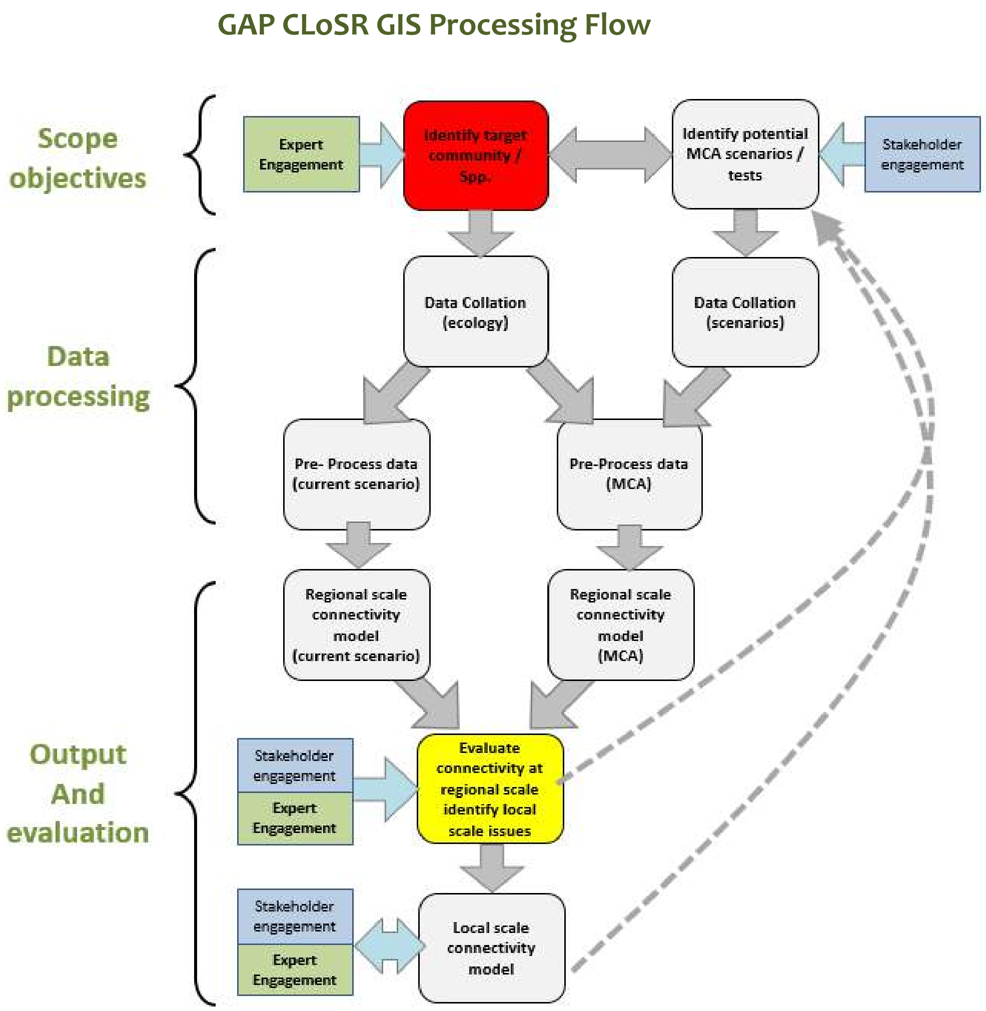


Figure 32 Flow diagram describing the process of scenario development and analysis and the points in which stakeholders and experts could be engaged.

For this report, we tested scenarios reflecting guiding Principle 2 (*Corridors should be designed and implemented in ways that benefit local communities*) and Principle 4 (*Effective corridors connect the landscape across a mosaic of land tenures and land uses without affecting property rights*). These guiding principles were tested through multiple land use scenarios (Table 10). Scenarios 1 to 5 represent potential future scenarios, while Scenario 6 and Scenario 7 identify how different forms of land use and land management contribute to connectivity.

Table 10 Land use scenarios tested in the Lower Hunter and the spatial data processing used to represent them. The scenarios reflect potential land use change (1-5) and the contribution of different land cover types and land tenures to connectivity (6 and 7).

Scenario	Description	Processing
Guiding Principle 2: Corridors should be designed and implemented in ways that benefit local communities		
Scenario 1: Local Environmental Plan (LEP) Development [LEP Dev]	The impact of urbanisation that results in the removal of all vegetation that functions as structural connectivity elements within urban areas identified from LGA LEPs. Assumption: areas zoned for development in LEPs 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: Lower Hunter Future (LHF) Development + LEP Development [LEP Dev + LHF Dev]	The impact of urbanisation that results in the removal of all vegetation that functions as structural connectivity elements within urban areas identified from LGA LEPs and future growth plans (for example, DoP). 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 3: Impact of the Hunter Expressway [Expressway]	The Hunter Expressway is expected to be completed by the end of 2013. This scenario tests the impact of highways and expressways posing a barrier to connectivity.	Creation of 100 m movement barrier based on express way centreline with infinite dispersal costs
Scenario 4: Avoid Important Agricultural Lands [IAL]	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'. We included the following IAL layer: Broad Acre Agriculture, Cultivated Turf, Viticulture, which are restricted by biophysical conditions. 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 5: Lower Hunter Future (LHF) Development + LEP Development + Expressway + Agricultural Lands [LEP Dev + LHF Dev + Expressway + IAL]*	All the above scenarios were incorporated into a single scenario.	See above
Scenario 6: Mineral and Coal Titles and Applications [Mining]	Areas with mineral titles, mineral applications, coal titles and coal application were removed from the analyses as	Removal of vegetation and change in land use

Scenario	Description	Processing
	representing habitat. Assumption: all land in this class will experience removal of vegetation and change in use to mining	value except in areas of pre-existing transport, hydrology and Infrastructure.
Guiding Principle 4: Cross tenure without affecting property rights		
Scenario 7: Protected Areas Only [Protected Areas Only]	Connectivity between vegetation in protected areas only was tested. Protected area includes: National Reserves, State Reserves, Regional Park, Forest NSW Protected areas, Flora Reserves, Aboriginal Area, state environmental planning policy protection (No.14 – Coastal Wetlands, No. 26 –Littoral Rainforest, No.71 – Coastal Protection), Ramsar Wetlands and heritage areas, and Private Land Conservation.	Dispersal limited only by inter-patch dispersal distance threshold (1100 m). Gap-crossing elements always available.

3.2.5. Comparing scenarios

The graph theoretic perspective (Minor and Urban 2008; Rayfield et al. 2010; Urban et al. 2009) was used to measure differences in connectivity for each scenario. Graph-networks are useful to characterise connectivity within landscapes by identifying patterns that are ecologically significant and patterns that may have consequences for conservation planning. The complex patterns resulting from the location of habitat nodes and the links between multiple nodes across a network can be quantified using graph metrics. A wide variety of graph metrics have been developed to describe these patterns (Rayfield et al. 2010). These measures can be calculated at multiple scales from patch (also referred to as node) to component (multiple isolated patches) and network.

A quantitative assessment using graph metrics and a qualitative assessment of the least-cost pathways and components was used to evaluate connectivity differences between scenarios. For each scenario, a range of network-scale graph metrics was calculated (Table 11). The magnitude of the difference between these metrics was used to assess the sensitivity of connectivity to the different scenarios. The metrics were chosen as they represent a range of approaches to characterising connectivity. We chose a combination of two (Route-Specific Flux and Connected Habitat Area) of the four connectivity-property measures that can be used for graph-based analyses identified by Rayfield et al. (2010) (see Chapter 2).

Table 11 Selection of landscape-scale (network) graph metrics used in the study with their definition and ecological significance.

Graph metric	Ecological Significance	Definition	Rayfield et al. (2011) Connectivity characteristic	Reference
Mean Size of Components (km^2)	Simple measure that describes the average component area.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Size of Largest Component (km^2)	A simple measure that describes the area of the largest component.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Number of Components	Simple measure that describes the number of isolated areas in the landscape. High number of components to total number of patches indicate that the landscape is highly fragmented.	Useful for describing the level of isolation between groups of landscape patches.	Route-specific flux	(Urban & Keitt 2001)
Harary Index	The number of patches that contribute to linking patches across the landscape. High value indicate a highly connected landscape.	Sum of the inverse of the number of links between all pairs of patches.	Route-specific flux	(Ricotta et al. 2000)
Class Coincidence Probability	Measure of dispersal relative to component isolation. High value indicate that the landscape is connected.	Probability that two randomly located points are found in the same component.	Connected habitat area	(Pascual-Hortal & Saura 2006)
Expected Cluster Size (km^2)	Indicate the mean area that a disperser has access to. Larger the value the greater the available area.	Area-weighted mean number of nodes within each component	Connected habitat area	(O'Brien et al. 2006)
IIC	Probability that two dispersers randomly located in the landscape within a patch can access each other. Higher value indicate greater connectivity.	Measure of connectivity weighted by area	Connected habitat area	(Pascual-Hortal & Saura 2006)

Mapping at the patch-scale was conducted using two patch-scale graph metrics (Table 12). Based on the previous assessment (Chapter 2), Clustering Coefficient provided a uniquely different characterisation of connectivity patterns compared to all other graph metrics. The other patch-scale graph metric mapped was Node Degree. The other graph metrics were not mapped to simplify the analysis as they were highly correlated with Node degree (see Chapter 2).

Table 12 Patch-scale graph metric used in the study with their definition and ecological significance.

Graph metric	Ecological Significance	Definition	Rayfield et al. (2011) Connectivity Characteristic	Reference
Node degree	Characterises connectedness of a focal patch and its potential accessibility. For example, node degree of zero indicate the patch is a dead end in a pathway.	A simple metric describing the number of links associated with a focal patch	Route-specific flux	(Ricotta et al. 2000)
Clustering coefficient	Measures the level of redundancy within a network. High values indicate that alternative paths exist and pathways through the focal patch is not unique.	Proportion of the neighbours to a focal patch that are also neighbours to each other.	Route-redundancy	(Minor & Urban 2008; Ricotta et al. 2000)

3.3. Results

Default Scenario

The default 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 (Figure 15, Component 1 and 2) representing 91% of the total patch area. These two components are divided by a highly fragmented area in the centre of the region made up of a number of small components. Table 13 lists the graph metrics calculated for this scenario (see Chapter 2 for further explanation). Figure 15 shows the Clustering Coefficient values calculated at the patch-scale and Figure 17 describes the distribution of node degree values.

Clustering Coefficient (number of alternative possible connections) for the Default Scenario

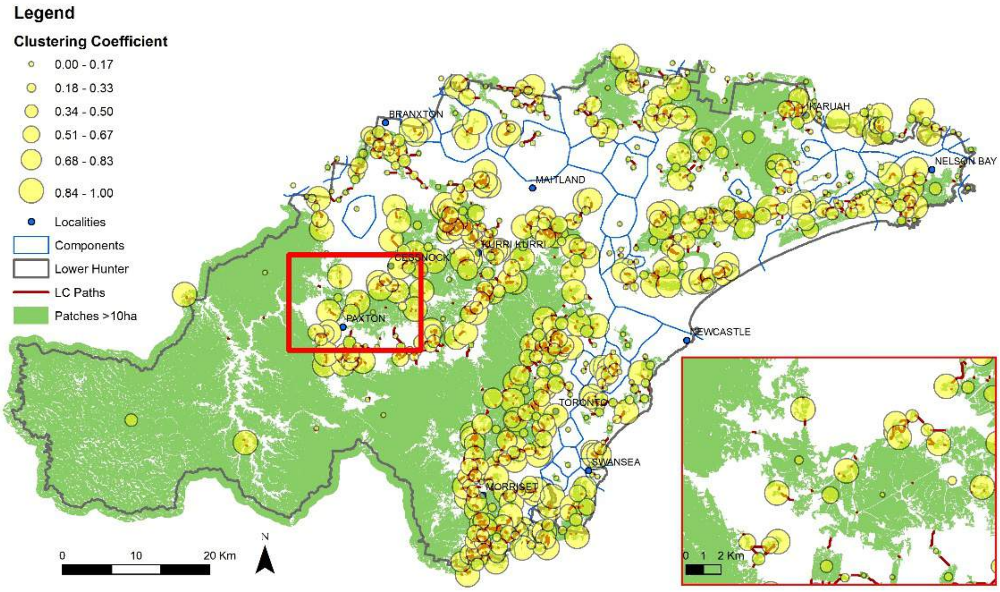


Figure 33 Regional-scale connectivity analysis for the default scenario showing least–cost paths in red for patches greater than 10 ha using Graphab. Circular symbols at the centre of each patch indicate the Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.

