TECHNICAL REPORT 21

Ecological Connectivity for Climate Change in the ACT and surrounding region

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Disclaimers, assumptions and limitations

This technical report has been commissioned by the ACT Government to address Action 34 of the ACT Climate Change Strategy.

The authors and the ANU accept no responsibility or liability for any decisions made based on the contents of this report.

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No guarantee or warranty as to the report's accuracy or factuality is given nor should any be implied. This report is a desk-top study. Any data used were not verified in the field.

The report uses model animals, not real animal data. We assume that the six model animals are a reasonable approximation of the sorts of fauna that require different types of connectivity. Model animals were used to assist the reader in interpreting the type of connectivity model discussed.

Figure 20 and 21 show the averaged Link Value and Neighbourhood Connectivity value for all six modelled species. Note: this data is intended to be indicative only because averaged data will, by definition, underestimate connectivity for some species, and overestimate it for others.

More detailed modelling based on data for real animals is required for detailed planning purposes. Undertaking sensitivity analyses was beyond the scope of this study, but would be needed for more detailed modelling and planning.

Model plants were not included in the study.

Priority locations for improving connectivity are indicative and based on the modelling. Remedial actions require detailed analysis of habitat and ground-truthing to confirm causes of weak connectivity.

It is essential that the effectiveness of remedial actions is assessed by targeted monitoring.

All responsibility for decisions based on this advice or any reliance founded on this technical report is the responsibility of the ACT Government.

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Executive Summary

Recognising wildlife corridors or planning for ecological connectivity as a means to promote fauna and flora conservation are not new concepts in the ACT. A short historical review of terms such as 'wildlife corridor' or 'connectivity' used in reports and strategies issued by ACT Government agencies over the last 20 - 30 years indicates some understanding of these general terms. However, notwithstanding this documented recognition of the concept of connectivity, there has not been a concerted effort to introduce measures designed to achieve stated connectivity goals, or to take decisive steps to implement requisite actions. Only since 2007 has the ACT's planning legislation included a reference to 'corridors for biodiversity' – in the context of environmental impact assessments.

This report has been commissioned by the ACT Government to address Action 34 ('Develop an Ecosystem Connectivity Map') of its Climate Change Strategy (ACT Government 2007a, 2007b).

Successive ACT administrations have focused on building the Territory's nature conservation estate. This now extends across over 54% of the ACT's land area and makes an impressive contribution to national goals of establishing a comprehensive, adequate and representative national reserve system. Links between the ACT and surrounding areas of New South Wales also have received attention in recent years. Ambitious programs have been designed to link the alpine areas of the ACT, New South Wales and Victoria (Australian Alps National Parks) to other natural areas (viz Kosciuszko (National Park) to the coast (NSW), and Alps to Atherton (Qld)).

Initially, ACT agencies regarded wildlife corridors in the sense of defined areas of land that identified (usually) mass movements of a species that migrated from one place to another in a particular season or time of year (NCDC 1984). However, more recently, there has been a growing awareness in the community and across all spheres of Government about the need to address the issue of habitat loss due to land use change and human-induced climate change and their impacts on the survival of plant and animals species (ACT Government 2007a).

Climate change is predicted to result in changed distributions of ecosystems and constituent species and many landscapes will be an evolutionary novelty to organisms because the environments in which they evolved were considerably less fragmented than modern landscapes. This makes it difficult for many organisms to respond and adapt by movement across modified landscapes.

The maintenance and expansion of reserve networks is widely recognised as vital to ensuring climate change adaptation. Furthermore, to assist mitigation of negative impacts of climate change and expansion of urban and rural developments, conservation biologists have advocated planning and managing land in a manner that recognises the need for wildlife to move across the 'whole landscape'. This implies an ecological network of reserves and biodiversity corridors embedded within a wider landscape matrix which is highly connected and, importantly, includes systematic management of 'off reserve' land, irrespective of land use and tenure, coordinated with the nature conservation estate. This does not equate to a 'parallel reserve system', but rather the application of an emerging applied science that is focused on the integration of conservation and human land uses.

There is considerable confusion related to the meaning of 'connectivity'. This report adopts the definition used by Lindenmayer and Fischer (2006) that is an amalgam of three concepts: (1) **habitat connectivity** – the connectedness of patches of habitat suitable for a given individual species (which varies on a species by species basis); (2) **landscape connectivity** – the human perception of physical connectedness of vegetation cover in a landscape; and (3) **ecological connectivity** – the connectedness of ecological processes at multiple scales. For the purposes of this report, we are using **habitat connectivity** as the working definition because of the anticipated species-specific effects of climate change. However, we translate this into **landscape connectivity** for planning recommendations, as this reflects the physical environment that planners and land managers manage. **Ecological connectivity** is not the focus of this report, though it is to some degree embedded in the other kinds of connectivity – particularly in-stream connectivity.

To assist the ACT Government to plan and manage land use in a manner that provides for movement of native fauna across landscapes, key places of connectivity concern and remedial or planning actions have been identified using tools developed by the NSW Department of of Environment and Climate Change. The Spatial Links Tool (Drielsma *et al*., 2007b) maps the location of links across a region using a methodology that evaluates the potential of habitat connections to contribute to landscape connectivity. Another view of connectivity was derived using the Cost Benefit Approach (CBA) (Drielsma *et al*., 2007a) to assess habitat arrangement in the landscape. Six model animals (a small woodland bird, strongly flying bird, arboreal marsupial, ground dwelling mammal, grassland reptile, and amphibian) were selected to illustrate the range of animal species that inhabit and move through the ACT's nature reserves system. Plants were not modelled in this study, but the general connectivity principles for them are the same as animals. Maps (Figures 8 to 19) summarise the connectivity modelled for each species at two scales (focused on the ACT and the entire study region). Figures 20 and 21 show averaged connectivity values for all six model species.

The results of this analysis of habitat connectivity highlighted some key issues for planning and land management in the ACT. These issues include:

- Linking existing ACT nature reserves to each other and to those in NSW;

- Avoiding further fragmentation of woodland habitat in the NSW part of the study area and where possible strengthening habitat links;

- Maintaining and enhancing, especially for aquatic biota, the integrity of the Murrumbidgee River as a key connectivity feature crossing the ACT and linking into NSW;

- Prioritising in-stream structures for removal or remediation to improve fish passage. Barriers could simply be ranked according to the length of stream that would be connected if the structure were removed or remediated. A more comprehensive scheme for prioritising works to improve fish passage would also take into account the position of the barrier in the stream network, the habitat quality of the connected streams, the potential to assist dispersal of exotic species and socio-economic costs and benefits (Gordos et al., 2007; Kemp *et al*., 2008; Meixler *et al.*, 2009). Remediation measures need not be prohibitively expensive. For example simple measures such as installing spoiler baffles in a pipe culvert can be cost effective (Macdonald and Davies, 2007).

- Recognising that all parts of a given landscape may play a role in conservation and connectivity (irrespective of that land use, tenure or formal designation). Current usage of the term biodiversity 'corridor' alone (viz. ACT *Planning and Development Act 2007*) does not necessarily mean that habitat and landscape connectivity across the ACT and into the surrounding region will be achieved;

- Considering connectivity in projects involving planning over the short, medium and long terms;

- Considering species-specific responses of organisms to climate change;
- Undertaking habitat recovery actions in key locations (see later list). It is essential that targeted monitoring assess the effectiveness of this;
- Maintaining and enhancing connectivity, plan and build urban developments that are permeable to multiple types of organism;
- Taking into account that the importance of a particular part of the landscape for an organism can change through time, e.g. change in habitat structure;
- Considering human-assisted translocation of animals to ensure genetic mixing, where remediation of isolated habitats cannot reasonably be implemented or natural movement of fauna is not expected (e.g. specialist flora and fauna of native grasslands);
- In the case of in-stream environments, particularly where roads cross or impact on creeks or wet areas, analysis of connectivity in the design and construction phase of all developments should encompass the following:
    - Considering the habitat and movement requirements of different aquatic species;
    - Incorporate weightings for different types of barriers according to their potential to impede movement;
    - Including key ecological processes:
        - Sediment processes
        - Hill slope processes
        - Nutrient movement
    - Assess barriers to sediment and nutrient movement.

A key implication of the above is that planners must now think of connectivity for biodiversity as a long-term process and one that recognises climate change, even as land uses change. At the same time, this does not mean all land used by native species should be conservation reserve, but rather that conservation, urban and rural land uses should be integrated and be mutually supportive as far as possible.

A consideration of recent understanding of the term 'connectivity' leads to several recommendations designed to assist planning in the ACT and region, particularly in the context of implementing the ACT Climate Change Strategy and achieving the goals of The Spatial Plan.

- All three forms of connectivity should be considered in the planning process and delivery of development projects. This would require a change in the Planning and Development Act 2007 insofar as environmental impact assessment is administered;
- A series of questions should be asked in the early stages of planning for connectivity:
    - What species or habitats are relevant in this landscape (i.e. which are important to the community and/or for ecological functions)?

  - How are they distributed?
  - How do they use elements in the landscape?
  - Are there ways to accommodate their future needs in planning and design?
  - Is it possible to create developments that are 'permeable and livable' for wildlife?
  - If not, can connectivity needs be enhanced elsewhere in the landscape through targeted restoration measures or possibly environmental offsets?

- Where connectivity is poor but critical for local flora and fauna, planning and management should enhance connectivity as a high priority and a condition for urban and other development;

- Reserves and biodiversity ‘corridors’ should be maintained and enhanced – with particular consideration for areas identified below (see Connectivity Priorities). Connectivity should be maximised in surrounding landscapes (e.g. leased and agisted rural land and urban developments);

- Develop short course training on connectivity for climate change for staff in agencies responsible for land planning and management in the ACT region;

- Undertake more detailed assessment of opportunities to improve connectivity across the ACT region, focusing on species of concern and places that modelling indicates are key connectivity areas. These assessments could include:

  - Modelling of ‘real’ species of concern using using existing data and new data collected in the ACT region as part of connectivity-related monitoring (see below);
  - Commissioning of a high-resolution survey of scattered trees in both urban and rural areas, including their condition and potential function as habitat for native species (e.g. nesting hollows);
  - A program of connectivity-related monitoring. This might focus on key places identified in this study and include studies into actual movement of native species across potential barriers to movement (e.g. roads, developments, unsuitable habitat). This work may lend itself to collaboration with post-secondary institutions and be a topic for post-graduate student projects;
  - Application of modelling at a scale that is specific to the particular species of interest (this report uses a 90 metre pixel, but a finer resolution (e.g. 15 metre pixel) may be appropriate for some species). Such modelling could include plants of interest;
  - Incorporation of additional parameters into modelling (e.g. environmental characteristics such as slope) that may influence habitat suitability / permeability could follow from suggested monitoring programs;

- Undertake a sensitivity analysis to explore the effect of model parameter values, data resolution and analysis scale on model outcomes;

- Model neighbourhood connectivity and link value under different climate change and / or landuse scenarios. This would require the ability to model future habitat distribution under each scenario and its suitability and permeability for each model animal;

- Compare current and future connectivity with that modelled for pre-European times;

- Improve the assessment of in-stream connectivity by considering the probability of passage by fish and other aquatic biota for each in-stream structure. This might be based on expert ratings assigned according to the design and construction characteristics of each structure relative to the swimming capabilities of the fish species of interest and stream discharge and where available field measurements. This activity could build on the audit of road crossings being undertaken by the NSW Department of Primary Industry (Kirby Burns, NSW Department of Primary Industry pers. comm. 26/5/09).

Results from modelling the six types of model animal have enabled us to identify several principles for planning and management that includes connectivity, and also some key locations that warrant high priority in considering remedial planning or management action to maintain or improve connectivity (Table 2). In some cases, existing urban development in the ACT means that enhancing connectivity may only be possible in neighbouring areas of NSW. This will require cross-border cooperation on planning and landscape management. These locations are listed below:

- Black Mountain to Belconnen Hills and the lower Molonglo River;

- Callum Brae/Jerrabomberra to NSW (via Hume);

- Hall to Mulligans Flat and Goorooyarroo nature reserves and then linked with Mt Ainslie and Mt Majura nature reserves and the Majura Valley (including land occupied by the Department of Defence);

- Mulligans Flat and Goorooyarroo nature reserves to NSW (Greater Goorooyarroo);

- East Jerrabomberra nature reserve to Queanbeyan nature reserve (NSW) (across railway line and Lanyon Drive);

- Strengthening the links between Mulligans Flat and Goorooyarroo nature reserves with the Majura hills and adjacent NSW land to their north (Greater Goorooyarroo) needs consideration before woodland habitat areas become more isolated and/or fragmented;

- Strengthening the habitat links between Naas/Tharwa and nearby land to the east in NSW needs consideration before these areas become more isolated;

- Strengthening the habitat links between the Tinderry Range and woodland habitat to the north and northeast of Lake George needs consideration before these areas become more fragmented.

Enhancement of connectivity in these key areas will require a range of approaches:

1. Strategic establishment of nature reserves in key locations. These would be selected using standard criteria for reservation, e.g. condition/quality (although scope to do this in the ACT is limited).

2. Strategic establishment of 'biodiversity corridors'. The aim in these would be to protect and restore loss of degraded ecosystems, e.g. box-gum grassy woodland, grassland or chain of ponds. These areas may not meet standard criteria for reservation, and initially may be highly degraded although capable of restoration.

3. Restoration of key connectivity elements in 'off reserve' land. For example, this might involve establishing trees, shrubs, water bodies, grassland, dead wood. Within suburbs this might involve 'mini habitat patches' focused on individual trees, pocket parks or mixed use areas. On leasehold or agisted land, integration of habitat elements with management for primary production, while in-stream structures at road crossings might be altered to improve passage of fish and other riverine biota. Mature trees outside nature reserves are likely to be a key factor in maintaining connectivity for some species. Continued loss of these trees is likely to weaken the current level of connectivity in the ACT and region.

Adopting these approaches would involve applying a range of legislative instruments, regulations, covenants and contracts to ensure long-term positive effects on connectivity.

Introduction

The interacting effects of land use change and climate change have brought new dimensions to the role of land use planners and managers in conserving biodiversity (Warren *et al*. 2001; Opdam and Wascher 2004; Hulme 2005; Harris *et al*. 2006; Steffen *et al.* 2009). Planning for sustainable development, and creating and maintaining ecologically sustainable landscapes for both people and biodiversity has never been so challenging. Rapid, human-induced climate change has significantly changed concepts of landscape from the static to the dynamic within ecology (Bengtsson *et al*., 2003; Opdam & Wascher 2004; Harris *et al*. 2006; Manning *et al*. 2009a). This is because habitat and reserves that may currently be suitable for particular organisms may not be suitable in the future under different climatic conditions (Manning *et al*. 2009a). Furthermore, organisms will need to move and respond to climate change over highly modified landscapes (Manning *et al*. 2009a; Lindenmayer *et al.* 2010).

In the recent past, corridors, primarily devoted to conservation, were thought to be the key to movement of biodiversity around landscapes (Bunnell 1999). In proposing corridors as a strategy, it was assumed that most biodiversity would use corridors to move across landscapes; however, empirical evidence for this is limited (Bunnell 1999; Doerr *et al.* 2010). Furthermore, if habitat continues to be lost in the surrounding matrix, corridors may only make a limited contribution to biodiversity conservation (Rosenberg *et al*. 1997; Harrison and Bruna 1999).

It is widely recognised that the maintenance and expansion of reserve networks is vitally important for climate change adaptation (Halpin 1997; Opdam & Wascher 2004; Opdam *et al*. 2006; Dunlop and Brown 2008; Hannah 2008). In addition, recent thinking and ecological knowledge suggests that corridors alone may not be an effective strategy for all species (Wiens 1997; Lindenmayer and Franklin 2002; Donald and Evans 2006; Lindenmayer and Fischer 2006; Boitani *et al*. 2007; Manning *et al*. 2009b). This has led to a shift towards the broader concept of landscape 'connectivity' and 'whole landscape' management (Lindenmayer and Fischer 2006). In this, **ecological networks of reserves and biodiversity corridors are embedded within a wider landscape matrix which is highly connected, but which may have integrated uses** (Lindenmayer and Franklin 2002; Bennett 2004; Opdam and Wascher 2004;Opdam *et al*. 2006; Manning *et al*. 2009b)

As part of the ACT's response to climate change, it will be important that new thinking on landscapes is incorporated into the land use planning process to ensure adaptation for climate change. The implication is that planners must now think of connectivity for biodiversity as a long-term process, even as land uses change. **This does not mean all land used by native species should be conservation reserve, but rather that conservation, urban and rural land uses should be integrated and be mutually supportive as far as possible. At the same time, it is important not to lose key areas of connectivity (Steffen *et al.* 2009)**

Integration of conservation and urban land uses can be expected to present challenges to existing approaches to planning and management of land in the ACT. Improving connectivity in rural or open space areas where the existing land use is immediately compatible may be relatively straightforward to achieve. However in those places where there is a pre-existing land use (e.g. urban development or infrastructure) the otherwise exclusive land use may have to accommodate a secondary land use activity or land management practice (e.g. sympathetic landscaping) that achieves connectivity. Retrospective treatments may be necessary to support adaptation to changing ecological conditions and to improve connectivity. Both these types of actions would represent examples of adaptation to climate change by seeking to achieve multiple objectives for land, including ecological and connectivity outcomes.

This technical report demonstrates the usefulness for land use planning of this 'new thinking' in which whole landscapes are managed for connectivity, and a range of approaches are used to achieve this. We use six 'model animals' with different connectivity and habitat needs, and model these animals with vegetation and land use data to illustrate 'whole landscape' connectivity issues in the ACT and surrounding region.

The aim of the project is to better inform the ACT's planning process and future policy and strategies for connectivity. It was commissioned by the ACT Government to address Action 34 of the ACT Climate Change Strategy: 'Develop an Ecosystem Connectivity Map'. Based on our modelling and results we make recommendations for incorporating connectivity into the ACT planning framework. **While the study is not intended to be comprehensive, it is intended to be a starting point for additional, more detailed application of whole-of-landscape connectivity approaches in planning the ACT.**

The report is broadly divided into three sections covering:

SECTION 1: the concept of connectivity is defined and discussed in relation to current ecological literature and the policy framework that operates in the ACT.

SECTION 2: the methods and results of the modelling exercise and implications for improving connectivity at both the ACT and regional scale.

SECTION 3: recommendations for ecological planning and conservation responses to climate change issues in the ACT context.

SECTION 1: Connectivity and policy

In this section, we outline recent developments in concepts about landscapes, outline the history of policy responses in ACT planning, and explain the modelling approach adopted in this study.

What is connectivity?

Definitions of connectivity

There is considerable confusion related to the meaning of 'connectivity', and it is actually an amalgam of three concepts. Lindenmayer and Fischer (2006) identify these as:

(1) **Habitat connectivity** – the connectedness of patches of habitat suitable for a given individual species (which varies on a species by species basis);

(2) **Landscape connectivity** – the human perception of physical connectedness of vegetation cover in a landscape; and

(3) **Ecological connectivity** – the connectedness of ecological processes at multiple scales.

In the context of landscape and climate change, connectivity should not be seen as a static property of a landscape. It will change through time and for different species (Manning *et al*. 2009a).

In the ACT, the term 'ecological connectivity' has been used in a context of identifying spaces in the landscape (or corridors) for local native animals to move between the major areas of native vegetation that are protected within the ACT's nature conservation estate. The term ecological connectivity was adopted after a long period of using the term 'wildlife habitat corridors' or wildlife movement corridors' in policy statements and strategic plans.

It is important to be specific about the kind of connectivity being considered to get the best research and management outcomes. For example, if we are interested in connectivity for a particular organism, we think of the landscape elements and functions from its perspective (to the extent we are aware of/understand it). This encourages a more realistic view of a landscape and therefore ensures that the practical solution, in planning terms, achieves its ecological aims.

Therefore, for the purposes of this report, we are using **habitat connectivity** as the working definition because of the anticipated species-specific effects of climate change (Steffen *et al.* 2009). However, we translate this into **landscape connectivity** for planning recommendations, as this reflects the physical environment that planners and land managers manage. **Ecological connectivity** is not the focus of this report, though it is to some degree embedded in the other types of connectivity – particularly in-stream environments. **Neighbourhood connectivity**, which is the term used in the modelling in this report can be broadly equated with habitat connectivity (see Glossary).

Why does planning for connectivity matter?

Connectivity is an important consideration in land use planning because of the effects of two interacting phenomena:

1. Climate change; and,
2. Land use change.

Climate change

There is a growing body of evidence that rapid climate change is having profound impacts on biodiversity. A major effect is to force species to shift their ranges (e.g. Parmesan & Yohe 2003; Root *et al.* 2003; Parmesan 2006; Steffen *et al.* 2009). In response to climate change, ecological communities are expected to disassemble and organisms will respond in different ways, with differing rates of movement; some will want to move laterally across landscape, others will want to relocate altitudinally (Peters 1990; Erasmus 2002; Thuiller 2004). There is already growing evidence that climate change is having major effects on some species leading to range shifts (Parmesan and Yohe 2003; Root *et al.* 2003; Hickling *et al.* 2005), as well as shifts in/effects on other key biological functions such as commencement of breeding (Crick *et al.* 1997). As climate change proceeds, these effects are expected to be exacerbated and become more widespread.

Land use change

Changes in land use from natural ecosystems, or from extensive to intensive uses, is a major cause of biodiversity loss and degradation of ecosystem services (Lindenmayer and Fischer 2006). A major consequence of land use change is fragmentation of habitat at many scales. Fragmentation (breaking up into smaller pieces), loss (total destruction) and modification (changes to remaining habitat) of ecosystems are widely recognised as negative ecological processes (Lord and Norton 1990; Saunders *et al.* 1991, Wiens 1994, Bunnell 1999, Haila 2002). This concept of fragmented landscapes has been called the ‘patch-corridor-matrix’ model (Forman 1995; Figure 1). Examples in the ACT include fragmented grasslands (Gungahlin, Majura, Jerrabomberra valleys), modified woodlands (Mulligans Flat, Goorooyarroo and Callum Brae nature reserves), and vegetation cleared to leave only scattered paddock trees (Bulgar Creek and Majura Valley).

The traditional conservation response to fragmentation (before climate change was a major concern) was often to: (1) preserve the best ‘patches’ for conservation; and (2) connect these patches with corridors to try to maintain the connectivity between patches (Lindenmayer and Franklin 2002). This response is illustrated in the approach adopted in the ACT, beginning with the protection of the forested hills and ridges surrounding the main urban areas, which reflect Burley Griffin's plan for a 'city in the landscape', and more recently with the establishment of grassland nature reserves across the best remaining native grasslands in the valley floors of Gungahlin and Jerrabomberra. Connecting these reserves is more problematic because land not reserved is usually assumed to have few of no natural values worth conserving and has been made available for urban development and associated works.

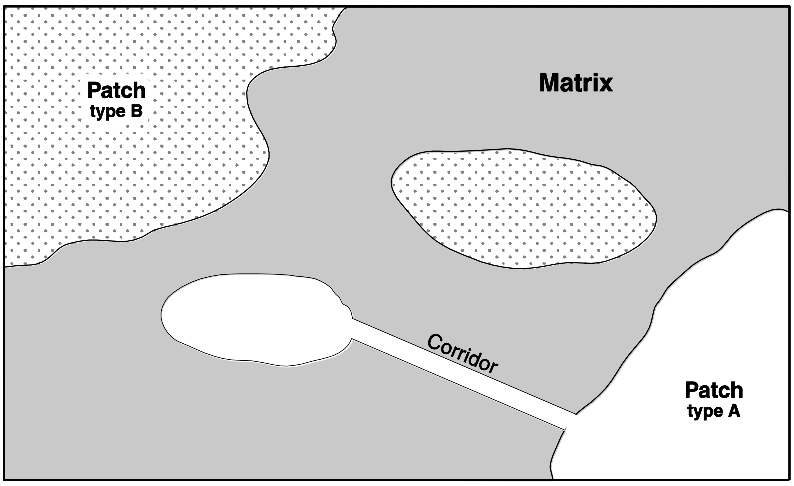

Figure 1 The patch-matrix-corridor model (Forman 1995).

More recent ecological research has lead to many authors questioning the assumptions underpinning traditional views of landscapes and ecological processes (see Box 1). **The patch-corridor-matrix model remains an important tool for conservation planning. However, the implications of these criticisms is that it should be used as part of an integrated whole-of-landscape approach, where**

reserves and corridors (i.e. ecological networks) should be embedded within a matrix managed for maximum possible conservation benefit.

The interaction of land use and climate change

Climate change and land use change are having a major effect on the distribution and abundance of global biodiversity (Warren *et al.* 2001; Steffen *et al.* 2009). However, the interaction of the two is expected to have a far more detrimental effect on biodiversity than either factor in isolation (Peters 1990; Erasmus *et al.* 2002; Mawdsley *at al*. 2009; Steffen *et al.* 2009; Lindenmayer *et al.* 2010). This is because many landscapes are an evolutionary novelty to organisms because the environments in which they evolved were considerably less fragmented than modern landscapes (Lima and Zollner 1996). This makes it difficult for many organisms to respond and adapt by movement across modified landscapes (Manning *et al.* 2009b).The key characteristics of novel ecosystems are (1) novelty: new species combinations, with the potential for changes in ecosystem functioning; and (2) human agency: ecosystems that are the result of deliberate or inadvertent human action, but do not depend on continued human intervention for their maintenance (Hobbs *et al.* 2006).

Box 1. Criticisms and assumptions of traditional views of landscapes

- The effectiveness of habitat patches or conservation reserves is affected by the management and condition of the surrounding landscape (Donald and Evans 2006; Kupfer *et al*. 2006). This is illustrated in Canberra by continued loss of species (particularly woodland birds and small native mammals) from reserves initially established to protect the ACT's flora and fauna.

- There is limited evidence that formal corridors are effective for facilitating movements of many kinds of organisms (Bunnell 1999; Donald and Evans 2006; Lindenmayer and Fischer 2006; Boitani *et al*. 2007).

- It is often assumed that habitat patches occur in a "sea" of hostile matrix (i.e. not usable for as habitat or movement by particular organisms) - yet this is rarely the case and the landscape between the reserves can still be important for many species (Bunnell 1999; Haila 2002).

- The majority of land throughout the world is outside reserves and/or privately owned. Effective conservation cannot be achieved through reserves alone (Norton 2000; Hilty and Merenlender 2003; Rodrigues *et al*. 2004; Hoekstra *et al*. 2005). The ACT has protected 54% of its land area in the nature conservation estate, although this needs to be considered in a regional context where over 90% of box-gum grassy woodlands and natural grasslands have been very significantly modified or lost.