Node Degree (number of connected patches to the focal patch) for the Default Scenario

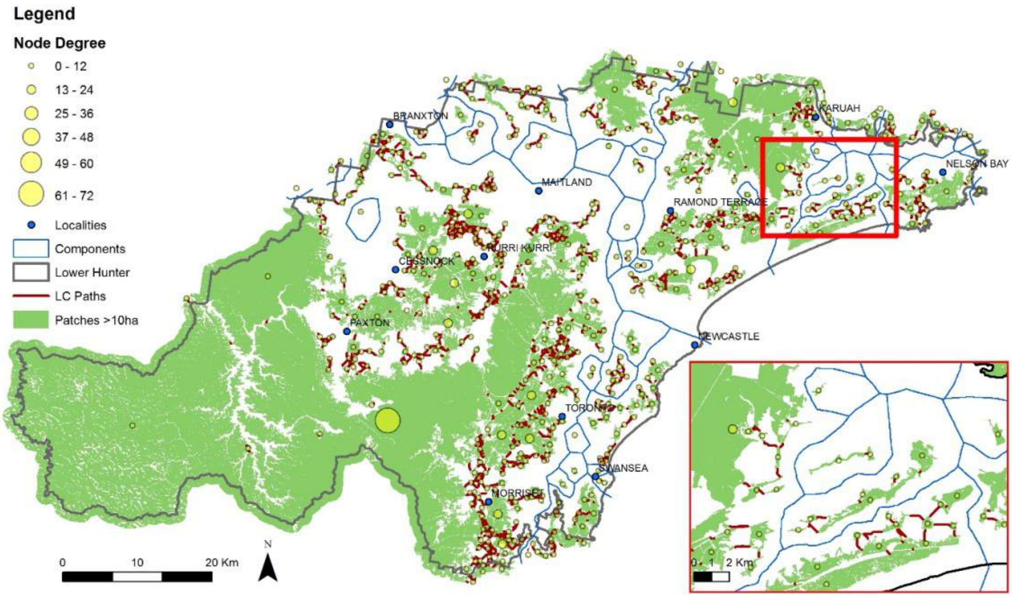


Figure 34 Regional-scale connectivity analysis for the default scenario showing least–cost paths in red for patches greater than 10 ha using Graphab. Circular symbols in the centre of each patch show the size of the Node Degree, which indicates the number of patches to which a focal patch is connected.

Table 13 Landscape-scale (network) graph-metrics and the number of patches for the scenarios tested.

Network characteristic	Default scenario	Scenario 1: LEP Dev	Scenario 2: LEP Dev + LHF Dev	Scenario 3: Expressway	Scenario 4: IAL	Scenario 5: LEP Dev + LHF Dev + IAL + Expressway	Scenario 6: Mining	Scenario 7: Protected Areas Only
Mean Size of Components (km^2)	56	50	36	50	51	29	34	21
Size of Largest Component (km^2)	1885	1842	1779	1846	1818	1692	1046	374
Number of Components	42	46	61	47	45	73	52	40
Harary Index	11954	10621	7915	9715	11646	6399	2755	1558
Class Coincidence Probability	0.651	0.66	0.66	0.63	0.64	0.64	0.39	0.27
Expected Cluster Size (km^2)	1538	1512	1460	1478	1475	1364	677	227
IIC	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.00
Number of Patches	574	579	541	626	580	523	420	271

Scenario 1: Local Environmental Plan Development [LEP Dev]

Scenario 1 describes the impact of development within current LEPs resulting in removal of all vegetation and conversion to urban land cover in all areas marked for future urban development (Table 13, Figure 35 and Figure 36). The most significant impacts of this scenario on graph metrics was the fragmenting the largest patch in Component 1 into two separate large patches (A in Figure 35 and B in Figure 35) as a result of a road corridor (Figure 35 inset). The remote sensing data and the land use data used in the default scenario did not identify these patches as separate. Compared with the default scenario, the distribution of high Node Degree values became less concentrated in the large patches due to fragmentation. However, these patches still had high Clustering Coefficient values indicating low path redundancy. The impact of LEP development on connectivity was as much a property of the amount of development as the location of the development. For example, in the Port Stephens area, a large area identified as LEP development had little impact on connectivity as it had little impact on the least-cost paths (Figure 35 and 36, between Raymond Terrace and Karuah). Overall there was a reduction in most connectivity measures except for the number of patches, the number of components that showed a decrease in overall connectivity across the Lower Hunter, and new components created as development isolated previously connected patches.

Clustering Coefficient (number of alternative possible connections) for Scenario 1 (LEP Dev)

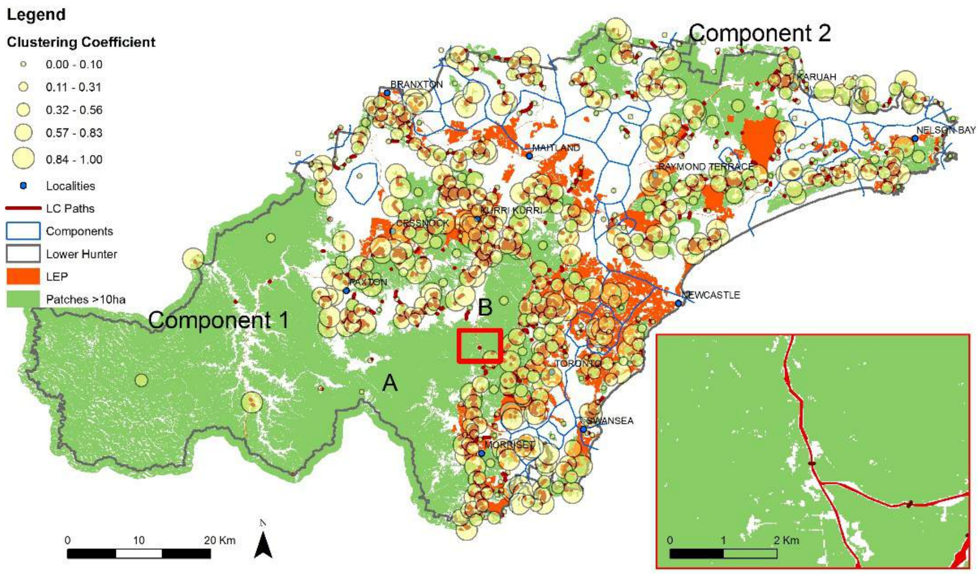


Figure 35 Regional-scale connectivity analyses for 'Scenario 1: LEP dev' showing least–cost paths in red for patches greater than 10 ha using Graphab. Circular symbols at the centre of each patch show the Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network. The inset shows the location of the road dividing patch A and B.

Node Degree (number of patches connected to the focal patch) for Scenario 1 (LEP Dev)

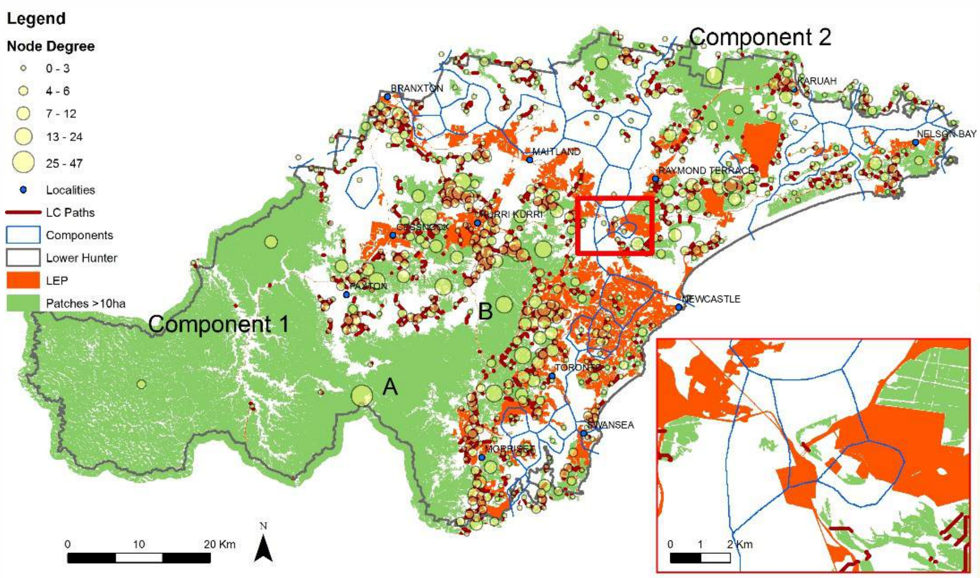


Figure 36 Regional-scale connectivity for 'Scenario 1: LEP Dev' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols at the centre of each patch show the Node Degree, which indicates the number of patches to which a focal patch is connected.

Scenario 2: Lower Hunter Future Development and LEP Development [LEP Dev + LHF Dev]

Scenario 2 describes the impact of urban development indicated in all current LEPs plus future urban development identified by the Department of Planning and Local Government Authorities in the region, resulting in removal of all vegetation in these areas and conversion to urban land cover (Table 13, Figure 37 and Figure 38). This scenario results in even greater fragmentation with an increase in the number of components from 42 to 61. Areas have been isolated around Branxton (A in Figure 37), Maitland (B in Figure 37 and inset) and Lake Macquarie (C in Figure 37). An overall decrease in the landscape-level graph metrics was observed, with values lower than the default scenario and Scenario 1 (LEP Dev).

Clustering Coefficient (number of alternative possible connections) for Scenario 2 (LEP Dev and LHF Dev)

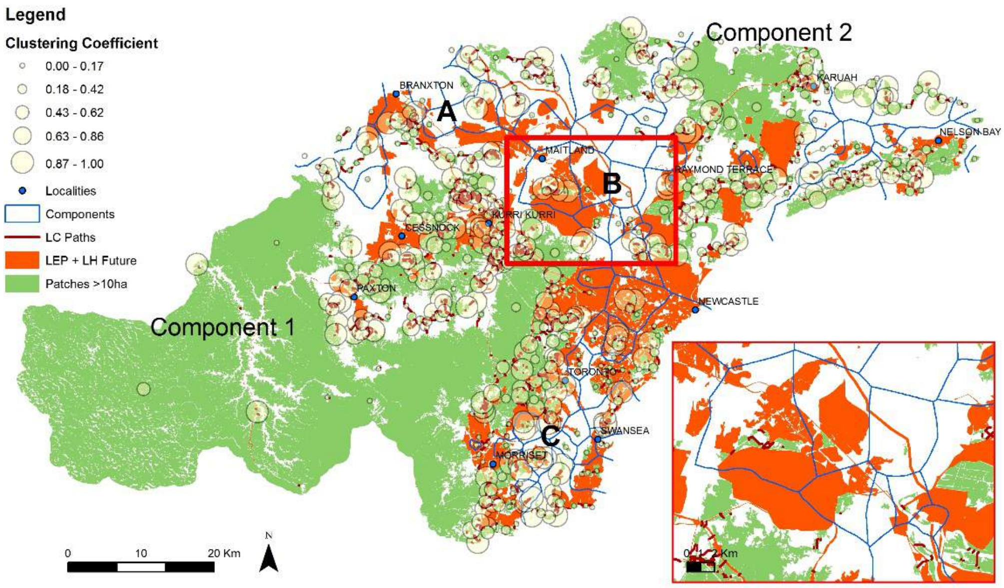


Figure 37 Regional-scale connectivity analyses for 'Scenario 2: LEP Dev and LHF Dev' showing least–cost paths in red for patches greater than 10 ha using Graphab. Circular symbols at the centre of each patch are the Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.

Node Degree (number of patches connected to the focal patch) for Scenario 2 (LEP Dev)

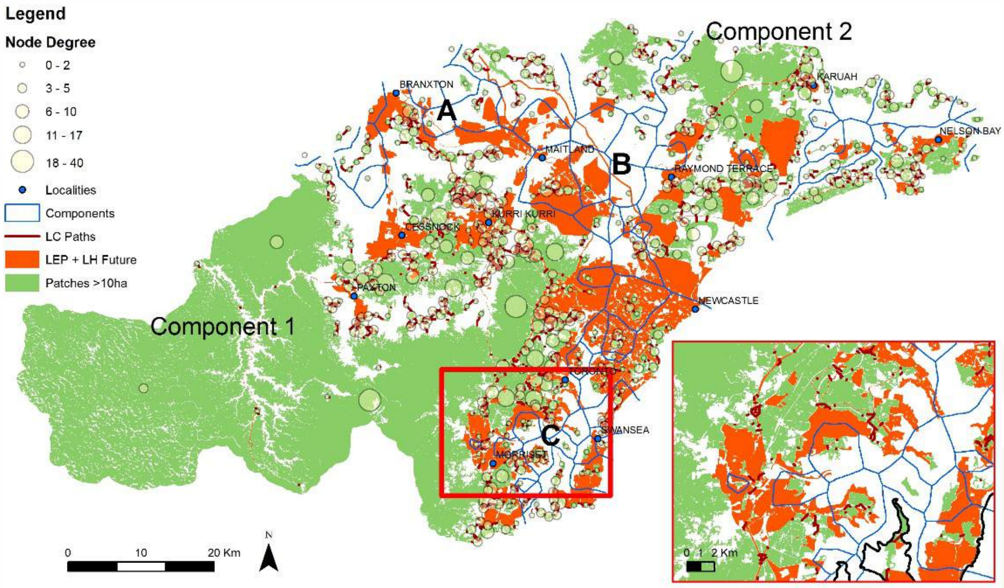


Figure 38 Regional-scale connectivity for 'Scenario 2: LEP Dev and LHF Dev' showing least–cost paths in red for patches greater than 10 ha using Graphab. Circular symbols show the value of the describing Node Degree, indicating the number of patches to which a focal patch is connected.

Scenario 3: Impact of the Hunter Expressway [Expressway]

This scenario quantified the extent to which the Hunter Expressway would pose a barrier to connectivity. Landscape-level graph metrics indicated less connectivity than Scenario 1 (LEP Dev) but greater connectivity than Scenario 2 (LEP Dev + LHF Dev). Multiple new components were created as a result of the barrier posed by the expressway (Figure 39 inset and Figure 40 inset). 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. This scenario demonstrated that the intensity of the impact (for example, dispersal barrier) and the location of the impact (centre of the Lower Hunter) were as important as the total area affected. Differences in patch-scale graph metrics compared to the default scenario were also concentrated around the Expressway.

Clustering Coefficient (number of alternative possible connections) for Scenario 3 (Expressway)

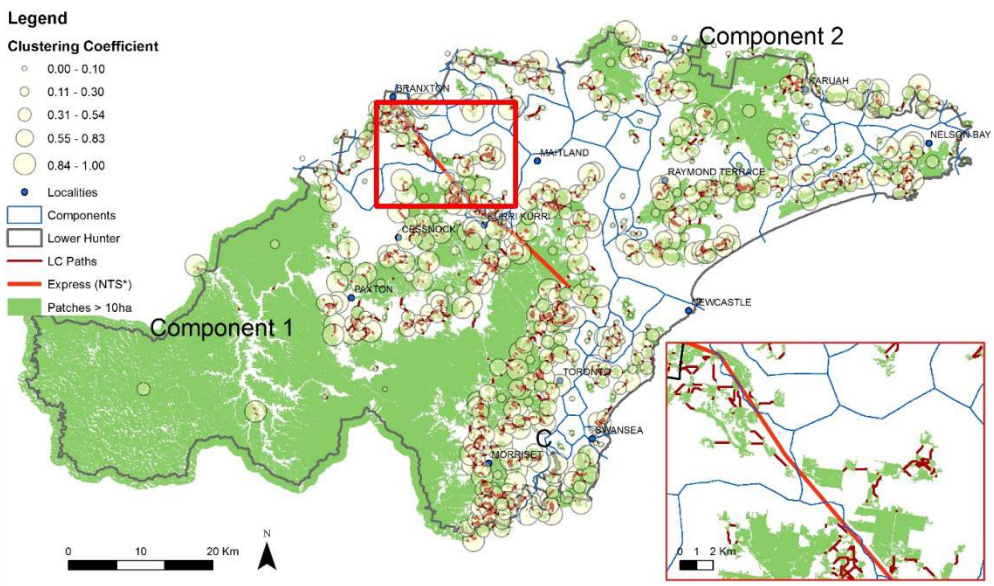


Figure 39 Regional-scale connectivity analyses for 'Scenario 3: Expressway' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network. * Expressway not to scale.

Node Degree (number of patches connected to the focal patch) for Scenario 3 (Expressway)

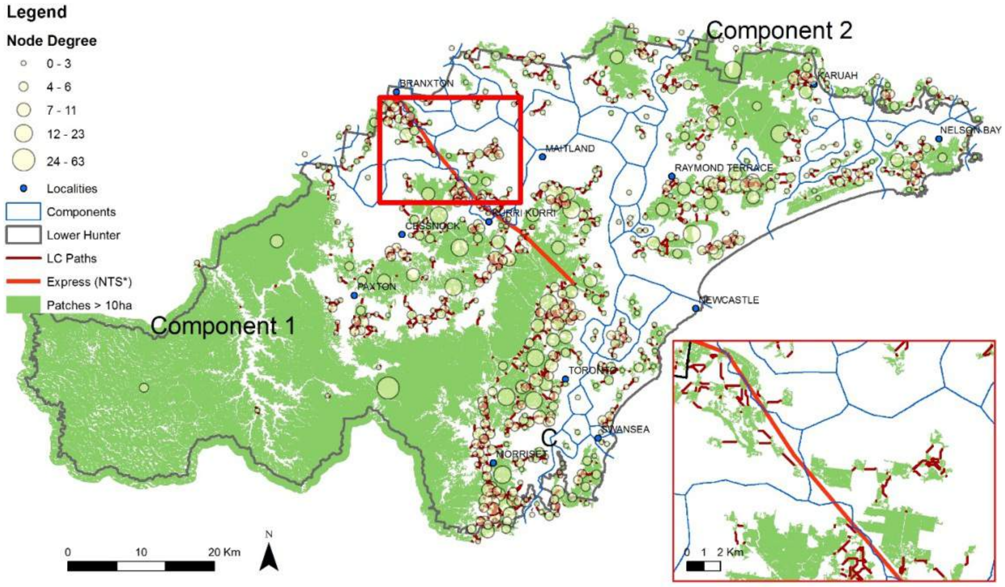


Figure 40 Regional-scale connectivity for 'Scenario 3: Expressway' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Node Degree, which indicates the number of patches to which a focal patch is connected. * Expressway not to scale.

Scenario 4: Avoid Important Agricultural Lands [IAL]

In this scenario, the contribution of 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 Branxton and Maitland. The impact on connectivity was most noticeable through lower values for expected cluster size when compared to Scenario 1 and 3, and higher values for the Harary's Index compared to Scenarios 1, 2 and 3. As with Scenario 3, the differences to patch-scale graph metrics compared to the default scenario were concentrated around a specific area as opposed to across the Lower Hunter Region as was the case for Scenarios 1 and 2 (Figure 41 and Figure 42).

Clustering Coefficient (number of alternative possible connections) for Scenario 4 (IAL)

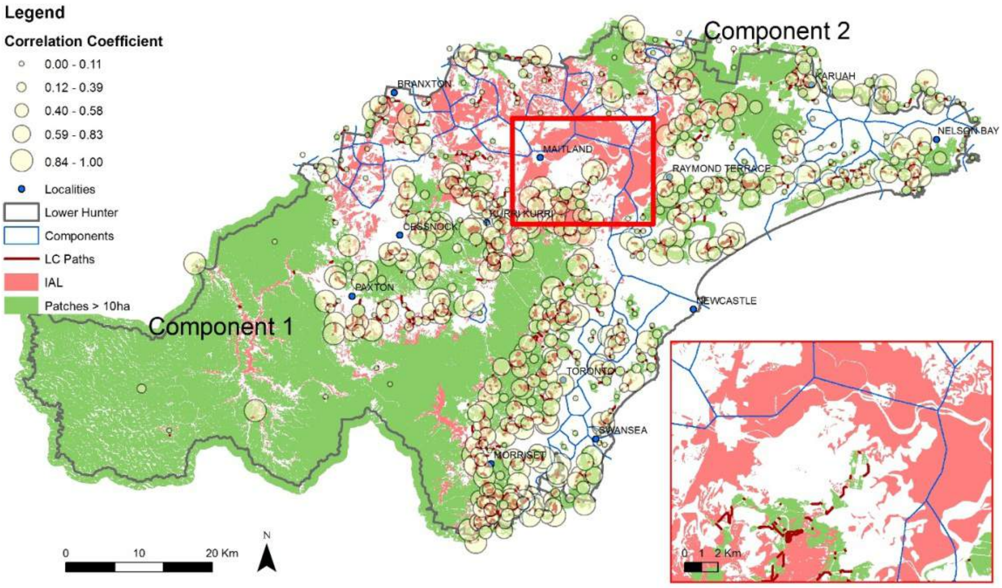


Figure 41 Regional-scale connectivity analyses for 'Scenario 4: IAL' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Clustering Coefficient, an indicator of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.

Node Degree (number of patches connected to the focal patch) for Scenario 4 (IAL)

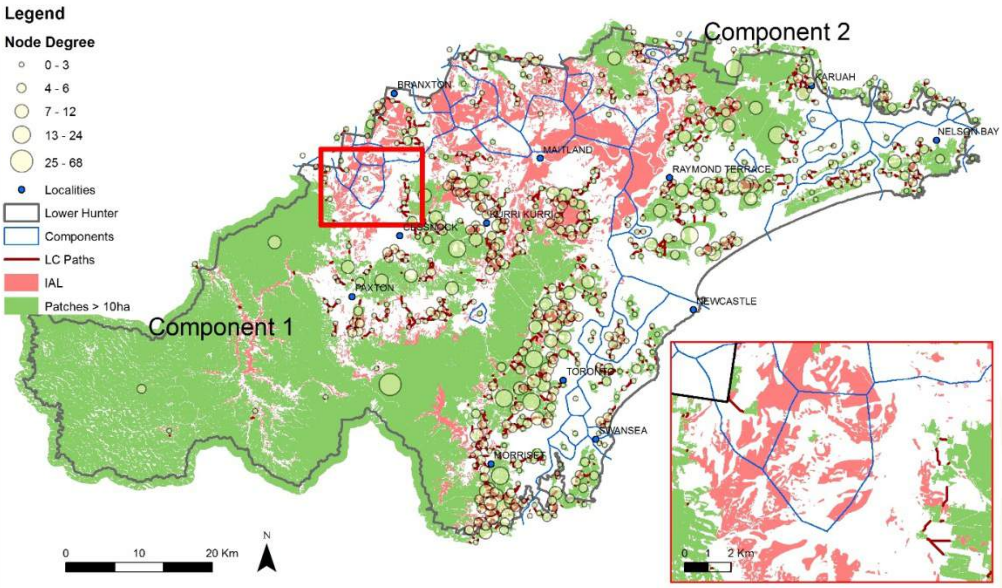


Figure 42 Regional-scale connectivity for 'Scenario 4: IAL' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Node Degree, which indicates the number of patches to which a focal patch is connected.