- Different organisms perceive and respond to the same landscape differently. This means that a hostile matrix to one species might be key habitat to another (Manning *et al*. 2004; Figure 2). For example, modified grassy ecosystems are favoured by kangaroos but this can result in the loss of grassland and woodland specialists.

- Organisms are responding individualistically to climate change and will not move as complete presently existing ecological communities (Peters 1990). This will result in the formation of novel ecosystems which have species compositions and relative abundances that have not occurred previously within a given biome (Hobbs *et al*. 2006, Lindenmayer *et al*. 2008).

(Box 1 continues)

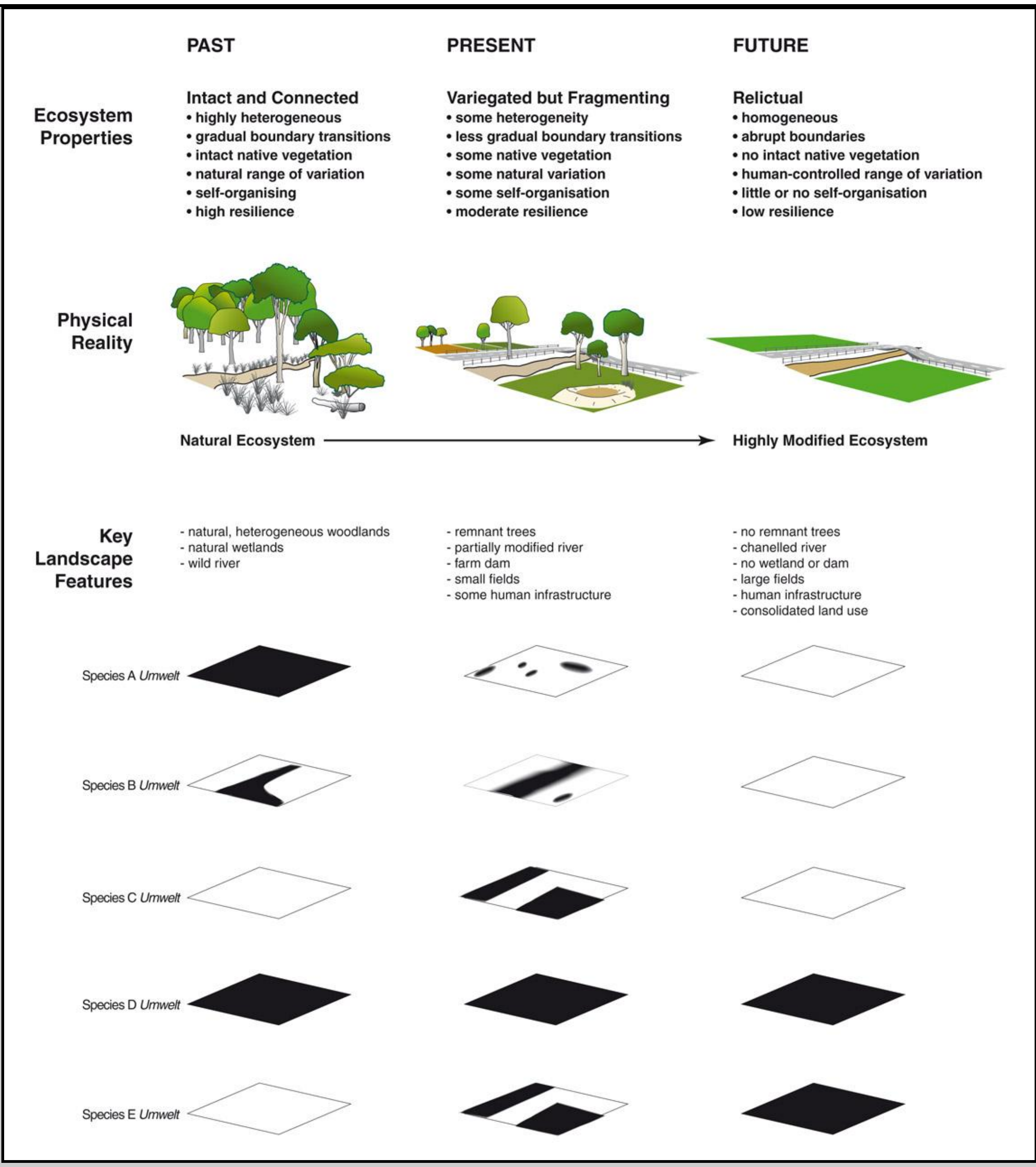

Figure 2 The Continua and Umwelt landscape model showing how different organisms percieve and respond to the same landscape in different ways through time. It also show how some organisms may percieve gradients where others percieve abrupt boundaries. This model emphasises that human perceptions of landscapes can differ significantly from those of organisms.

- It is often assumed that fragmentation is a binary process resulting in either habitat or non-habitat. However habitat can be modified and not destroyed (McIntyre and Barrett 1992; McIntyre and Hobbs 1999). An example would be scattered remnant paddock trees which continue to have important ecological values (Manning *et al.* 2006a) and woodlands described as moderately modified (ACT Government 2005) which still retain very significant biological values and potential for ecological recovery.

(Box 1 continues)

- It is often assumed that inter-patch distance equals level of isolation - when in fact the condition of the intervening matrix greatly affects levels of connectivity (Haila 1999).

These criticisms and assumptions are relevant to planning and land management in the ACT because it is important that adaptation strategies are based on the best scientific knowledge. Not addressing these issues in relevant regulations and decisions making risks compromising the future capacity of biodiversity to adapt to climate change.

Planning for Connectivity in the ACT - a brief history

National Capital Development Commission

Reference to wildlife movement within and through the ACT and surrounding region was first documented in 1979 by the National Capital Development Commission (NCDC) in a review of published and unpublished information about the ecological resources of the ACT (subsequently published as Technical Paper No. 42 (NCDC 1984). Examples of migrating animals then included: the annual summer movement of bogong moths into upland environments of the Brindabella ranges, the migration each autumn of several species of honeyeater along the Murrumbidgee River, and the annual trans-hemisphere migration of wading birds, most commonly the Japanese Snipe (*Gallinago hardwickii*), that visited natural and created wetlands across the ACT.

The NCDC report noted that the movement patterns of native wildlife had gone largely unnoticed, because they did not follow clearly defined corridors or undertake concentrated migrations, except perhaps the autumn movement of honeyeaters. The 1979 report also identified some scope for assisting movement by maintaining habitat links with sufficient cover and structural diversity. Several areas were nominated as wildlife movement corridors: the lower Molonglo River valley, upper Majura valley, south Canberra Hills and Murrumbidgee River valley. The New Chums Road area in the Cotter Catchment also was listed as a location where migrating birds were regularly monitored.

The unbroken natural links between the Gudgenby and Cotter catchments (later to be incorporated into Namadgi National Park) and the adjacent natural areas of NSW (mainly Kosciuszko National Park) also were noted in the NCDC report. The extensive natural connections across Australia's sub-alpine and alpine areas has been maintained and supported through the Australian Alps Agreement (Commonwealth, NSW, Victoria and ACT Governments) and the Tri-State National Park System which includes Namadgi National Park and Tidbinbilla Nature Reserve in the ACT.

A later, updated review of the ACT's ecological resources (Hogg, 1990) introduced a series of ecological objectives for the ACT which included:

> *"Maintenance of wildlife movement corridors – To establish and maintain corridors for the movement of native wildlife between areas of natural habitat within and adjoining the ACT, thus assisting in the conservation of such wildlife at the regional scale*."

Inclusion of a key ecological process (wildlife movement) in a set of ecological objectives marked a significant change in the planning approach to the natural environment which until then had focused on special ecological areas (e.g. Gudgenby, Black Mountain, Murrumbidgee River Corridor, Jerrabomberra wetlands). The connection theme was subsequently taken up in two strategies developed for the ACT and region in 1998: The ACT and Sub-region Planning Strategy and the ACT Nature Conservation Strategy (see below).

ACT and Sub-region Planning Strategy

The ACT and Sub-region Planning Strategy was prepared by ACT and NSW government planning and environment agencies (including the Queanbeyan City Council) (ACT and Sub-region Planning Committee, 1998). It outlined a strategic framework for development in the Canberra region and endorsed the need to develop a consistent approach to ecological surveys and assessment of threatened species and communities. The ACT and Sub-region Planning Strategy mapped indicative wildlife corridors that link the ACT into the surrounding natural areas, particularly along the eastern and northern ACT/NSW border.

ACT Nature Conservation Strategy

At about the same time the ACT Government published the ACT's first Nature Conservation Strategy (ACT Government 1998). It addressed the issue of ecological connectivity directly by including in its strategic vision:

> *"a regional conservation network links national parks, nature reserves, habitat corridors and significant vegetation remnants."*

To guide its implementation the Strategy adopted as one of its actions:

> *"To develop a nature conservation network linking protected areas, habitat corridors and significant vegetation remnants"*

together with a corresponding performance indicator:

> *"ACT nature conservation network incorporated into regional corridor network at compatible scale."*

The ACT Nature Conservation Strategy envisaged patches of remnant vegetation being linked by corridors of native vegetation, including along roadsides, railway lines, water-courses as well as along shelter belts on farms. The Strategy may have influenced or supported the rationale for some Government community programs and projects such as revegetation projects, farm corridors and maintaining conservation objectives in the forefront of land management policies in reserve and off-reserve areas, however there is little evidence of a coordinated approach to achieving the key relevant Action.

The Canberra Spatial Plan

The ACT Spatial Plan (ACT Government 2004b) consolidated growing community understanding about the importance of maintaining connectivity by including as one of its Goals:

> "*Protect and enhance biodiversity through nature reserves and maintaining connectivity between them.*"

The policy response included:

> *"The major river corridors, the urban hills and ridges, and the hills and reserves east and north of Gungahlin that create the main links for wildlife movement and connect into natural areas south and west of the Murrumbidgee River will be protected as wildlife corridors. At a smaller scale the numerous parks, waterways and landscape features in the urban area that provide links between private gardens and nearby bushland areas will also be recognised in planning policy"*

with a corresponding action:

> *"Initiate a Territory Plan variation to ensure wildlife corridors are maintained primarily for wildlife movement."*

The Spatial Plan included a map (see Figure 3) showing indicative locations in the ACT where ecological connectivity is likely to be an issue for consideration. The map was based on material prepared for the first comprehensive and strategic conservation plan for a key element of the ACT's native vegetation and its associated land and animal species (Action Plan 27 Woodlands for Wildlife: ACT Lowland Woodland Conservation Strategy (ACT Government 2004a)). The Spatial Plan (see Figure 3) reflected the ACT Nature Conservation Strategy and illustrated the 'stepping stone' approach to connectivity, envisaging the need to connect separated islands of good habitat quality that are usually protected in nature reserves.

Planning Framework for Natural Ecosystems of the ACT and NSW Southern Tablelands

Growing pressure on the region's grassy woodland and grassland ecosystems from urban expansion and rural sub-division generated a cooperative response by ACT and NSW government natural resource management agencies with other relevant organisations and community groups. Building on the 1998 sub-region planning strategy they prepared 'A Planning Framework for Natural Ecosystems of the ACT and NSW Southern Tablelands' (Fallding 2002). This document set out principles for strategic planning at the regional level and included information designed to assist the community maintain native flora and fauna habitats while allowing responsible development.

The Planning Framework does not directly identify locations important for connectivity. Rather, it included mapped information on threatened species distributions and native habitats that are a foundation for developing planning criteria for habitat connectivity (Fallding 2002).

The boundaries to the area covered by the Planning Framework, which followed local government boundaries, were adopted as the boundaries for this study because they encompass up-to-date and comprehensive mapping of vegetation communities for the ACT and NSW southern tablelands.

ACT Planning legislation

As may be observed from the reports, plans and maps referred to above, development of concrete plans for connectivity in the ACT have evolved over more than two decades, gradually gaining recognition as an issue that should be addressed by agencies responsible for planning and managing the natural resources of the ACT. The most recent and explicit recognition of this issue and proposal for action was included in the in the 2004 Canberra Spatial Plan.

Subsequently, a review of ACT planning legislation and development of new planning legislation (*Planning and Development Act 2007*) recognised wildlife movement corridors as one element of the planning and development system, albeit in the context of environmental impact assessment.

The *Planning and Development Act 2007* includes definitions of several types of corridor, including: "***biodiversity corridor*** means a river corridor or wildlife corridor identified in the territory plan or in a nature conservation strategy, or action plan, under the *Nature Conservation Act 1980"*, and "a ***linear transport system corridor*** (includes construction of new corridor or realignment outside existing corridor) intended to result in a major road, bus way, railway, light rail or tramway, and that is likely to have a significant impact on air quality or ambient noise or cause a significant level of vibration, significant visual intrusion or significant impact on a residential area.

These definitions illustrate what appears to be a consistent approach by identifying a defined space or area of land having a particular function or purpose in a land use planning framework. The qualifications added to the biodiversity corridor are a major limitation on the usefulness of areas identified as corridors for plant and animal conservation as they seem to assume that movement of biota will conform to pre-determined places or spaces. As outlined earlier in this report this may be true for some species but will not be for others.