Scenario 5: All scenarios - Lower Hunter Future Development and LEP Development, Expressway and Important Agricultural Lands [LEP Dev + LHF Dev + IAL + Expressway]

In this scenario, all previous scenarios were included. Graph metric values for all landscape levels were lower than those in all previous scenarios. This scenario results in the most fragmented landscape with the number of components increase from 42 in the default scenario to 73 (Figure 43 and Figure 44). 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 Branxton in the north, to Maitland then New Castle and finally to Lake Macquarie. The impacts are especially concentrated in areas such as Kurri Kurri (Figure 43 inset).

Clustering Coefficient (number of alternative possible connections) for Scenario 5 (LEP Dev + LHF Dev + IAL + Expressway)

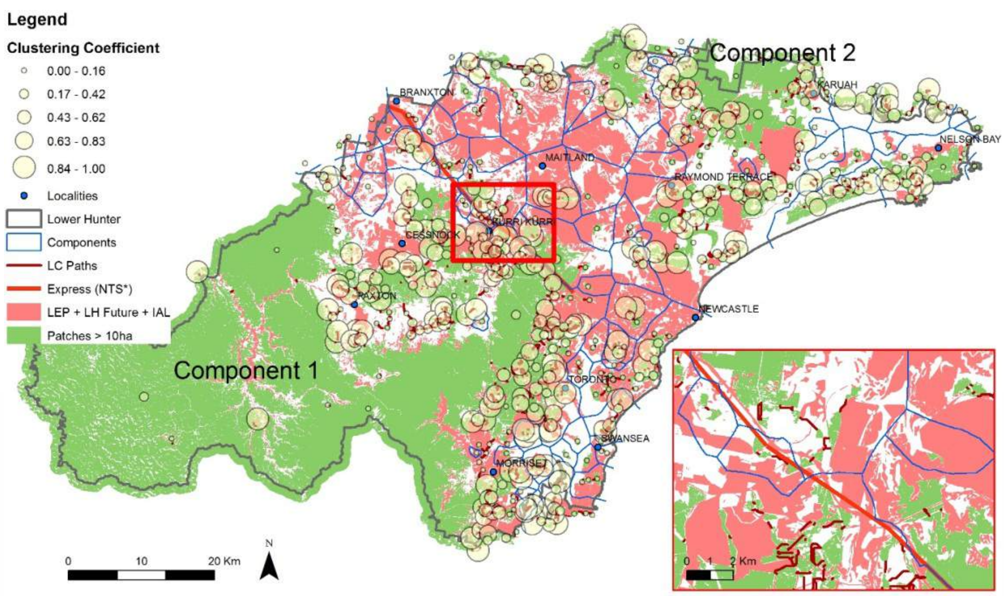


Figure 43 **Regional-scale connectivity analyses for 'Scenario 5: LEP Dev + LHF Dev + IAL + Expressway' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Clustering Coefficient, a measure of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.**

Node Degree (number of patches connected to the focal patch) for Scenario 5 (LEP Dev + LHF Dev + IAL + Expressway)

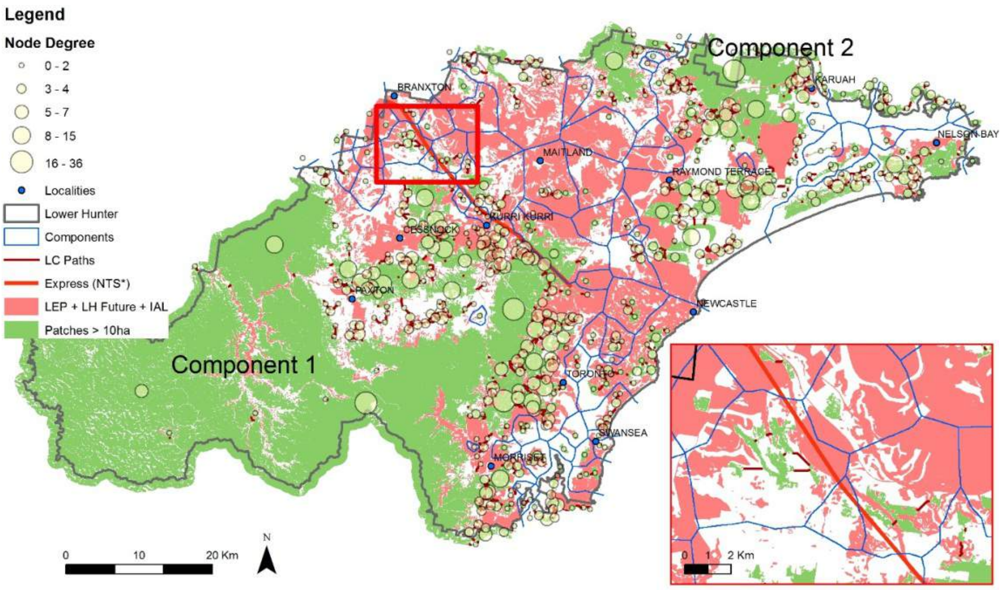


Figure 44 Regional-scale connectivity for 'Scenario 5: LEP Dev + LHF Dev + IAL + Expressway', showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Node Degree, which indicates the number of patches to which a focal patch is connected.

A local-scale connectivity analysis was conducted for the area within the centre of the Lower Hunter for this scenario using Circuitscape. 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. A comparison of local-scale connectivity between the default scenario and Scenario 5 (: LEP Dev + LHF Dev + IAL + Expressway) is shown in Figure 45. The Circuitscape analysis show that the connectivity across the region of interest was constrained to small narrow corridors in Scenario 5, with multiple bottlenecks represented by high connectivity values along these pathways. The development scenarios result in the removal of vegetation predominantly to the west (Figure 44 default scenario - Component 6 and Scenario 5 Component 1) that represented sources of connectivity.

Local-Scale Connectivity in Focal Area for Scenario 5 (LEP Dev + LHF Dev + IAL + Expressway)

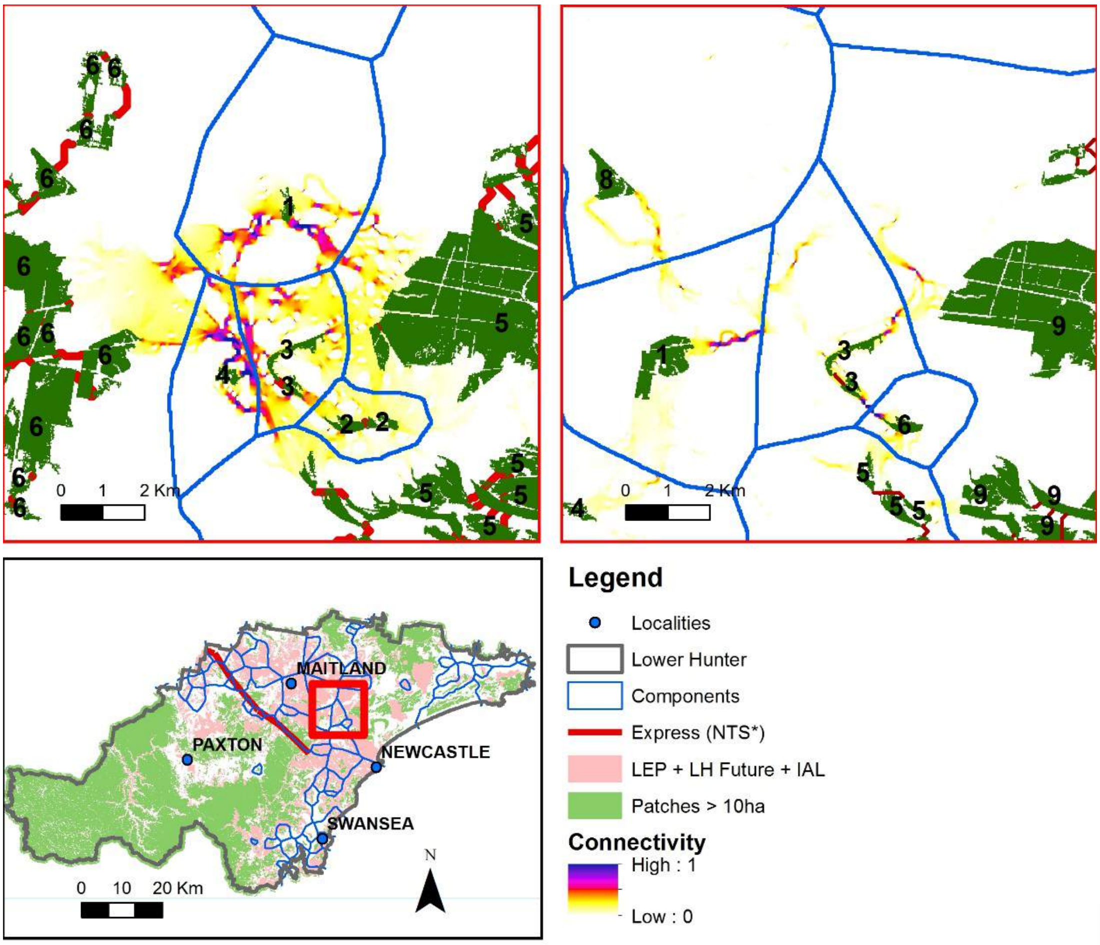


Figure 45 Local-scale connectivity calculated with Circuitscape software between six focal groups of isolated remnants for the 'default scenario' [top left] and nine focal groups for 'Scenario 5: LEP Dev + LHF Dev + IAL + Expressway' [top right]. Links identified with Graphab software are identified in as red lines.

Scenario 6: Mineral and Coal Titles and Applications [Mining]

In Scenario 6, the impact on the connectivity network of removing tree cover within areas with a current mining lease or an application for a coal or mineral lease tested (Figure 46 and Figure 47). This scenario resulted in the in the second lowest landscape-scale graph metric connectivity values of all the scenarios tested (the lowest being Scenario 5, LEP Dev + LHF Dev + IAL + Expressway) primarily due to the large amount of patch area that was lost. As described in Chapter 2, most graph metrics are highly correlated with patch area.

Clustering Coefficient (number of alternative possible connections) for Scenario 6 (Mining)

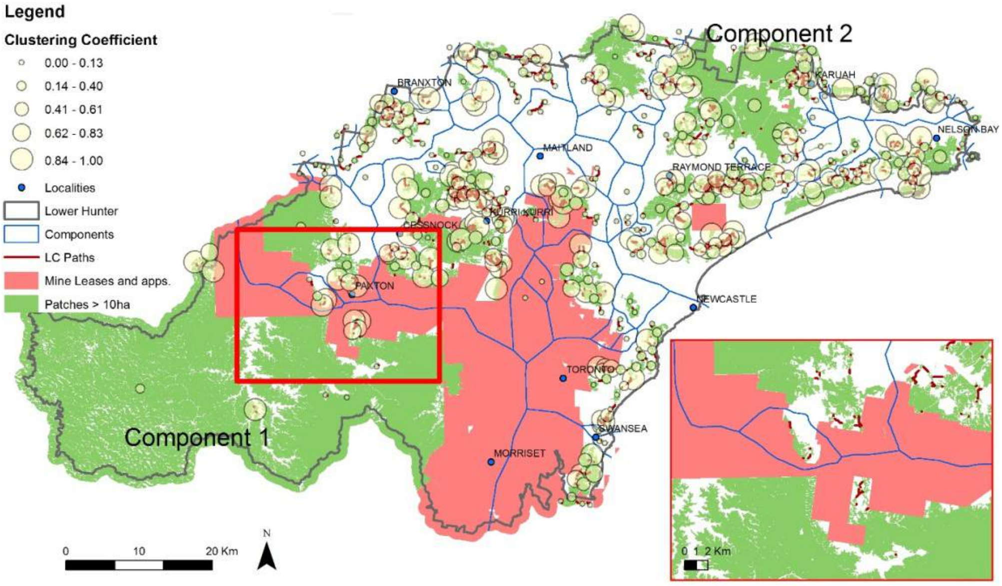


Figure 46 **Regional-scale connectivity analyses for 'Scenario 6: Mining' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Clustering Coefficient, a measure of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.**

Node Degree (number of connected patches to the focal patch) for Scenario 6 (Mining)

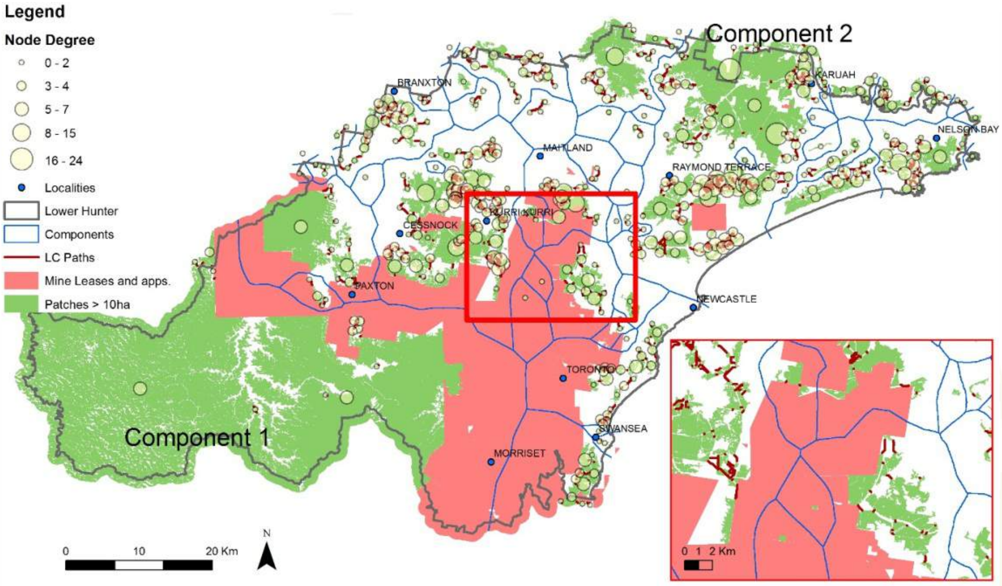


Figure 47 **Regional-scale connectivity for 'Scenario 6: Mining' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols describing Node Degree, which indicates the number of patches to which a focal patch is connected.**

Scenario 7: Protected Areas Only

This scenario characterises connectivity between protected areas only, illustrating an extreme scenario when only those areas protected by their formal conservation status constitute the network of habitat in the region. This scenario demonstrates the extent to which many of the large patches in protected areas are isolated from each other (Figure 48 and Figure 49. In this scenario, there were 271 patches found in 40 components as opposed to the default scenario of 574 patches within 42 components. This scenario had the lowest value for all landscape-scale graph metrics of all the scenarios tested. As in Scenario 6, total patch area was reduced, and as graph metrics are commonly highly correlated with area, their values were also lower.

Clustering Coefficient (number of alternative possible connections) for Scenario 7 (Protected Areas Only)

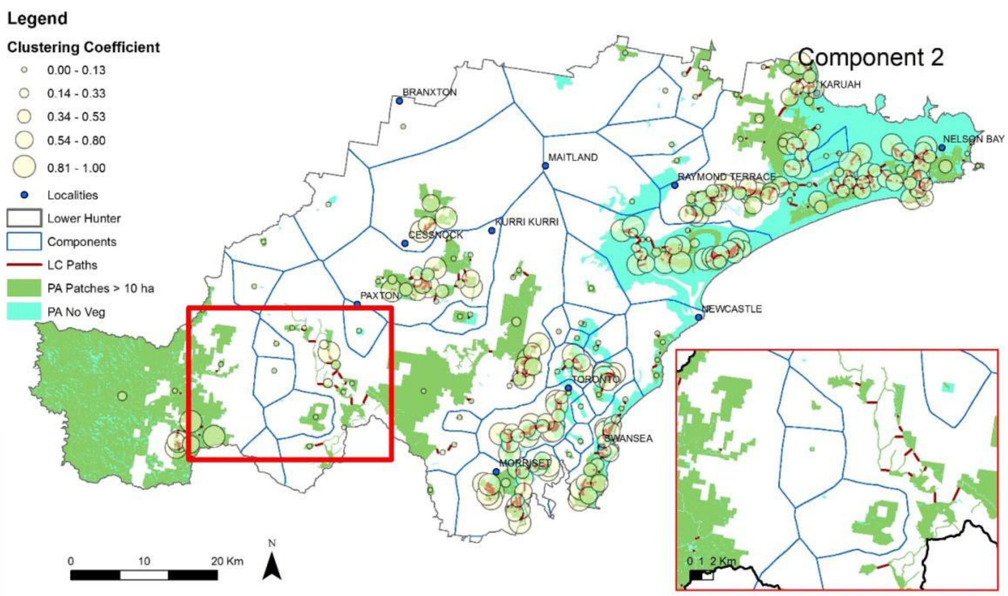


Figure 48 Regional-scale connectivity analyses for 'Scenario 7: Protected Areas only' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Clustering Coefficient, a measure of patch redundancy where the larger the value, the more alternative connections exist between patches in a network.

Node Degree (number of patches connected to the focal patch) for Scenario 7 (Protected Areas Only)

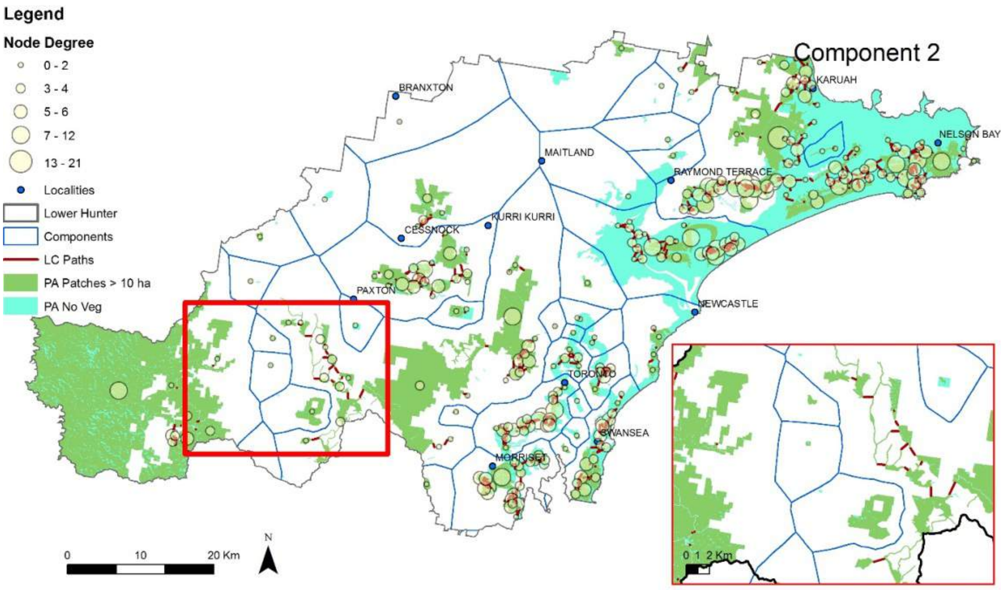


Figure 49 Regional-scale connectivity for 'Scenario 7: Protected Areas only' showing least–cost paths in red between patches greater than 10 ha using Graphab. Circular symbols indicate the Node Degree, which is the number of patches to which a focal patch is connected.

3.4. Discussion

3.4.1. Overview

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 and Lake Macquarie areas within the Lower Hunter. Furthermore, it showed that for some scenarios, notably Scenario 3 (Expressway) and Scenario 4 (IAL), 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 development scenarios (scenarios 1, 2 and 5) tested there will be limited potential to connect the two large components in the east and the west 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) if development proceeds without consideration for improving connectivity. However, a more detailed on the ground analysis at the local/patch scale should is recommended to assess the validity of this conclusion.

The framework presented here is also useful for assessing the contribution of land cover types and management units to connectivity, such as shown in the protected area scenario (6) and the mining scenario (7). These scenarios do not represent realistic future land use scenarios,

but enable quantification of the existing and possible future contribution of those land cover types and management units to connectivity. The protected area scenario shows the extent to which vegetation on private land, lying outside protected areas, is critical to maintaining connectivity across the Lower Hunter. The analysis of the mining scenario shows that the impacts of mining within lease boundaries also has an important role to play in connectivity.

The characterisation of future scenarios represented here assumed homogeneous impacts that did not include heterogeneity in the form of vegetation retention or even restoration that could potentially occur as a condition of actual development. In all of the scenarios, the assumption was made that development resulted in the removal of structural connectivity elements, making these areas a barrier to dispersal. Therefore, there is the potential to address some of the impacts on connectivity through the provision of structural elements important to connectivity as part of the development of these areas. For example, by providing open space areas that can be used 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 that are often lost to future developments.

3.4.2. Conservation planning, land use scenarios and the Guiding Principles of the National Wildlife Corridors Plan

GAP CLoSR provides land managers with a tool to assess the impact of future land uses on connectivity. The framework can be used to guide management decisions by conducting 'what if' scenarios and assessing impacts at a range of scales both regionally and locally. It can also be used to assess the contribution of a range of conservation planning instruments such as in protected areas, offsets and covenants. 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. We recommend that it should be used iteratively at a local scale for development scenarios with a range of stakeholders, as opposed to using it to generate a single regional map. The local-scale output should be used along with the regional-scale output to guide to planning and management decisions. Our approach aligns with other authors that suggest systematic (target-driven) conservation planning products need to be user-friendly and useful if local government officials, their consultants and the elected decision makers are likely to make use of them (Pierce et al. 2005).

The framework should be used alongside other systematic conservation planning tools (Margules & Pressey 2000; Sarkar et al. 2006), be guided by policy and used as part of planning frameworks such as conservation action plans (see The Nature Conservancy 2007) and stakeholder engagement. The focus of the development of GAP CLoSR was the National Wildlife Corridors Plan, but it may be applicable to any connectivity conservation-planning scenario. In this report we specifically tested guiding Principle 2 (Corridors should be designed and implemented in ways that benefit local communities) and Principle 4 (Cross tenure without affecting property rights), while guiding Principle 3 (Multi-scale: local, regional and national) and Principle 5 (Corridor design based on science, traditional knowledge and local experience) were implicitly addressed as part of Chapter 2 through the development of the

connectivity model. Principle 3 and Principle 5 have the potential to be tested as scenarios through using different ecological data and connectivity modelling methods.