The intent of ACT planning legislation in regard to biodiversity corridors is to ensure that this issue is considered when development proposals will have an environmental impact due to it involving: (a) the clearing of more than 0.5ha of native vegetation; or (b) the clearing of native vegetation if the clearing could have a significant impact on land identified in a nature conservation strategy, or action plan, under the *Nature Conservation Act 1980,* or a biodiversity corridor**.**

Unfortunately, the legislation reflects the strategies and thinking of the past 20 years, that is: islands of habitat (primarily nature reserves), to be connected by natural vegetation or similar links. A more realistic application of ecological understanding as to how organisms actually respond to their environment needs to encompass the likelihood that some corridors will not be effective for some species as they respond to climate change.

The ACT Climate Change Strategy 2007 -2025

The ACT Government's Climate Change Strategy 'Weathering the Change' (ACT Government 2007a) and subsequent Action Plan 1 (2007-2011) (ACT Government 2007b) address four objectives:

- to be smarter in how we use resources;
- to design and plan our city to be more sustainable;
- to build our capacity to adapt to and manage the changes to climate that we are now beginning to face, as well as respond to possible future changes; and
- to improve our understanding of climate change, its causes and effects, and how we need to respond.

Action 34 of the Action Plan is to 'Develop an Ecosystem Connectivity Map'. The explanatory statement for this action refers to the need to:

> "*boost the resilience of ecosystems to the effects of climate change by increasing their connectivity*"

so that they

> "*contain a continuum of different climatic zones, altitudes and ecosystem types*."

SECTION 2: Modelling Connectivity for the ACT and region

Recent thinking on landscapes, and the implications of rapid human-induced climate change, and the history of planning for connectivity in the ACT provide the context for this study. **Our landscape analysis is based on the idea of connectivity across whole landscapes, irrespective of land use and tenure, and also reflects the different landscape 'perceptions' of six model animals that illustrate potential preferences for different levels of connectivity and types of habitat.**

To identify key places of connectivity concern and remedial or planning actions, we applied tools developed by the NSW Department of Environment and Climate Change: i) the Spatial Links Tool (SLT) (Drielsma et al., 2007b) to map habitat linkage values, and ii) the Cost Benefit Approach (CBA) to assess habitat arrangement in the landscape (Drielsma et al., 2007a). **These tools integrate the benefits that a habitat supplies to an organism with the costs associated with movement between habitats. They produce alternative but complementary views of connectivity**. SLT maps the landscape connectivity value of potential linkages between areas of habitat, while CBA produces an indication of the landscape context of habitat areas. To apply these tools, gridded data layers of habitat value and movement costs were prepared in the following five key steps:

1. Prepare gridded data layers of major vegetation and land cover types;
2. Identify indicative model fauna (note: plants were not modelled in this study);
3. For each model animal, assign a habitat suitability and permeability value to each vegetation/land cover type, then assign these values to each grid cell according to its type;
4. For each model animal, determine the range of day to day movement abilities; and
5. Select source and destination points for SLT analysis.

Below we discuss the key details of each step.

Step 1. Preparation of gridded data layers of major vegetation and land cover types. Patches of vegetation or land use type are interpreted as relatively homogeneous patches of habitat forming a mosaic across the landscape.

Step 1 required the preparation of a digital map of the ecological communities occurring in the ACT and the surrounding Southern Tablelands region, from a total of 126 data-sets or data categories available for analysis. Data were provided by the relevant ACT and NSW Government agencies, namely Parks, Conservation and Lands (ACT Department of Territories and Municipal Services) and the NSW Department of Environment and Climate Change (Southern Region). The boundaries of the study area were selected with reference to the 'Planning Framework for Natural Ecosystems of the ACT and Southern Tablelands' (Fallding 2002). This was because of the readily available and broadly compatible data layers across the region.

Other data-sets that were used include:

- *land use* (such as pine plantations, street trees and urban vegetation);
- *land tenure* (such as public land and services); and
- *infrastructure* (such as arterial roads, local roads and vehicular tracks).

The street tree database records numbers of trees by species and street for Canberra suburbs. It is based on a departmental survey undertaken in 2000, updated with data on more recent plantings gathered by Paul Killey from the ANU Fenner School of Environment and Society. A spatial layer of street tree counts was derived by matching street and suburb names to road segment features in the transportation layer of the 1:25,000 scale, NSW Department of Lands Topographic database.

The various sources of data provided a multiplicity of vegetation classes, many of which overlapped in extent and differed in quality and definition. Resolving this complexity required a process of simplification, giving priority to classes with similar definitions, amalgamating some smaller classes within surrounding classes, and giving priority to the more recent and detailed surveys over older data sets. Data-sets that had similar structural and/or community characteristics were combined.

The many different types of road were grouped into three classes according to standards and traffic volume: (1) dual carriageway/high volume roads, (2) sealed roads, (3) unsealed roads. Most classes of roads associated with urban development were combined into one category (Cultural), however two classes of street trees, based on the age of the plantings (+/- 20 years) and the origin of planted species, were each retained as separate classes.

All spatial data layers were supplied in vector form and were gridded at 15m resolution, compatible with grids mapping native grasslands across the region prepared for the NSW National Parks and Wildlife Service in 2001 by ERIC (Environmental Research and Information Consortium). However, this resolution was found to be finer than could be analysed using the available computing resources**. Accordingly, a coarser 90m grid resolution layer was derived by assigning to a grid cell the dominant vegetation/landcover category within each 6x6 block of the finer resolution grid cells, unless the block of cells contained any major roads of class 1 or 2 (excluding those with urban street trees), in which case the road class was given priority**.

Where data layers overlapped in geographic extent, the values assigned to grid cells were prioritized according to the currency and mapping scale of the source data. In general, highest priority was assigned to ACT vegetation mapping, and in particular the recent mapping of lowland woodlands and natural temperate grasslands in the ACT, and riparian vegetation along the Murrumbidgee River.

As a result of this combinatory process, 126 possible classes of data were reduced to 25 classes that were used in all subsequent analyses (46 vegetation communities reduced to 14; 34 land use/tenure classes reduced to 8; and 46 types of road infrastructure reduced to 3).

The map that was produced from the combined data (Figure 4) was checked with the agency staff from whom the data-sets were sourced to confirm its suitability for this project.

Step 2. Identification of indicative fauna. This step required selection of 'model animals' to be used in the analysis of connectivity. Model animals were selected to represent fauna found mainly in lower elevation landscapes where habitat fragmentation, development pressures and significant road infrastructure may be a major threat to ecological connectivity. Those parts of the ACT within Namadgi National Park and adjacent rural land and national parks in the ACT and NSW were given less attention.

The following six model animals were chosen:

- **Small woodland bird**, associated with woodland mosaic habitats, grassy and/or shrubby understorey, low capacity to move between habitat patches (e.g. Brown Treecreeper, Hooded Robin).
- **Strongly flying bird**, associated with lowland habitats and isolated 'paddock' trees (e.g. Superb Parrot, Crimson Rosella).
- **Arboreal marsupial,** associated with woodland and forest habitats, mature trees with hollows (e.g. Sugar Glider, Ringtail Possum).
- **Ground dwelling mammal**, with a large home range (e.g. Echidna).
- **Grassland reptile**, with restricted distribution and specialist habitat requirements (e.g. Grassland Earless Dragon, Striped Legless Lizard).

- **Amphibian,** associated with riparian and wetter habitats, possibly using drainage lines and roadside habitats (e.g. *Litoria peronii)*

Step 3. Assignment of a Habitat Suitability score (on a scale of 0 (not suitable) to 10 (most suitable) **and a permeability, i.e. ease of movement, score** (on a scale 0 (most permeable) to 10 (least permeable) to each vegetation/land cover type from the perspective of each of the six model animals (see Table 1 for the assigned values) based on our judgement of relevant connectivity attributes and reference to literature.

For example, based on the procedures in Step 3, the model grassland reptile was assigned a habitat suitability score of 10 for its primary habitat (native grassland) and 0 for montane woodland, while the small woodland bird scored 10 for box-gum grassy woodland and 0 for exotic (Radiata pine) plantations. Most model animals were assigned habitat suitability scores of 0 for urban land, although the strong flying bird scored 2 by virtue of its assumed ability to fly across urban land, perhaps using remnant trees as staging posts.

Similarly the model grassland reptile was assigned a permeability score of 0 for native grassland (highly permeable) and 10 for montane woodland (not permeable), while the small woodland bird scored 0 for permeability in box-gum grassy woodland (key habitat = 0) and 8 for exotic plantations (assuming this habitat will allow some passage). Most model animals scored 10 for permeability across urban land, although the strong flying bird scored 8.

Step 4. Determination of the range of day-to-day movement abilities for each model animal based on the average distance each might move in (i) low quality habitat and (ii) high quality habitat (see Table 1 for the assigned values). These values were used to convert the gridded permeability scores (range standardized) into grid cell effective distance measures (in metres) (the 'costs' used by the SLT tool to identify the least-cost links between high quality habitat areas).

For the model grassland reptile, very limited mobility (10m) was assigned to low quality habitat and a value of 100m was assigned to high quality habitat. For the modelled strongly flying bird, values of 1000m and 10km were assigned respectively.

Step 5. Identification of points to act as source/destination points for the SLT analysis. SLT identifies the least cost paths (links) between these pairs of points. For each model animal, a total of 5000 points were selected by randomly sampling grid cells of high habitat suitability (i.e. cells with the highest or next highest assigned habitat suitability scores) proportional to their frequency of occurrence.

The SLT and CBA tools were run separately for each model animal to produce gridded layers of link value and neighbourhood habitat area respectively. Permeability scores were range standardized and expressed in the range of 0 (least cost, most highly permeable) to 1 (highest cost, least permeable) for the CBA analysis. For the SLT tool, we adopted the parameter settings suggested by Michael Drielsma (NSW DECC, pers. comm. 29th. May, 2009) for the Brown Treecreeper as an example of a small woodland bird (Table 1). We accepted the default parameter settings for the CBA analysis, including those that determine the sampling strategy (window size 7x7) and resolution to apply with distance from the focal grid cell (zone ratio 4) to improve computational efficiency (Drielsma et al., 2007a).

For a full description of the models used and explanation of the habitat and alpha values (see Drielsma 2007a, 2007b).

Habitat quality and permeability scores can be varied and the model run again in the light of new information and/or detailed data obtained for a known animal. This may assist in identifying specific planning and management requirements to address a particular location, place or set of circumstances.

For each model animal, the following data layers were produced:

1. **Habitat Quality** (see Figure 5 for example map of one model animal);
2. **Habitat Permeability** (see Figure 6 for example map of one model animal);
3. **Movement Cost Scores (Effective Distance)** (see Figure 7 for example map of one model animal); and,
4. **Neighbourhood Connectivity and Link Values for each model animal** (see Figures 8 – 19 for paired maps of each model species (ACT and regional scales) and Figures 20 & 21 for all species combined (ACT and regional scales).

Some caution is required in interpreting the maps. The maps are for modelled parameters and are not to be interpreted as indicating actual conditions for a particular species. Modelling of this kind would require species-specific data for each parameter in the model.

Stream connectivity

A similar approach was applied to evaluate connectivity for freshwater dependent species. **We have chosen fish as a model to illustrate the potential effect of barriers on in-stream movement**. We could find no suitable classification of freshwater habitat for the region. Instead, we assessed regional connectivity for riverine biota by describing the frequency of occurrence and location of constructed features that could act as barriers preventing the migration and dispersal of aquatic biota. We mapped the length of connected stream up and downstream of each barrier and calculated for each barrier the length of stream that would be connected if the barrier were to be removed. We focused on barriers to fish passage as this is an issue of particular concern both in Australia (Pethebridge *et al*., 1998; Thorncraft and Harris, 2000; Gordos *et a*l., 2007) and elsewhere (Kemp *et al*., 2008; WWF, 2006; Resh, 2005).

For this analysis, the study region was extended further to the south to take in the entire Murrumbidgee River catchment upstream of Burrinjuck Dam. Those parts of the Natural Ecosystems Planning Framework study region to the east of the Murrumbidgee River catchment were excluded. Data on artificial features known to affect fish passage were compiled from the NSW Department of Lands 1:25000 scale topographic database with additional information on culverts and bridges provided by the ACT Department of Territory and Municipal Services. These included all waterbodies attributed as artificial, that intersected a mapped streamline, all dam walls and dam batters, and all mapped road crossings including floodways, fords and culverts. Just 93 road crossings were mapped, comprising less than 1% of the road crossings identified by spatially intersecting the NSW Department of Lands 1:25,000 scale road and stream data layers. To provide a more comprehensive coverage, these road/stream intersection points were added to the database of potential barriers, except where a bridge was present and fish passage was thus unlikely to be impeded (New South Wales Department of Primary Industries, 2005).

To calculate the connected stream length up and downstream of each potential barrier a model of surface flow pathways was derived from a DEM (Digital Elevation Model). The 20m resolution DEM was developed using the ANUDEM elevation gridding program (Hutchinson, 2006) from 1:25,000 scale source contour, elevation spot height and directed streamline data extracted from the NSW Department of Lands topographic database. A stream network for analytical use was derived by tracing the flow pathways from the mapped channel heads to their outlet at the edge of the study region (Burrinjuck Dam), following the method of Stein (2007). The length of connected stream was assessed both for all streams and for those of Strahler order 3 and above. At this map scale, streams of order less than 3 are likely to be ephemeral streams that provide only limited habitat for fish.

Limitations

This report uses model animals, not real animal data. We assume that the six model animals are a reasonable approximation of the sorts of fauna that require different types of connectivity. Model animals were used to assist the reader in interpreting the type of connectivity model discussed. More detailed modelling based on data for real animals is required for detailed planning purposes.