3.4.3. Participatory approach using MCDA-GIS

The MCDA approach developed for this project is best used with scenarios developed by stakeholders, where the final scenarios tested are a combination of a range of stakeholder interests. Participatory tools such as GAP CLoSR try to satisfy multiple-objectives related to the interests of multiple-stakeholders through a shared decision making process. They provide a method for facilitating decisions in order to explicitly account for the needs of multiple individuals or groups of individuals in the decision making process, with a focus on eliciting values, understanding the trade-offs and relationships and exploring potential outcomes (Lesslie 2012; Mendoza & Martins, 2006).

In this project, the MCDAs methods we employed were relatively simple, with a focus on MCDA GIS. Geographic Information System based Multi-criteria Decision Analysis (GIS-MCDA) is a specific type of MCDA that combines the value judgments based on decision maker's preferences using the MCDA approach with spatial data (Malczewski 2010). This approach is particularly well suited to natural resource management and conservation. The GIS-MCDA (for example, see Lesslie 2012) is more suited to small-scale applications where collaborative decision-making among stakeholders is practical and needed, especially where balancing priorities (social, economic, ecological etcetera) is important.

3.4.4. Limitations and future research

A key future research task is to develop methods for assessing uncertainty in the input maps and the parameterisation of scenarios. Where particular input data can be identified as a source of uncertainty, new data can be gathered to make the outputs more robust. Furthermore, more realistic scenarios can be developed that better describe impacts on dispersal costs and patch area. For example, incorporating viaducts on the expressway that allow for dispersal will provide a more accurate modelling result. Future work the second case study region, the Tasmanian Midlands, will concentrate on the multiple aspects of uncertainty that are associated with scenario development, along with existing forms of uncertainty in the connectivity model identified in Chapter 2.

3.5. 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. GAP CLoSR provides a tool for conservation biology that can be used in conjunction with other planning processes to highlight the likely consequences of alternative scenarios for biodiversity and to identify interventions that have least impacts for conservation in the face of other needs and interests.

Chapter 4
Synthesis and future directions

4.0 Summary

This project set out to develop a framework capable of assessing connectivity at regional-scale to provide a defensible, scientific basis for wildlife corridor planning, and incorporating a range of other values and interests such as described in the seven principles of the National Wildlife Corridor Plan (DSEWPaC 2012). This has been achieved by developing a connectivity model that can be used to carry out GIS based multi-criteria analysis. Called the General Approach to Planning Connectivity from Local Scales to Regional (GAP CLoSR) framework; this framework is targeted at government and non-government natural resource management organisations and runs with commonly available spatial data and computer hardware and requires non-specialised GIS expertise. Enabling these organisations to conduct their own spatial analysis of connectivity has been recognised as important to the success of wildlife corridor projects (Whitten et al. 2011). Furthermore, the nature of conservation planning and assessment, such as strategic assessment and regional sustainability planning, means that limited time is usually available to develop and run such models as inputs to the planning process. GAP CLoSR was developed with these considerations in mind by taking a pragmatic approach that balances the needs of simplicity and generalisability with a robust approach to representing the connectivity requirements of a wide range of species using the best available ecological knowledge.

This report described the development of the prototype GAP CLoSR Framework, which includes a connectivity model and ArcGIS tools for preparing input data (Chapter 2). This report also demonstrated the capacity of GAP CLoSR to explore the implications of different development and conservation scenarios on connectivity using the Lower Hunter Region of New South Wales as a case study. In practice, the scenarios would ideally be developed and explored in collaboration with stakeholder representing a range of different interests. In this instance, the scenarios were based on publicly available plans and proposals plus discussions with stakeholders, and were chosen to demonstrate the framework rather than design connectivity networks for conservation or produce recommendations. The mapping outputs from this project are in draft form and will be updated toward the end of 2014 addressing sources of uncertainty identified from end-user feedback.

Table 14 provides list the guiding principles in the National Wildlife Corridors Plan and the available spatial data that could potentially be used for developing scenarios. Future work in the Lower Hunter Region could potentially use GAP CLoSR in conjunction with recently commissioned community values mapping (Raymond & Curtis 2013), as well as distribution modelling 597 species currently being undertaken by the Environmental Decisions NERP Hub (www.nerplandscapes.edu.au/system/files/ED%20-%20Biodiversity%20Assessment%20-%20Information%20Sheet.pdf). This research will be published in separate peer-reviewed papers due to the complexity of integrating these methods within the short time frame required for the delivery of this report.

Table 14 The guiding principles from the National Wildlife Corridors Plan showing spatial data that could potentially be used to represent them within the General Approach to Planning Connectivity from Local Scales to Regional.

Guiding Principle	Analysis objective	Spatial Data Description
1. *Incorporating community activities* Building wildlife corridors across Australian landscapes is a cooperative endeavour*	Integrate local, state, NGO and private landholder conservation initiatives proposed and operating to ensure cross-jurisdictional and cross-community support for corridor conservation activities.	Local and state corridor plans – map of local wildlife corridors# Planned offset locations – map of planned offsets# Natural restoration and management areas managed by NGO and private landholders - map of areas currently undergoing restoration or management by NGO groups such as greening Australia and Landcare#
2. *Local Benefits* Corridors should be designed and implemented in ways that benefit local communities*	Include areas identified by the community as significant for conservation or to provide ecosystem services and avoid where possible areas where development is proposed.	Community values mapping (Raymond & Curtis 2013) – maps of social values identified through PPGIS including areas to develop and not to develop. Ecosystem services mapping - maps of ecosystem services provided Planning map – maps development and infrastructure Important agriculture lands
3. *Multi-scale: local, regional and national* Healthy, functioning landscapes require connectivity at a variety of scales	Develop a map of corridor networks at the regional scale and integrate this with national, state and continental wildlife corridor plans.	National, state and continental wildlife corridor planning maps – integrate connectivity networks developed at courser spatial resolutions but larger extent with regional connectivity maps. This ensures that wildlife corridors do not lead to dead-ends at the edge of study area#
4. *Cross tenure without affecting property rights* Effective corridors connect the landscape across a mosaic of land tenures and land uses without affecting property rights	Avoid where possible private land or integrate private land with land conservation programs.	Land tenure mapping and private land conservation mapping
5. *Corridor design based on science, traditional knowledge and local experience*	Integrate areas that provide habitat for species of conservation	MNES patches (conservation target) Species Distribution Models (for example, ED Hub conservation target)

Guiding Principle	Analysis objective	Spatial Data Description
The design and location of corridors should be based on the best available information derived from scientific research, traditional Indigenous knowledge and practitioner experience	significance (MNES listed species, iconic species and species representative of a range of dispersal behaviours).	Zonation modelling output (for example, ED Hub conservation target) EPBC listed ecological communities#
6. *Accommodate climate change* Corridors should be designed to assist native species' adaptation to the impacts of climate change	Develop connectivity model with modelled future habitat and model connectivity between current habitat and future habitat.	Species distribution models based on future climate models # Biophysical climate refugia#
7. *Consider invasive species and fire* Corridor design recognises and manages for potential risks such as those posed by invasive species and fire	Reduce connectivity in order reduce dispersal or invasive spp. and provide fire refugia.	Local and regional fire management# Invasive species mapping

 # indicates future application of GAP CLoSR planned for the Tasmanian Midlands.

*** indicates that only certain aspects of this guiding principle can be quantified spatially.**

In the next phase of this project, GAP CLoSR will be applied to the Tasmanian Midlands. This research will be conducted between October 2013 and December 2014 and include further development of methods to manage uncertainty, incorporation of more sophisticated multi-criteria analysis and the preparation of a user's manual.

A key direction for future research in the Tasmanian Midlands is a more robust assessment of uncertainty in the modelling framework (see below and Figure 49). The aim of this work will be to quantify the limitations of the method and identify the types of ecological knowledge required to achieve greater certainty in the parameterisation of the connectivity modelling. Future research into uncertainty will also include a comparison of the general connectivity approach parameterised with data from mammals and birds to single species models based on a range of other plants and animals not included in the review.

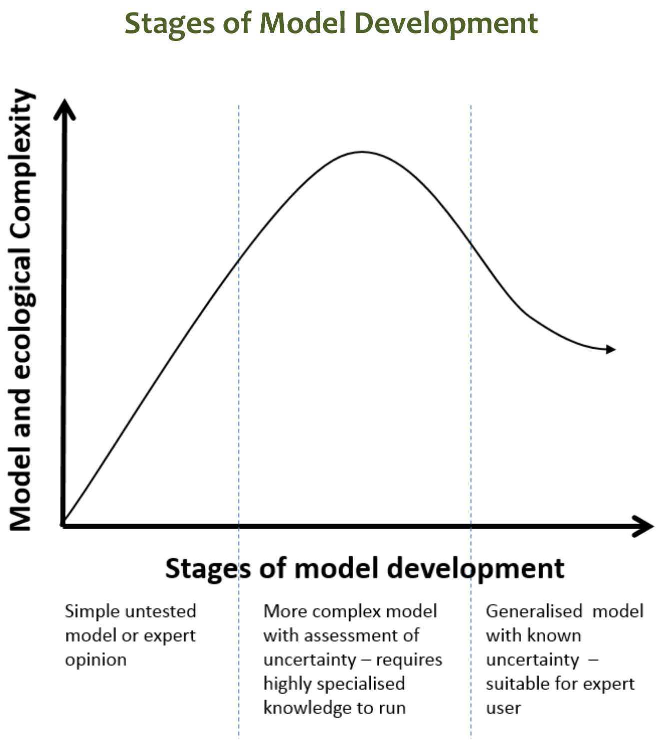


Figure 50 **Stages of model development showing the initial model development phase focused on characterising ecological processes, complexity increasing in the second phase as methods are incorporated to address uncertainty and the final phase in which methods to address uncertainty are implicitly integrated.**

Another important direction for future research is investigating methods of representing multiple stakeholder interests (Section 4.1.3). While care was taken to consult widely during development of GAP CLoSR, a more formal approach will be taken in the development of future scenarios and their spatial representation. Stakeholder engagement will be based on more formal participatory approaches to modelling (Mendoza & Martins 2006) using the MCAS-S multi-criteria software to facilitate this process (Lesslie 2012).

4.1. Outputs of GAP CLoSR

There are five classes of MCCP framework outputs that vary in complexity and level of certainty that may be used to assessment connectivity for conservation planning (Figure 51). The order in which they are interpreted and whether all classes of output will be used depend on the conservation objectives and the context. Generally, an analysis will start by using outputs that have a low complexity of interpretation. 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 distances and landcover between patches. While, 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 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 more complex analyses will be more useful in response to well-defined research questions. For example, what is the effect of this development that results in the removal of a specific set of patches?

Five Classes of Model Output

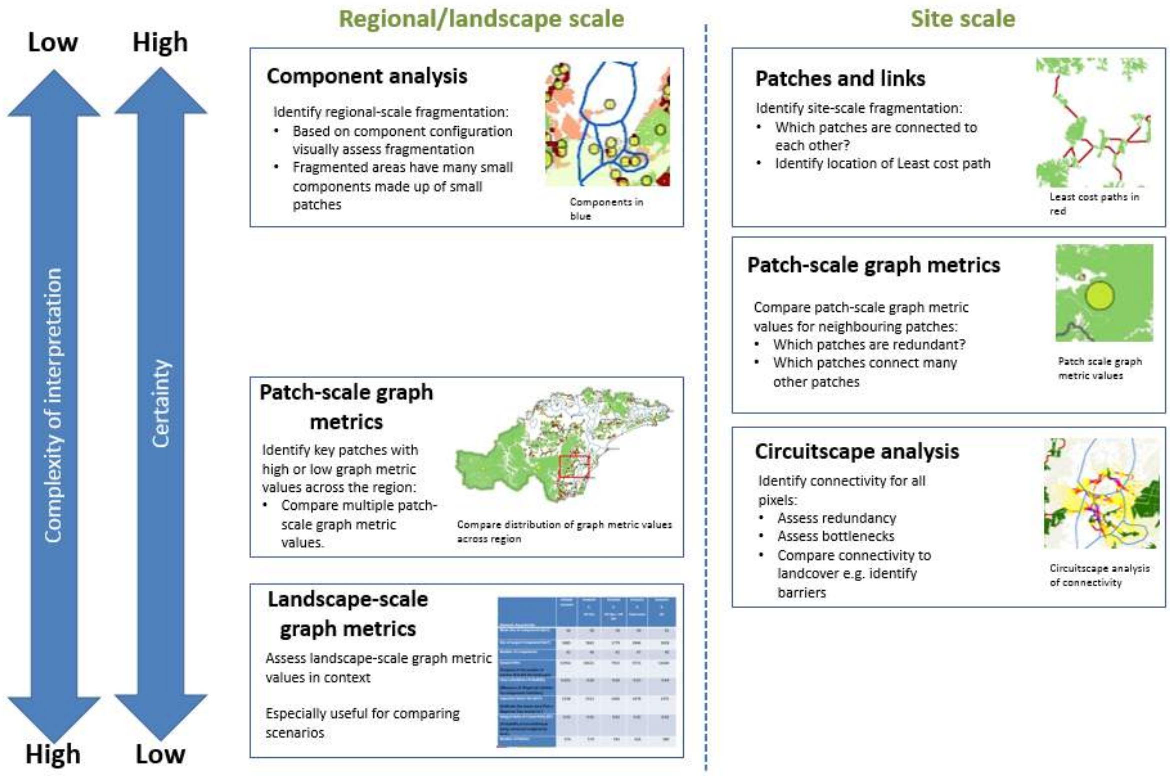


Figure 51 **Summary of the five classes of model output and their complexity and certainty.**

Figures 32--54 provide examples on how the set of outputs from GAP CLoSR may be used within the conservation planning in response to specific research questions/objectives. Future research in the second part of this project will focus on further development of a conceptual framework to support end-users interpreting the multiple outputs of GAP CLoSR for conservation planning.

Identifying Conservation Priorities

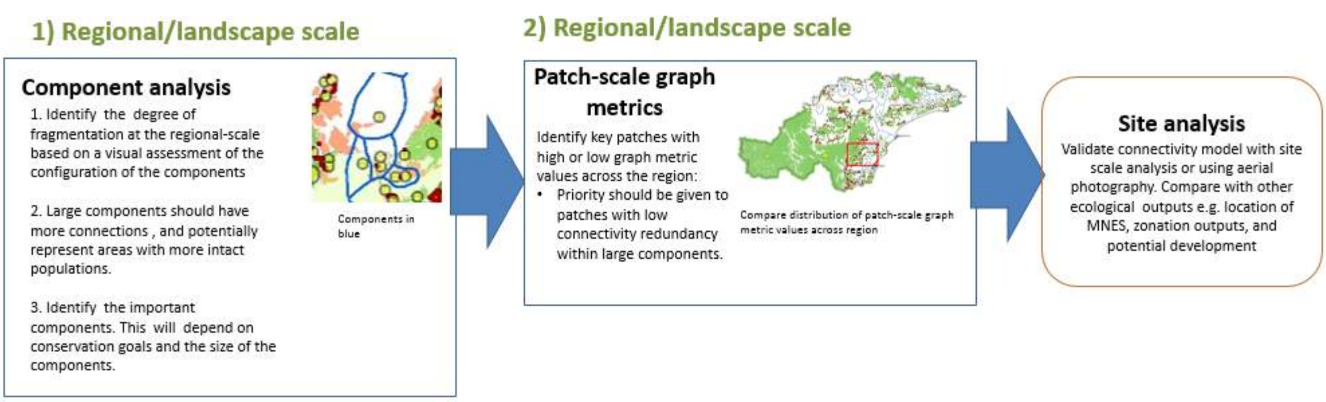


Figure 52 **An example of how GAP CLoSR outputs may be used to identify conservation priorities for vegetation patches at the regional scale.**

Identifying Restoration Locations

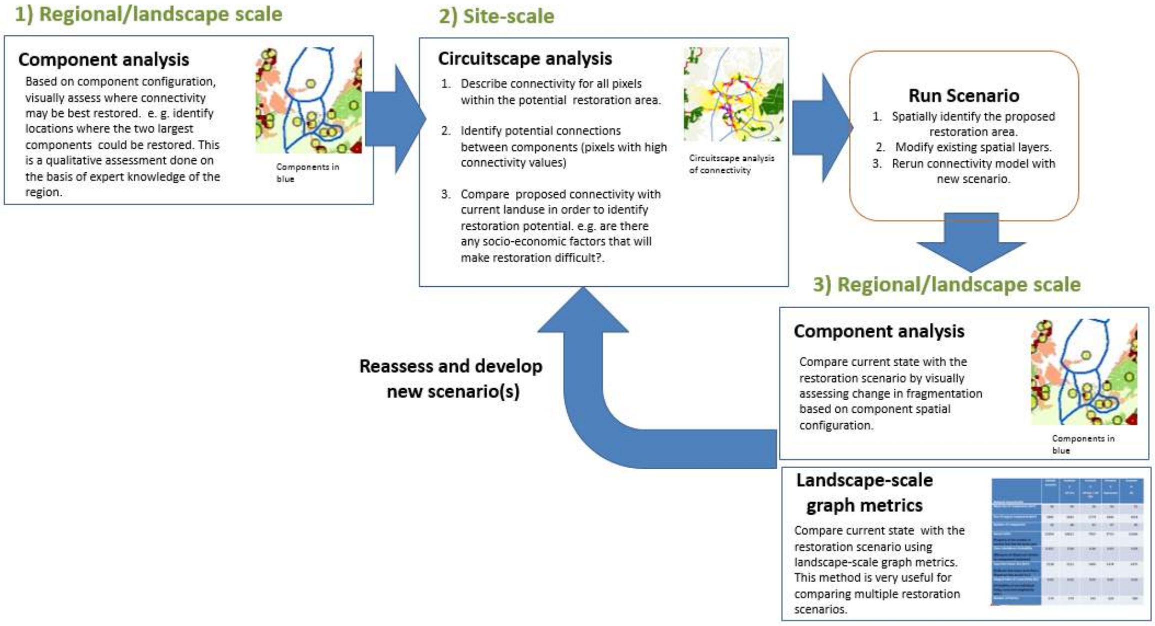


Figure 53 An example of how GAP CLoSR outputs may be used to identify potential locations for restoring regional scale connectivity

Assessing impacts on connectivity

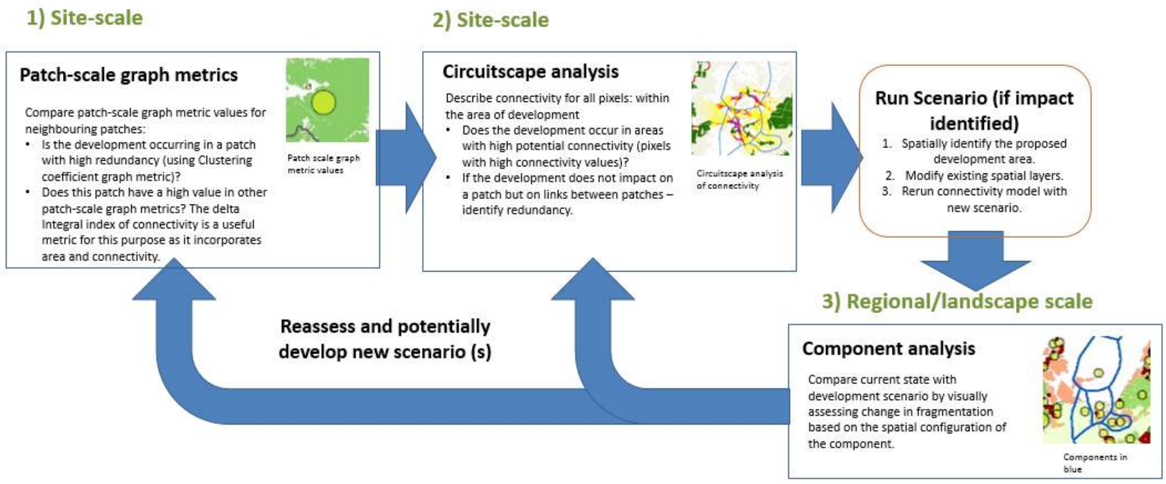


Figure 54 An example of how GAP CLoSR outputs may be used to identify the impact of proposed developments at site-scale

4.2. Spatial data inputs

A minimum of two spatial data inputs are required for modelling and were used in the Lower Hunter example. However, in other regions due to data quality and scale multiple spatial datasets may be used to identify all the necessary features required for modelling. For example, a medium resolution landuse layer may be combined with a road layer to identify fine-scaled road features that are not present in the landuse layer. Table xx describes the spatial data inputs used in the model and provides a qualitative assessment of minimum requirements. In practice, the minimum requirements will depend on the target species/communities and its ecological requirements.

Table xx Spatial data input layers used in the connectivity model and qualitative assessment of minimum requirements.

Spatial Data	Purpose	Scale	Source	Comment on data quality and scale requirements
Vegetation layer	Patch locations	2.5 m	SPOT satellite Greater Hunter mapping (Siggins et al. 2006)	As the minimum patch size is 10 ha medium resolution data can be used (for example, 30 m).
	Gap-crossing layer	2.5 m	As above	It is important that this layer has a high spatial resolution in order to assess gap-crossing threshold that occur at 106 m.
LULC layer	Dispersal cost-surface	1:25000 ~12.5 m	NSW LULC layer based on 1998-2000 air photo interpretation	This layer needs to be at spatial resolutions that can identify features that are signficant for dispersal such as roads and rivers.

4.3. Limitations of the General Approach to Planning Connectivity from Local Scales to Regional and future research

4.3.1. Assess methods within the Tasmanian Midlands

Application of GAP CLoSR in the Tasmanian Midlands will provide an opportunity for greater stakeholder engagement than was possible in the development phase in the Lower Hunter Region. In the Tasmanian Midlands, all seven of the guiding principles will be tested using the MCDA approach wherever possible. Discussions are underway with relevant researchers in the Landscapes and Policy NERP Hub to provide the spatial layers needed for this analysis. An interesting area of research for addressing guiding Principle 6 (*Corridors should be designed to assist native species' adaptation to the impacts of climate change*) will be access to future species distributions based on fine-scaled climate projections developed by the Climate Futures for Tasmania project (Harris et al. 2013) and the ability to incorporate these into connectivity models. Another additional area of research will be the inclusion of co-benefits

associated with wildlife connectivity planning such as those associated with carbon sequestration, water quality improvement and other ecosystem services.