The results are also potentially sensitive to the choice of model parameters and ratings for habitat quality and permeability, and to grid resolution. Further research is required to understand the impact of these choices and identify appropriate values specific to each of the model animals, or indeed adding model animals' characteristics of montane habitats and extensive areas of continuous natural vegetation. Undertaking sensitivity analyses was beyond the scope of this study, but would be needed for more detailed modelling and planning. 90 metre pixels were used for this modelling, due to the large computing resources needed for the area covered. More detailed analyses for individual, real species may require finer resolutions analyses (e.g. 15 metre pixels).

High resolution data layers for scattered trees (remnants from highly modified box-gum grassy woodlands) were not available. Yet we know that these are critically important for connectivity for a range of species e.g. Superb Parrot (Manning *et al.* 2006b). Hence, some areas containing undetected scattered trees may provide more connectivity for some organisms than the modelling suggests.

Similarly, connectivity may be underestimated for species dependent on habitat typically distributed as narrow linear features (e.g riparian vegetation) because habitat quality scores were assigned according to the dominant vegetation type at the coarser grid cell resolution. Conversely, connectivity may be overestimated where environmental factors reduce the likelihood of movement in otherwise suitable habitat, for example, where steeper hillslopes are avoided.

The combination of data from different sources, employing a range of different classifications and based on mapping compiled at different times and at a variety of spatial scales, introduced further uncertainty. Occasional anomalies were evident, for example, where vegetation mapping sourced from the ACT merges with that provided by NSW agencies because of overlapping and/or incompatible vegetation class descriptions.

The analysis of stream connectivity similarly contains uncertainty due to the limitations of data and analytical methods. Some of the data lack currency. Recently constructed impoundments and road crossings might have been omitted while older structures may no longer be operational. For example, the NSW Department of Lands digital topographic database still records the presence of a weir on the Murrumbidgee River at Casuarina Sands although this was removed in 1991 (Lintermans and Environment ACT, 2002).

The likelihood that fish will be able to traverse a structure depends on its design characteristics and method of construction, patterns of stream discharge and sedimentation and the swimming capabilities of the fish (New South Wales Department of Primary Industries, 2005). However, in the absence of detailed information for individual structures and fish species, all in-stream structures were assumed to present equal difficulties for fish passage. For instance, a ford or floodway that is designed to be regularly inundated may allow fish passage under some discharge conditions, yet for the vast majority of road crossings the type of structure present was not specified. The absence of suitable data also prevented consideration of other anthropogenically derived impediments to fish passage, including habitat degradation due to pollution, loss of riparian shading, sedimentation (sand slugs) and lining of channels with concrete in urban areas.

Modelling results and implications

In this section, we outline and explain the results of the connectivity modelling and discuss the implications for planning and policy aimed at climate change adaptation.

Results

This analysis has produced a large spatial database that is best explored within a GIS system. Here we provide a summary and a description of model outputs and maps.

Link Value and Neighbourhood Habitat Area

Figure 5 shows the areas in the study region that were most suitable for the model small woodland bird species and corresponds generally with box-gum grassy woodland. In the ACT this includes the hills from Hall to Mulligans Flat and Goorooyarroo nature reserves and the Majura Military Training Area, the lower Molonglo valley, and the Tharwa and Naas woodlands, broadly the location of known or recently recorded habitats of the Brown Treecreeper.

Figure 6 shows areas with extant woodland and scattered trees and indicates areas of greatest permeability for the model small woodland bird species with urban and montane areas being least permeable. Much of the NSW land surrounding the ACT indicates medium to high permeability for woodland birds (as modelled).

Figure 7 shows those parts of the landscape which are of least cost to the model small woodland birds species, and conversely the highest cost (e.g. urban land and unsuitable native habitats) for this model species. The scale for this modelled map is 90m of uniform vegetation. Modelling could be undertaken for shorter distances in a more detailed study.

Figures 8 & 9, 10 & 11, 12 & 13, 14 & 15, 16& 17, 18 & 19 show the Link Value (red colour gradient, darker values indicating higher values) and Neighbourhood Connectivity (green gradient), which are indicators of where potential habitat connection is good for each modelled species (note: Figures 8 to 19 are paired for each model animal at the ACT and regional scales).

Thus, for the model small woodland bird species the Tinderry Range stands out as a well connected area. Although the habitat quality scores are fragmented, permeability is high leading to the movement cost being very low, and therefore the area appears to be well connected with surrounding areas.

Figure 20 and 21 show the averaged Link Value and Neighbourhood Connectivity value for all six modelled species. Note: this data is intended to be indicative only because averaged data will, by definition, underestimate connectivity for some species, and overestimate it for others.

A summary of the key features of the maps for each model animal at the ACT and regional scales and the implications for connectivity is given in columns 2 and 3 respectively in Table 2. Key connectivity issues, including constraints on and opportunities for enhancing connectivity for each model animal, are summarized in column 4 of the Table, and provide the basis for identifying priorities areas for connectivity actions (see below).

Connected streams

Figure 22 shows the locations of more than 22,500 physical structures potentially forming a barrier to fish passage identified in the Murrumbidgee River catchment upstream of Burrinjuck Dam (summarised in Table 3). Just over one-third of these are impoundments, including both small in-stream dams and weirs, with large reservoirs with road crossings comprising the remainder. The great majority of all types of structures were found on streams of Strahler stream order 3 or less, reflecting the numerical dominance of smaller streams in the catchment (Table 3) and the use of bridges at road crossings over larger streams.

Figure 23 maps the length of connected channel upstream of each structure (summarised in Table 4). The maximum length of connected channel unaffected by structures that potentially impede fish passage is 2364km, being the sections of the Murrumbidgee and Goodradigbee Rivers upstream of Burrinjuck Dam. This length of connected channel is however only about 5% of the total length of channel in the upper Murrumbidgee River catchment. Moreover much of it is inundated by Burrinjuck Reservoir. For streams of order 3 or larger, the maximum connected length is 682km out of a total of nearly 9,000km. In most cases however, the length of channel free of potential barriers to fish passage is substantially less. Just six sub-catchments with a total length of connected channel of 275 km or more were identified (Table 4).

Discussion and Implications of Results

Planning and conservation responses to climate change

To date, some suggested approaches to facilitate adaptive responses by organisms to climate change (hereafter termed 'adaptation') include: increasing the number of parks and reserves (Halpin 1997;Hannah 2008, Stefan *et al.* 2009); assisted colonization and translocations (Hoegh-Guldberg *et al.* 2008); off-reserve conservation (Heller and Zavaleta 2009, Felton *et al.* 2009); *ex situ* conservation (e.g. seed banks, zoos, breeding programmes, Hannah 2008); limiting threats, such as habitat loss (Hannah 2008); enhancing connectivity, in particular through 'ecological networks' (Opdam & Wascher 2004; Opdam *et al.* 2006), the encouragement of scattered trees across landscapes (Manning *et al.* 2009b); and 'anticipatory restoration' (Manning *et al.* 2009a).

A number of these strategies have particular relevance to the ACT. These include:

Ecological networks and climate change

An important large-scale strategy for facilitating adaptation to climate change will be a shift from a protected area-only approach towards an 'ecological network' strategy that includes protected areas, corridors and surrounding landscapes that will provide connectivity across landscapes (Opdam & Wascher 2004; Opdam *et al.* 2006). Opdam *et al.* (2006) define an ecological network as:

> *"a set of ecosystems of one type, linked into a spatially coherent system through flows of organisms, and interacting with the landscape matrix in which it is embedded"*

There are over 150 landscape-scale and regional ecological networks under development around the world (Bennett 2004). For example: Yellowstone to Yukon in the United States (http://www.y2y.net/home.aspx), The Pan-European Ecological Network in Europe (http://www.coe.int/t/dg4/cultureheritage/regional/EcoNetworks/PEEN_en.asp) and Mesoamerican Biological Corridor (http://www.tbpa.net/case_10.htm).

In Australia, similar initiatives are being developed for the Great Eastern Ranges (http://www.environment.nsw.gov.au/) and Kosciuszko to Coast (http://www.k2c.org.au).

While ecological networks will provide the backbone of adaptation strategies, they may not be enough on their own. This is because landscape connectivity (e.g. corridors), as perceived by humans does not always increase functional connectivity for other organisms (Donald & Evans 2006; Lindenmayer and Fischer 2006; Boitani *et al.* 2007). Thus, the importance of the landscape context surrounding ecological networks extends far beyond management of the 'permeability' of the matrix to organisms. For example, Sekercioglu *et al.* (2007) found forest birds in Costa Rica did not commute from extensive area of intact forest; rather they fed and bred in the agricultural countryside.

The implication is that connectivity is something that must be adopted as part of the planning process and applied across whole landscapes, irrespective of the tenure or use of the land. An example of this in practice is the ACT Government's land management agencies approach to feral animal control, which operates irrespective of tenure. In essence, this is a 'whole-of-landscape' approach. This could potentially provide a model for a wider adoption of a whole-of-landscape approach to conservation and planning in the ACT that includes identifying critical places (for example, nature reserves and connectivity links) that should not be lost or should be treated as a priority location for habitat resoration measures.

Scattered trees

Scattered trees are common in the lowlands of the ACT, and are derived from the modification of box-gum grassy woodland for agriculture. These areas are favoured for new suburb development. Scattered trees could facilitate climate adaptation by many species because of their sparse, but continuous cover across whole landscapes and they can complement reserves and ecological networks by creating 'blurred' edges (Manning *et al.* 2009b). To maintain and enhance scattered trees, existing mature trees must be protected/incorporated into planning decisions and cover enhanced in the long-term through anticipatory restoration.

Anticipatory restoration

Ongoing landscape and climate change that effects landscape suitability and connectivity for organisms may mean that it will be necessary for land managers, developers and land use planners to anticipate the current and future needs of organisms - and restore or establish suitable habitat and connectivity in advance (Manning *et al.* 2009a). This may increasingly become an important part of environmental planning and assessment of mitigation measures in response to environmental impacts. For example, in a part of a given landscape identified as critical for connectivity (see SECTION 3), tree regeneration and new plantings might be planted as part of a program to ensure a mix of age classes and the long-term replacement of current mature trees by a certain date in the future.

Assisted translocations

In some cases, organisms with limited colonisation abilities, or ones that are isolated by insurmountable barriers to movement due to loss of habitats, e.g. as a consequence of urban developments, may require assistance to maintain connectivity (Peters 1990, Hoegh-Guldberg *et al.* 2008, Richardson *et al.* 2009). Where connectivity is identified as poor in the ACT and region for such species, this approach could be considered.

Implications of for ACT Policy

A major challenge for land use planners is that different organisms perceive and respond to the same landscape differently (Box 1). This will be a particularly substantial change because of anticipated species-specific responses to climate change (Steffen *et al.* 2009). The usability of a landscape for a particular organism will often vary on a continuum rather than occur as either habitat or non-habitat

(Lindenmayer *et al.* 2003; Manning *et al*. 2004; see Figure 2). Planners therefore need to consider the needs of a range of species with different views of landscape connectivity.

A planning approach incorporating continua in landscapes would integrate connectivity through time into plans in the short, medium and long-term. For example, in the ACT, many new residential developments are being built on land formerly occupied by box-gum grassy woodlands - and remnant scattered trees remain. If these trees are preserved and continue to provide key habitat elements, particularly for birds, bats and arboreal mammals, how will replacement trees be planted, allowed to grow, and maintained into the future?

New thinking and understanding of how animals and plants perceive and/or respond to landscapes requires a more nuanced and ecologically realistic concept of habitat in the planning process. Therefore, the type of ecological corridor or area for connectivity adopted in this report envisages plant and animal movement as potentially occurring anywhere where conditions are suitable. Such conditions might extend from high quality habitat at one extreme to single, mature trees in a residential development at the other. The only fundamental characteristic is that the individual animal or plant perceives or responds to the environment in such a way that it is enabled to move across the landscape.

Unless there is a change in the definition of a biodiversity corridor towards the concept of whole-of-landscape connectivity, an adoption of a broader interpretation of how an environmental impact assessment is undertaken, the conclusions of the work undertaken for this report are likely to have very limited influence on achieving the goals of the Spatial Plan. In addition, there may be scope for special training programs for officers in agencies responsible for planning and management of the ACT's natural resources on the topic of planning for biodiversity conservation in response to climate change. These would aim to equip agencies with the knowledge and skills to ensure best practice into the future.

Some of the most modified, but also most productive parts of the landscape in the ACT are used for agriculture and urban development and are the least well protected (ACT Government 2004a; Section 6.3). Yet many organisms do, or did in the past, use these areas for some or all of their lifecycles; including connectivity. In fact, in some 'natural' situations, higher densities of many organisms are skewed towards the most productive parts of the landscape (Braithwaite *et al.* 1993). Ecological communities that were typical of these parts of the landscape are now endangered, for example, box-gum grassy woodlands and derived grasslands and native grasslands (ACT Government 2004, 2005). Those that remain are often highly modified, and may no longer fulfill the criteria for listing as threatened under Territory or Commonwealth legislation (e.g. scattered box-gum trees). Nevertheless, these areas can still be of high ecological value for many organisms, and can provide high levels of connectivity (e.g. for the Superb Parrot; Manning *et al.* 2006b).

The policy statements contained in the current ACT Spatial Plan and the legislated definition of a biodiversity corridor do not adequately address the issue of the conservation and connectivity value of these off-reserve areas and the characteristics of wildlife movement. This does not mean that these areas must therefore necessarily be reserved in the traditional sense, but that plans for conservation and connectivity management outside reserves must be included in the planning process early to ensure (a) maximum ecological effectiveness; and (b) minimum disruption to the development process once underway. **Critical to achieving this is sound knowledge of which species are relevant (in terms of those actually or potentially naturally occurring in the subject area), where they are distributed, and how they use elements in their environment and move across the landscape, long before planning for land use change occurs.** This would require a more comprehensive, long-term monitoring system than currently occurs in the Territory.

The application of the patch-matrix-corridor model alone to the conservation of native vegetation that is modified, but not destroyed, could have unintended negative consequences. For example, using such an approach to planning would select patches of habitat according to their size, quality, and distance from each other. Where possible, these would then be connected by corridors.

This approach can lead to:

1. protection of only the 'best' quality habitat areas (for example the box-gum grassy woodlands least modified by previous land use) leaving other areas available for development; and
2. their previous history as a land bank or under farm management disqualifying them from selection due to unsubstantiated and narrow criteria, notwithstanding their continued habitat value and potential for recovery and their status as endangered ecological communities.

However, modified habitat, such as scattered paddock trees in the rural/urban matrix often has great value for biota (Manning *et al.* 2006a). Consolidation and protection of 'best' habitats only according to a patch-matrix-corridor perspective could potentially become a self-fulfilling prophecy that fails to meet the intended objectives, particularly those now adopted for the ACT's Spatial Plan and Climate Change Strategy. **Planning for climate change adaptation will require both the patch-matrix-corridor and the newer continuum approaches.**

It is important to recognize that while a habitat element may have the same basic ecological value wherever it is; threats may vary depending on land use. For example, scattered paddock trees in rural or urban areas may serve similar ecological roles for some species, however the threats to their survival are often quite different between rural and urban environments. In urban areas there is an opportunity to design around viable trees in order to retain some permeability for native fauna. However authorities need to be pro-active and consider long-term survivability, mandate improved criteria for tree retention in estate developments, and provide ecologically defensible boundaries around trees or groups of trees.

If it is assumed that conservation measures in the urban matrix are unnecessary, important elements such as small patches of habitat and isolated trees will be lost. It is imperative that ecologically successful land use planning:

1. integrates the needs of different of species into the urban planning process and design of urban developments;
2. embeds nature reserves in a connected landscape matrix that contains key habitat elements; and
3. embraces an approach that recognises the potential of achieving ecological objectives as well as planning objectives.

SECTION 3: Ecological planning for climate change in the ACT

In this section, we outline key research needs and recommended changes in light of new thinking in landscape ecology, and the outcomes of modelling in this study.

Recommendations for research to inform planning

- Undertake more detailed assessment of opportunities to improve connectivity across the ACT region, focusing on species of concern and places that modelling indicates are key connectivity areas. These assessments could include:
  - Modelling of 'real' species of concern using using existing data and new data collected in the ACT region as part of connectivity-related monitoring (see below).
  - Commissioning of a high-resolution survey of scattered trees in both urban and rural areas, including their condition and potential function as habitat for native species (e.g. nesting hollows).
  - A program of connectivity-related monitoring. This might focus on key places identified in this study and include studies into actual movement of native species across potential barriers to movement (e.g. roads, developments, unsuitable habitat). This work may lend itself to collaboration with post-secondary institutions and be a topic for post-graduate student projects.
  - Application of modelling at a scale that is specific to the particular species of interest (this report uses a 90 metre pixel, but a finer resolution (e.g. 15 metre pixel) may be appropriate for some species). Such modelling could include plants of interest.
  - Incorporation of additional parameters into modelling, e.g. environmental characteristics such as slope, that may influence habitat suitability / permeability could follow from suggested monitoring programs.
- Undertake a sensitivity analysis to explore the effect of model parameter values, data resolution and analysis scale on model outcomes.
- A future connectivity study could identify connectivity issues in rural sub-divisions as this is an emerging landuse that may affect connectivity.
- Model neighbourhood connectivity and link value under different climate change and/or landuse scenarios. This would require the ability to model future habitat distribution under each scenario, and its suitability and permeability for each model animal.
- Compare current and future connectivity with that modelled for pre-European times.
- Improve the assessment of in-stream connectivity by considering the probability of passage by fish and other aquatic biota for each in-stream structure. This might be based on expert ratings assigned according to the design and construction characteristics of each structure, relative to the swimming capabilities of the fish species of interest, stream discharge and, where available, field measurements. This activity could build on the audit of road crossings

being undertaken by the NSW Department of Primary Industry (Kirby Burns, NSW Department of Primary Industry pers. comm. 26/5/09).

Key issues and principles for planning and management that includes connectivity

Consideration of connectivity issues should always be a requirement during the design and construction phase of all developments, with a view to incorporating connectivity enhancement and remediation measures in subsequent development. Key issues to be considered include:

- Linking existing ACT nature reserves to each other and to those in NSW;
- Avoiding further fragmentation of woodland habitat in the NSW part of the study area and where possible strengthening habitat links;
- Maintaining and enhancing especially, for aquatic biota, the integrity of the Murrumbidgee River as a key connectivity feature crossing the ACT and linking into NSW;
- Prioritising in-stream structures for removal or remediation to improve fish passage. Barriers could simply be ranked according to the length of stream that would be connected if the structure were removed or remediated. A more comprehensive scheme for prioritising works to improve fish passage would also take into account the position of the barrier in the stream network, the habitat quality of the connected streams, the potential to assist dispersal of exotic species and socio-economic costs and benefits (Gordos *et al*., 2007; Kemp *et al.*, 2008; Meixler *et al*., 2009). Remediation measures need not be prohibitively expensive. For example, simple measures such as installing spoiler baffles in a pipe culvert can be cost effective (Macdonald and Davies, 2007).
- Recognising that all parts of a given landscape may play a role in conservation and connectivity (irrespective of that land use, tenure or formal designation). Current usage of the term biodiversity 'corridor' alone (viz. ACT *Planning and Development Act 2007*) does not necessarily mean that habitat and landscape connectivity across the ACT and into the surrounding region will be achieved;
- Considering connectivity in projects involving planning over the short, medium and long terms;
- Considering species-specific responses of organisms to climate change;
- Undertaking habitat recovery actions in key locations (see later list). It is essential that targeted monitoring assess the effectiveness of this;
- Maintaining and enhancing connectivity, plan and build urban developments that are permeable to multiple types of organism;
- Taking into account that the importance of a particular part of the landscape for an organism can change through time, e.g. change in habitat structure;

- Considering human-assisted translocation of animals to ensure genetic mixing, where remediation of isolated habitats cannot reasonably be implemented or natural movement of fauna is not expected (e.g. specialist flora and fauna of native grasslands).

- In the case of in-stream environments, particularly where roads cross or impact on creeks or wet areas, analysis of connectivity in the design and construction phase of all developments should encompass the following:

    - Considering the habitat and movement requirements of different aquatic species;

    - Incorporating weightings for different types of barriers according to their potential to impede movement;

    - Including key ecological processes:
        - Sediment processes,
        - Hill slope processes,
        - Nutrient movement;

    - Assessing barriers to sediment and nutrient movement.

A key implication of the above is that planners must now think of connectivity for biodiversity as a long-term process and one that recognises climate change, even as land uses change. At the same time, this does not mean all land used by native species should always become traditional conservation reserve, but rather that conservation and urban land uses should be integrated and be mutually supportive as far as possible. This leads to several recommendations designed to assist planning in the ACT and region, particularly in the context of implementing the ACT Climate Change Strategy and achieving the goals of The Spatial Plan:

- All three forms of connectivity should be considered in the planning process and delivery of development projects. This would require a change in the *Planning and Development Act 2007*, insofar as environmental impact assessment is administered;

- A series of questions should be asked in the early stages of planning for connectivity:
    - o What species are relevant in this landscape (i.e. which are important to the community and/or for ecological functions)?
    - o How are they distributed?
    - o How do they use elements in the landscape?
    - o Are there ways to accommodate their future needs in planning and design?
    - o Is it possible to create developments that are 'permeable and livable' for wildlife?
    - o If not, can connectivity needs be enhanced elsewhere in the landscape through targeted restoration measures or possibly environmental offsets?

- Where connectivity is poor but critical for local flora and fauna, planning and management should enhance connectivity as a high priority and a condition for urban and other development;

- Reserves and biodiversity ‘corridors’ should be maintained and enhanced – with particular consideration for areas identified below (see Connectivity Priorities). Connectivity should be maximised in surrounding landscapes (e.g. leased and agisted rural land and urban developments);

- Develop of short course training on connectivity for climate change for staff in agencies responsible for land planning and management in the ACT region.

Identification of priority areas of connectivity

Results from modelling the six types of native animal have led to the identification of several principles for planning and management that include connectivity, and also some key locations that warrant high priority in considering remedial planning or management action to maintain or improve connectivity. In some cases, existing urban development in the ACT means that enhancing connectivity may only be possible in neighbouring areas of NSW. This will require cross-border cooperation on planning and landscape management.

Modelling of six selected model animals (Figures 8 - 21) indicates a number of locations in the ACT and region where high priority should be given to maintaining or improving connectivity. These locations, drawn from Table 2 and listed below, add emphasis and extent to the wildlife corridors identified in the Spatial Plan and Action Plan 27 (ACT Government 2004a, b):

- Black Mountain to Belconnen Hills and the lower Molonglo River;
- Callum Brae/Jerrabomberra to NSW (via Hume);
- Hall to Mulligans Flat and Goorooyarroo nature reserves and then with Mt Ainslie and Mt Majura nature reserves and the Majura Valley (including land occupied by the Department of Defence);
- Mulligans Flat and Goorooyarroo nature reserves to NSW (Greater Goorooyarroo);
- East Jerrabomberra nature reserve to Queanbeyan nature reserve (NSW) (across railway line and Lanyon Drive);
- Strengthening the links between Mulligans Flat and Goorooyarroo nature reserves with the Majura hills and adjacent NSW land to their north (Greater Goorooyarroo) needs consideration before woodland habitat areas become more isolated and/or fragmented;
- Strengthening the habitat links between Naas/Tharwa and nearby land to the east in NSW needs consideration before these areas become more isolated;
- Strengthening the habitat links between the Tinderry Range and woodland habitat to the north and northeast of Lake George needs consideration before these areas become more fragmented.

Enhancement of connectivity in these key areas will require a range of approaches:

1. Strategic establishment of nature reserves in key locations. These would be selected using standard criteria for reservation, e.g. condition/quality (although scope to do this in the ACT

is limited).

2. Strategic establishment of 'biodiversity corridors'. The aim in these would be to protect and restore loss of degraded ecosystems, e.g. box-gum grassy woodland, grassland or chain of ponds. These areas may not meet standard criteria for reservation, and initially may be highly degraded although capable of restoration.

3. Restoration of key connectivity elements in 'off reserve' land. For example, this might involve establishing trees, shrubs, water bodies, grassland, dead wood. Within suburbs this might involve 'mini habitat patches' focused on individual trees, pocket parks or mixed use areas. On leasehold or agisted land, integration of habitat elements with management for primary production, while in-stream structures at road crossings might be altered to improve passage of fish and other riverine biota. Mature trees outside nature reserves are likely to be a key factor in maintaining connectivity for some species. Continued loss of these trees is likely to weaken the current level of connectivity in the ACT and region.

Adopting these approaches would involve applying a range of legislative instruments, regulations, covenants and contracts to ensure long-term positive effects on connectivity.