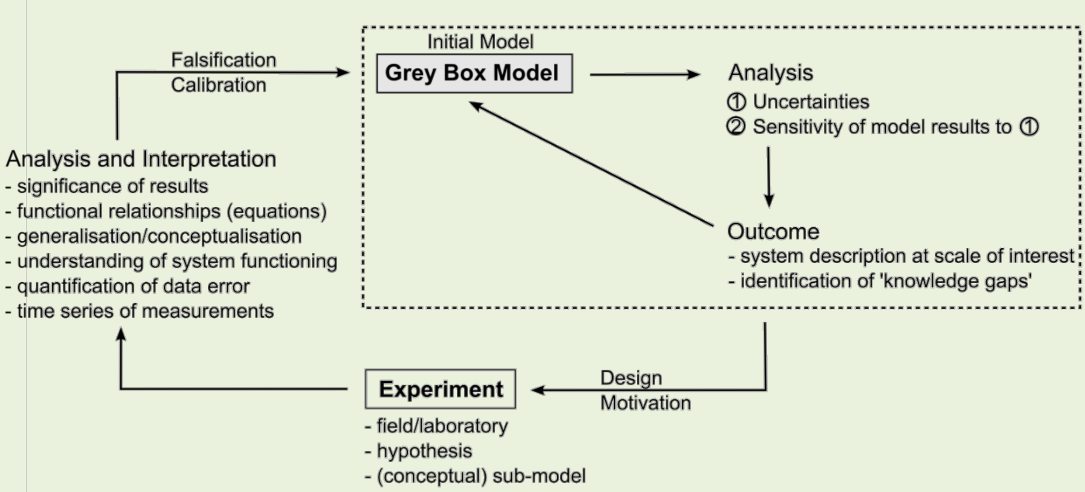
4.3.2. Addressing uncertainty

In the Tasmanian Midlands, the project will test the impact of a range of sources of uncertainty on GAP CLoSR. This will include an assessment of spatial data accuracy, connectivity model type, target species and community and ecological parameterisation. This will be carried out using a combination of real data and simulation models (Lechner et al. 2012a; Lechner et al. 2008; Lechner et al. 2012c; Lechner et al. 2013; Lechner et al. 2009). Uncertainty has the potential to confound spatially explicit modelling methods and needs to be assessed to ensure the robustness of the output (Lechner et al. 2012b; Lechner et al. 2013). The assessment of uncertainty will involve quantifying the trade-off between model complexity and data accuracy versus simplicity of use from the perspective of non-experts who may apply these models to their local government area or catchment.

Sensitivity analyses will be used to assess the sources of error and uncertainty. Where uncertainty confounds the analyses, these input parameters will be remodelled or remeasured in the tradition of the 'cycle of scientific discovery' framework (see Comment Box).

Cycle of Scientific Discovery

In the 'cycle of scientific discovery', we accept that all models are wrong; however, through an iterative process of testing for uncertainty and redesign, improvements can be made.



Schematic representation of the cycle of scientific discovery. The grey-box model denotes both the start and 'end point' of synthesising scientific knowledge and conducting experiments. Identifying the sensitivity of a model to uncertainty can result in either rejection or reconsideration of a model, leading to a re-structured model (dashed frame) or design of an empirical or manipulative experiment (from Arnold et al. 2012).

Of key importance will be assessing the accuracy of mapping at the property scale. Many vegetation maps are accurate at estimating change in the extent of forest cover at the state or catchment level, but are inaccurate when representing boundaries at the property or patch level. Furthermore, the accuracy of data is relative to the types of species being modelled. Highly mobile large species have different habitat requirements to small cryptic species that need to be characterised using data produced at different scales.

4.3.3. Stakeholder engagement

The development of decision making tools that incorporate participatory modelling approaches require significant effort to ensure stakeholder engagement is meaningful and representative (McIntosh et al. 2011; Voinov & Bousquet 2010). Stakeholder input is required to both parameterise the connectivity model and to assess whether the model outputs are of practical use to decision makers (Figure 50). While stakeholder engagement is not the prime focus of this research, its role in ensuring the relevance and utility of GAP CLoSR is recognised. Stakeholder engagement is needed to ensure that any model developed to support public policy and decision making will 1) produce understandable results, 2) support the analyst in producing results and 3) produce results addressing end user questions (McIntosh et al. 2011).

A more rigorous assessment of stakeholder interests will take place in the Tasmanian Midlands. This will make use of the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) software (Lesslie 2012). Discussions are already underway with the Tasmanian Department of Primary Industries, Parks, Water and Environment, Greening Australia and the Tasmanian Land Conservancy, organisations actively involved in connectivity planning and other biodiversity conservation strategies in the Tasmanian Midlands.

4.3.4. Further development of multi-criteria decision analyses methods

In this project, the MCDA methods employed were relatively simple, with a focus on Geographic Information System-based Multi-criteria Decision Analysis (GIS-MCDA). This is a specific type of MCDA that combines value judgments and decision maker's preferences using the MCDA approach with spatial data (Malczewski 2010). The field of multi-criteria decision analyses also includes mathematical methods that quantify the interests of stakeholders and decision makers as well as technical information to aid selection of the most appropriate solutions to different problems (Linkov 2012). These have been used in a range of disciplines from economics to engineering, but are not commonly applied within systematic conservation planning (except for Moffett et al. 2005). Future work will investigate the possibility of applying these methods to GAP CLoSR.

Schematic Representation of the Stages in the Participatory Modelling Process

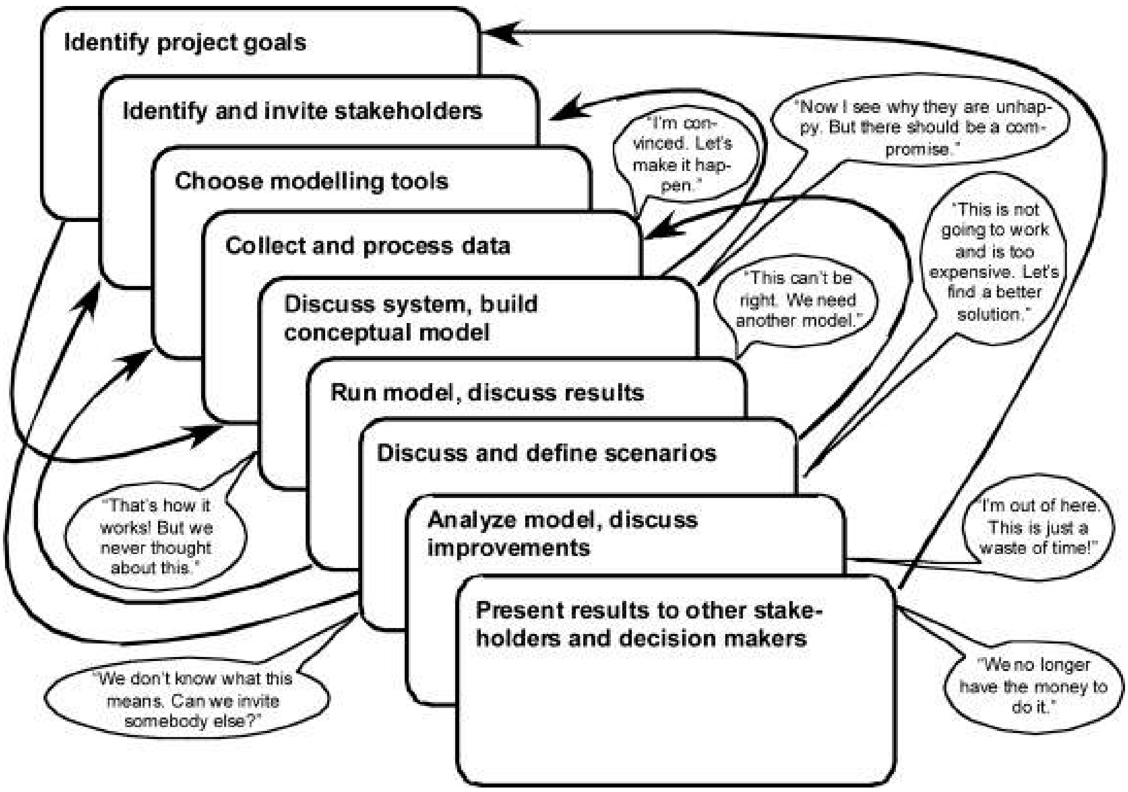


Figure 55 Schematic representation of the stages in the participatory modelling process, indicating that the stages are not necessarily sequential, but usually involve several feedback loops (from Voinov & Bousquet 2010).

4.4. Conclusion

This pilot study presents one of the first examples of a decision support tool that integrates graph-based connectivity modelling with multi-criteria analysis, enabling social and economic information to be incorporated with ecological data on landscape connectivity. A key challenge for conservation planning is achieving the feasibility and acceptability of proposed conservation actions. This requires an understanding of the complex social, economic and institutional environments in which conservation occurs, and having methods to represent these needs and interests spatially. Single, static maps of conservation priorities while useful cannot accommodate the complexity of a decision making process that is influenced by community values, demographic change, government policies, the economic environment as well as new ecological knowledge and technical capacity. Decision makers need tools than are sufficiently flexible and dynamic to incorporate these various drivers of change without being too complex or difficult to use. A major challenge for the second phase of this project is to ensure that MCCP Framework and its outputs achieve the twin goals of adequacy and simplicity.

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Appendix A

R code for calculating appropriate pixel size for gap crossing layer

```
# R code for calculating the average distance between two randomly located pixels within two neighbouring larger pixels
# Alex Lechner alex.lechner@utas.edu.au
# 23/09/2013
#
# Use the formula sqrt((x1-x2)^2 + (y1-y2)^2)
# Use a subset of all x,y combinations using resampling http://www.pmc.ucsc.edu/~mclapham/Rtips/resampling.htm
library(gplots)
#Parameters
startlist <- 60
finishlist <- 120
pixelsize <- 2.5
SampleSize <- 10000
countpixelsizes <-0

#Processing
AggregatedPixelSizelist <-seq(startlist,finishlist,by=pixelsize)

for(AggregatedPixelSize in AggregatedPixelSizelist){
  start <- pixelsize
 finish <- AggregatedPixelSize
 sequence <-seq(start,finish,by=pixelsize)
 numberOfCombinations <- length(sequence)^4
 x1x2y1y2Matrix <- matrix(nrow=numberOfCombinations,ncol=4)
 colnames(x1x2y1y2Matrix) <-c('x1','x2','y1','y2')
 count<-1
 for(x1 in sequence) {
  for(y1 in sequence) {
   for(x2 in sequence) {
    for(y2 in sequence) {
     currentLocations <- c(x1,x2,y1,y2)
     x1x2y1y2Matrix[count,1:4]<-currentLocations
     count <- count+1
    }
   }
  }
 }

 Randomizedx1x2y1y2Matrix <- x1x2y1y2Matrix[sample(1:nrow(x1x2y1y2Matrix)),]
 RandomRowVector<- sample(seq(1:numberOfCombinations) )
 SubsetRandomRows<-RandomRowVector[1:SampleSize]
 count2 <- 0
```

```
for(RandomRow in SubsetRandomRows){
 Pos<- Randomizedx1x2y1y2Matrix[RandomRow,1:4]
 #
 x1 <-Pos[1]
 x2 <-Pos[2]
 y1 <-Pos[3]
 y2 <-Pos[4]

if(y1 < y2){y22<-y2-pixelsize}else{y22<-y2} #adjust so that measurements are taken from closest corner
 distance <- sqrt((x1-(x2+AggregatedPixelSize-pixelsize))^2 +(y1-y22)^2)
 if(count2 == 0){vector<- distance}
 else{vector <- rbind(vector,distance)}
 count2 <- count2+1
}
print('last example')
print(Pos)
print(distance)
#Add to superlist
if(countpixelsizes == 0){
 finallist <-  matrix(nrow=1,ncol=3)
 colnames(finallist) <-c('Pixel Size','Mean Distance','SD')
 finallist[1,1:3]<- c(AggregatedPixelSize,mean(vector),sd(vector))
}
else{finallist <- rbind(finallist ,c(AggregatedPixelSize,mean(vector),sd(vector)))}
print('mean, SD')
print(paste(mean(vector),sd(vector)))
countpixelsizes <- countpixelsizes+1
}
print(finallist)
plotCI(finallist[,1],finallist[,2], uiw =finallist[,3], xlab='Pixel Size (m)', ylab = 'Mean Distance (m)')
grid()
lines(finallist[,1],finallist[,2], lty=1, col=2, lwd=3)
points(finallist[,1],finallist[,2])
fname <- 'Z:\\fname.txt'
write.table(finallist, file= fname, quote=F, row.names=F)
```

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