Glossary

arboreal	living in or connected with trees.
altitudinally	up or down with respect to height above sea-level.
biodiversity	the variability among living organisms from all sources (including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part) and includes diversity within and between species and the diversity of ecosystems. It is usually considered at three levels: genetic diversity, species diversity and ecosystem diversity.
climate change	any long-term significant change in the 'average weather' that a given region experiences. In recent usage, the term 'climate change' often refers to human-induced changes in modern climate due to global warming.
conservation	protect, retain, usually in context of land set aside for this purpose
connectivity	the extent to which particular ecosystems are joined with others of similar kind; the ease with which organisms can move across the landscape. Also applies to the extent to which populations of a species are able to interact with each other through gene flow (interbreeding).
corridor (wildlife or biodiversity)	an area of land, usually narrow, that differs from the surrounding matrix and is usually assumed to allow animals and plants to move from one part of the landscape to another.
ecological connectivity	the connectedness of ecological processes at multiple scales.
ecological processes	all the processes that occur between organisms, and within and between communities, including interactions with the non-living environment, that result in existing ecosystems and bring about changes in ecosystems over time.
ecological community	an assemblage of plant and animal species that occur together in space and time.
ecosystem	a dynamic complex of organisms and their environment, interacting as a functional unit.
ecosystem services	the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life.
ex situ conservation	conservation undertaken outside the habitat within which an organisms naturally occurs (e.g. a zoo or breeding facility).
fauna	the animal species characteristic of a region.
feral animal	an animal that is not native to Australia (e.g. fox, goat, cat).
flora	the plant species characteristic of a region.
habitat connectivity	the connectedness of patches of habitat suitable for a given individual species.
human-induced	effects on (natural systems) generated from human activities.
habitat (patch):	an area or areas occupied, or periodically or occasionally occupied, by a

	species, population or ecological community. A habitat is composed of and influenced by both abiotic and biotic factors.
habitat recovery	the process of ecological change (assisted or natural) following disturbance or degradation of a habitat.
landscape	a heterogenous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout. Landscapes vary in size, down to a few kilometres in diameter.
landscape connectivity	the human perception of physical connectedness of vegetation cover in a landscape.
lifecycles	the progression of an organism through a series of stages of development.
matrix	the most extensive and most connected landscape element type present which plays the dominant role in landscape functioning. Also, a landscape element surrounded by a patch. “Hostile matrix” is a matrix which is not usable for as habitat or movement by particular organism or organisms. “Friendly matrix” is a matrix which is usable for as habitat or movement by particular organism or organisms, and complements the conservation values of the patches and reserves that it surrounds.
migrated	moved from one place to another (usually at a landscape scale) in response to seasonal, reproductive or other natural processes.
nature reserve	an area formally set aside (usually under legislation) for the purpose of protecting natural ecosystems and their constituent plant and animal species.
neighbourhood connectivity	a term used in connectivity modelling tools developed by Drielsma et al., 2007a, b. It can be broadly equated with habitat connectivity and is an organism-specific measure of the extent of connected habitat that is generated for each pixel/grid cell across the landscape. It is the ‘connectivity’ of a site to its ‘neighbourhood’ (defined by access to resources or colonisation sites). This includes considerations of patch size, condition, shape, proximity to other patches etc. How good a site is in terms of its access to resources is determined by the Cost Benefits Approach tool (Drielsma et al., 2007b). The role that a site plays in connecting other sites to each other, its ‘link value’ is determined using the Spatial Links tool (Drielsma et al., 2007b).
novel ecosystems	new species combinations, with the potential for changes in ecosystem functioning; including those that are the result of deliberate or inadvertent human action, but do not depend on continued human intervention for their maintenance.
‘off reserve’ land	biodiversity conservation conducted on land or water outside the formal conservation reserve system.
patch	a non-linear surface area differing in appearance from its surroundings (Forman and Godron 1986). Often associated with the term ‘habitat’.
permeability	the level of ease with which an organism or organisms can move through an element of a landscape.

restoration	returning habitats to a known past state or to an approximation of the natural condition by removing threatening processes such as introduced species or by reinstatement of lost processes.
riparian	any land that adjoins, directly influences, or is influenced by a body of water.
scattered paddock trees	trees that represent the original woodland or forest vegetation that was cleared to establish farming land. Paddock trees are usually widely spaced, over 100 years old and provide nesting hollows used by native birds and other animals, other resources and connectivity.
threatened (species and communities)	an umbrella term for various categories of risk of extinction (includes Extinct, Vulnerable and Endangered), applying to a species or ecological community.
translocation	to deliberately move members of a species from one place to another, usually because this cannot occur naturally.
'whole-of-landscape' management	management of a landscape as a whole unit rather than individual parts.

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Appendix 1 – Tables

Table 1 Amalgamated vegetation and land cover categories (Figure 4) showing classes included from original source data (Appendix 3)

Table 1	Raw data used in modelling												
Vegetation Class Description (composite)	Vegetation Classes Included in Composite Class	Habitat quality	Permeability	Habitat quality	Permeability	Habitat quality	Permeability	Habitat quality	Permeability	Habitat quality	Permeability	Habitat quality	Permeability
		Small woodland bird		Large strongly flying bird		Arboreal marsupial		Ground dwelling mammal		Grassland reptile		Amphibian	
Natural Temperate Grassland (ACT known sites, NSW modelled sites)	Natural Temperate Grassland	5	5	7	0	0	7	8	0	10	0	8	0
Natural Temperate Grassland (NSW remote sensing) & Native Pastures	native grassland (high prob of occurrence), native grassland (low prob of occurrence), native pasture, grassland (unspecified)	5	5	7	0	0	7	8	0	8	0	8	0
Lowland woodland (ACT known sites)	partially_modified_lowland_woodland(woodland), partially_modified_lowland_woodland(open forest), partially_modified_lowland_woodland(open woodland)	10	0	10	0	10	0	10	0	0	6	8	0
Grassland-woodland mosaic (ACT known sites & NSW modelling)	box-gum woodland, grassland-woodland mosaic, moderately_modified_lowland_woodland(woodland), melliodora-blakelyi woodland, moderately _modified_lowland_woodland (open forest)	7	0	10	0	7	0	10	0	2	4	8	2
Substantially modified lowland woodland/forest (ACT known sites & NSW modelled)	substantially modified lowland woodland, secondary grassland(high prob of occurrence),secondary grassland(low prob of occurrence), secondary grassland(moderately modified lowland woodland), secondary_grassland(partially modified	2	0	10	0	5	7	7	0	0	6	4	2
Heath/shrubland	heathland-shrubland-herbfield-rock, heathland-shrubland-herbfield-rock	7	0	4	0	2	2	6	0	0	10	8	2
Riparian	riparian forest, riparian woodland, wetlands, aquatic and fringing veg complex, Callistemon-Kunzea riperian, Casuarina riparian woodland, Casuarina woodland, viminalis riparian	7	3	6	0	7	0	8	0	0	10	10	0
Wetlands	wetlands	0	3	2	0	0	2	4	2	0	10	10	0
Montane /subalpine woodland	subalpine woodland, montane woodland	7	8	4	0	7	0	8	0	0	10	8	4
Forest	upland montane forest, dry forest, wet forest, macrorhyncha-rossii forest,	2	8	2	6	7	0	8	0	0	10	8	4
Open forest	bridgesiana-dives woodland, macrorhyncha-rossii woodland, pauciflora-rubida woodland	7	3	4	6	7	0	10	0	0	10	8	4
Callitris woodland	callitris woodland	7	3	7	0	2	0	10	0	0	10	8	4
Kunzea derived shrubland	kunzea derived shrubland	3	3	2	0	0	5	8	0	0	10	8	4
Former pine plantation	former pine plantation post-2003, former pine plantation pre-2003	0	8	4	0	0	7	6	0	0	10	4	5
Exotic plantation	softwood production, plantation/arboretum, oleaginous fruit, exotic plantation, Plantation (Horticulture-Orchard)	0	8	4	4	0	7	4	3	0	10	4	6
Native plantation	native plantation	3	8	4	2	2	4	4	3	0	10	6	5
Exotic pastures & degraded native pastures (natural & derived	modified grassland/urban vegetation complex,modified pasture,exotic pasture,no data areas in natural Ecosystems Project extant vegetation cover, runway (grassed	0	8	7	0	0	0	3	2	0	10	2	7
Native street trees	street trees(native species > 60% street tree-count, and 20+ years)	0	10	6	0	0	8	0	10	0	10	2	10
Exotic street trees	street trees (exotic,young (< 20 years) natives)	0	10	4	0	0	4	0	10	0	10	2	10
Cultural	urban, residential, building, built up area, all roads and tracks (excl. pathways), runway, building complex, general industry, transport facility (airport, railway stations, car park, helipad, bus interchange, marina), Plantation	0	10	2	4	0	9	0	10	0	10	2	10
Lakes/water	lakes/water, hydroarea (waterbody	0	10	2	2	0	10	0	10	0	10	8	0
Road: dual carraigeway sealed		0	10	0	0	0	8	0	10	0	10	0	8
Road: sealed		3	6	0	0	0	2	0	5	0	10	0	6
Road: unsealed		1	0	0	0	0	0	0	0	0	5	0	0
	1/alpha (values in metres)	Small woodland bird		Large strongly flying bird		Arboreal marsupial		Ground dwelling mammal		Grassland reptile		Amphibian	
	Low quality habitat	43		1000		20		50		10		50	
	High quality habitat	869		100000		100		500		100		500	

Table 2 Summary of key features and connectivity issues for modelled species indicated in Figure 8 to 21

Model Animal	**Key features (ACT)**	**Key features (NSW)**	**Key Connectivity Issues**
Small woodland bird See Figures 8 & 9	Strong connectivity indicated along Murrumbidgee River and Naas/Tharwa, Callum Brae and Jerrabomberra, Gungahlin Hills/Majura hills,.	Good connectivity in Tinderry Range, but fragmented nature of rural habitats may be a developing problem.	Poor connectivity in urban areas, especially in north-west ACT, especially between the Murrumbidgee/Molonglo to the Hall to Mt Ainslie woodlands may require connectivity enhancement in nearby NSW. Strengthening links between Mulligans Flat and Goorooyarroo with Majura Hills and adjacent NSW land to their north (Greater Goorooyarroo) needs consideration before woodland habitat areas become more isolated and/or fragmented. Callum Brae is in danger of further isolation unless links to NSW are strengthened. Strengthening the links between Naas/Tharwa and adjacent land to the east in NSW needs consideration before these areas become more isolated. Strengthening the links between the Tinderry Range and woodland habitat north to northeast of Lake George needs consideration before these areas become more fragmented. Further fragmentation of woodland habitat in the NSW part of the study area should be avoided and where possible links

			strengthened.
Strongly flying bird See Figures 10 & 11	Some connectivity indicated across nature reserves and in rural areas, particularly outside urban developed areas.	Strong connectivity indicated in rural areas. Poor connectivity across areas without mature trees (see Lake George).	Mature trees outside nature reserves likely to be a key factor in maintaining connectivity. Continued loss of these trees is likely to weaken the current status of connectivity in the ACT and region.
Arboreal marsupial See Figures 12 & 13	Strong connectivity indicated in Namadgi National Park and adjacent NSW lands, but weaker around northern ACT/NSW border. Weak connectivity between nature reserves located in and around urban areas.	Strong connectivity indicated in Tinderry Range and eastern forested habitats. Weaker connectivity in area bounded by the Hume, Federal and Barton highways and along the Monaro Highway.	Linking existing ACT nature reserves to each other and into NSW may be a priority for further study. Priorities indicated are Black Mountain, Mt Ainslie, Mt Majura, Callum Brae, Mulligans Flat and Goorooyarroo nature reserves. Consideration of connectivity issues should always be required at the design and construction phase of all major road developments, with a view to remediation measures.
Ground dwelling mammal See Figures 14 & 15	Excellent connectivity in all areas except urban development. Mt Ainslie, Mt Majura and Black Mountain natre reserves vulnerable to further weakening of connectivity. Callum Brae woodland/grasslands weakly connected to NSW.	Excellent connectivity in all areas except urban development and Yass valley. However this may be vulnerable to continued fragmentation of native vegetation habitat.	Consideration of connectivity issues should always be required at the design and construction phase of all developments involving major roads and/or developments likely to weaken habitat continuity and links to nature reserves (e.g. Black Mountain, Ainslie/Majura, Callum Brae, Mulligans Flat and Goorooyarroo). Linking Callum Brae/Jerrabomberra into NSW may be a priority for further study.
Grassland Reptile	Extremely poor connectivity between grassland reserves due to fragmented habitat and major roads	Grassy habitats potentially still	Key connectivity potential in Jerrabomberra valley across ACT/NSW border between East

See Figures 16 & 17	a barrier.	connected northeast of ACT.	Jerrabomberra NR and Letchworth NR (NSW). May need to consider human-assisted translocation of animals to ensure genetic mixing.
Amphibian See Figures 18 & 19	Strong connectivity indicated along Murrumbidgee River, Lower Molonglo River and Lake Burley Griffin. Cross city connectivity indicated via Sullivans Creek, Black Mountain and Belconnen Hills, Callum Brae-Farrer Ridge-Woden Hills and along Gungahlin Hills.	Good connectivity indicated.	Consideration of connectivity issues should always be required at the design and construction phase of all developments with a view to remediation measures where roads cross or impact on creeks or wet areas. May need detailed analysis of different types of barriers to connectivity.
All model animals combined See Figures 20 & 21	The impact of Canberra's urban development and pine plantations on connectivity patterns is very clear: low neighbourhood connectivity corresponds with major urban development areas. Links between Callum Brae and NSW, Callum Brae and the Murrumbidgee River, Black Mountain to the Belconnen hills, native habitat from Hall - Mulligans Flat –Goorooyarroo - Ainslie/Majura-Majura hills are potentially weakened by urban development including roads and may require actions to strengthen connectivity. Links between ACT and NSW north of Gungahlin hills and from Naas/Tharwa to Tinderry Range are significant. The Murrumbidgee River Corridor provides a strong connectivity feature in the landscape between where it enters and leaves the ACT.	Generally connectivity across NSW appears relatively good (but see comments on individual model animals). The impact of Queanbeyan's urban development on connectivity patterns is similar to that of Canberra. However, rural sub-division is also disruptive to habitat conservation and connectivity.	Strengthening links between Naas/Tharwa and Tinderry Range needs consideration before these areas become more fragmented. Strengthening links between the Gungahlin Hills and adjacent land in NSW (Greater Goorooyarroo) needs consideration before rural sub-division or development of these areas isolates the Mulligans Flat-Goorooyarroo nature reserves. Strengthening links in rural land along the ACT/NSW border west of Hall. This will link with the Gungahlin Hills and Greater Goorooyarroo. Strengthening links between Callum Brae/Jerrabomberra and NSW needs consideration before the important Callum Brae/Jerrabomberra area becomes more

			isolated. Maintenance of the Murrumbidgee River as a key connectivity area should be maintained as a high priority. Consideration of connectivity issues should always be required at the design and construction phase of all developments associated with rural sub-division development south of Queanbeyan, with a view to remediation measures where habitat is fragmented and/or roads cross watercourses. Due to the diminished connectivity in existing urban areas, NSW may be the only place where connectivity can be enhanced. Maintaining connectivity will require cross-border cooperation on planning and landscape management issues, particularly where rural sub-divisions are now located or planned on NSW land near to or adjacent to the ACT.

Table 3 Number of physical structures potentially impeding fish passage in the upper Murrumbidgee River catchment by type of structure and Strahler stream order. Small dams are those represented in the database as a point features. Larger dams are those mapped as an areal feature or intersect a mapped dam wall or weir.

Stream order	Number of stream links	Length of stream (km)	Number of Dams		Number of road crossings	Totals
			Small	Larger		
1	55,702	22,882	5,156	709	7,695	13,560
2	26,501	8,563	2,034	570	3,052	5,676
3	13,190	4,193	564	225	1,419	2,214
4	7,132	2,149	144	54	516	714
5	3,767	1,187	25	18	207	250
6	2,471	754	2	9	90	101
7	1,222	347	0	14	23	37
8	684	193	0	5	10	15
9	325	105	0	1	0	1
Totals	110,994	40,373	7,925	1,605	13,012	22,542

Table 4 Upper Murrumbidgee River Catchment sections of channel free of potential barriers to fish passage with a total connected length greater than 275km

Length of connected stream upstream of barrier (km)		Major Stream	Barrier
Total	Stream order 3+		
2,365	682	Murrumbidgee, Goodradigbee River	Burrinjuck Dam
1,167	365	Murrumbidgee River	Dam adjacent pumping station, north-west of Cooma
543	121	Goodradigbee River	Ford, McLeods fire trail
368	110	Murrumbidgee River	Tantangara Reservoir
341	99	Bredbo River	Road crossing at Cappawidgee
335	109	Molonglo River	Road crossing north of Carwoola
296	65	Gudgenby River	Orroral Road crossing at Rocky Crossing

Appendix 2 – Figures

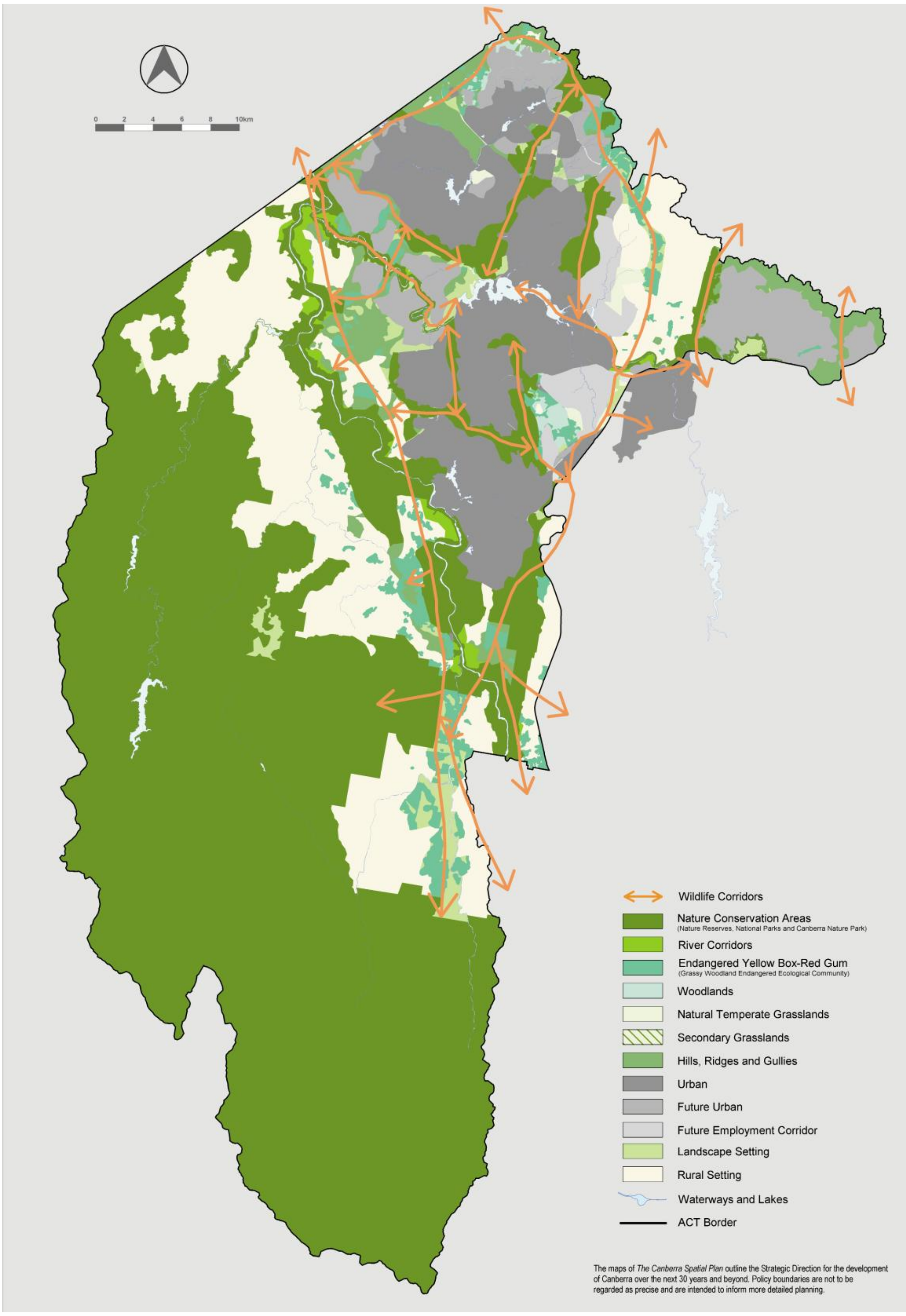

Figure 3 Indicative wildlife corridors connecting nature conservation areas; from The Canberra Spatial Plan (Map 7 Biodiversity Conservation) (ACT Government 2005).

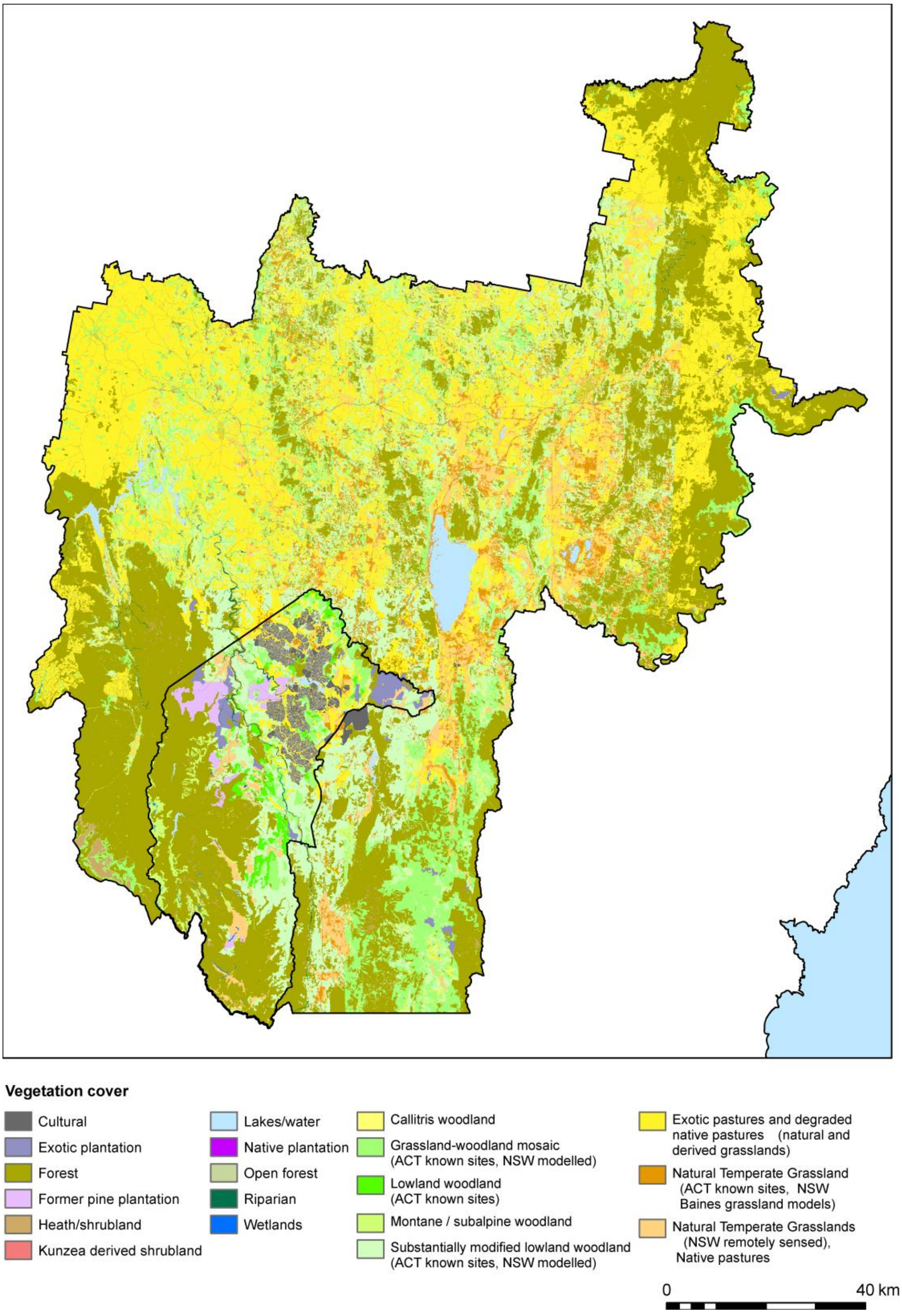

Figure 4 Composite map of vegetation communities and land uses in the ACT and surrounding region (compiled from multiple data sources listed in Appendix 3).

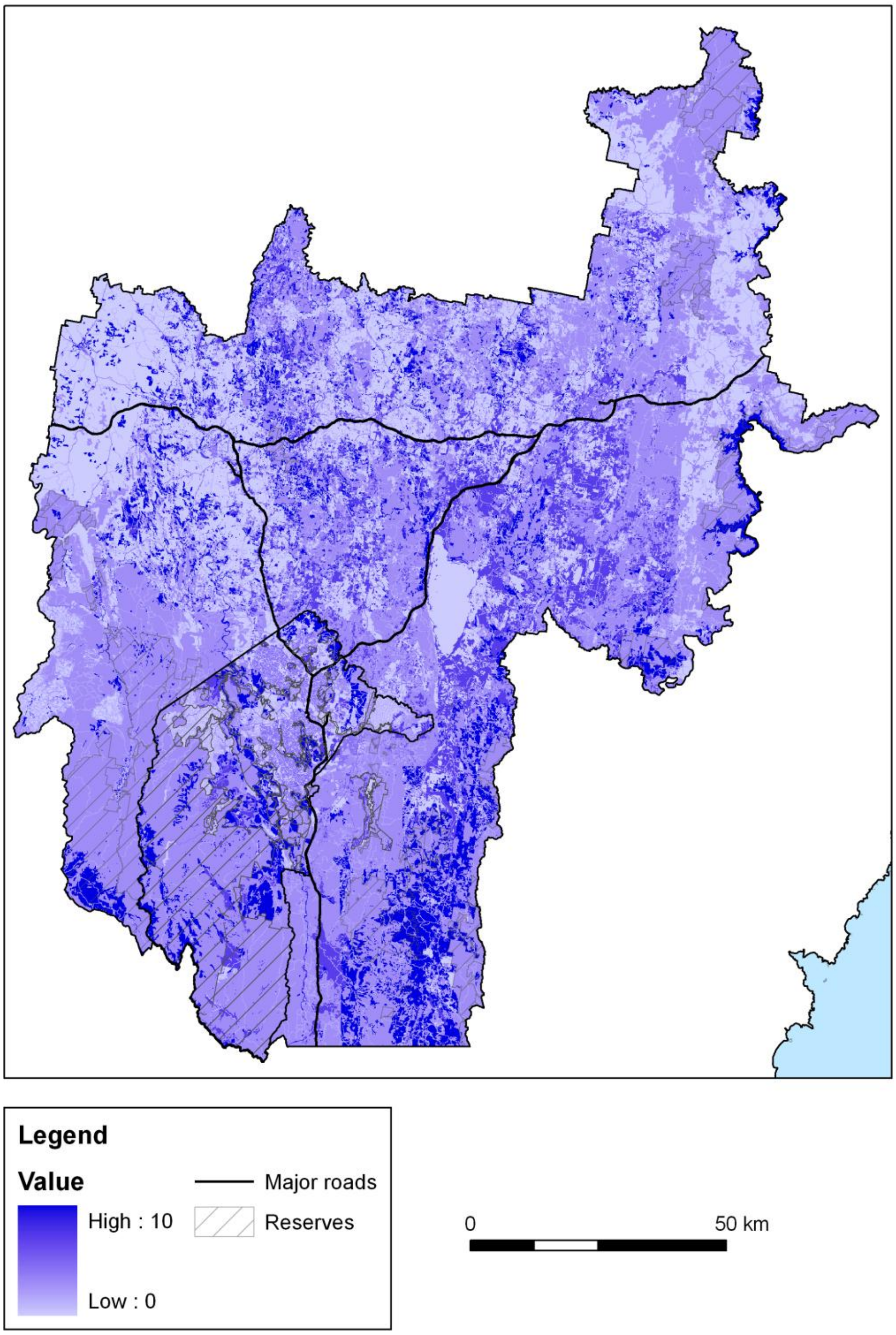

Figure 5 Map of habitat quality scores assigned to vegetation / landcover classes (example used: model small woodland bird species analysed at the 90m grid scale).

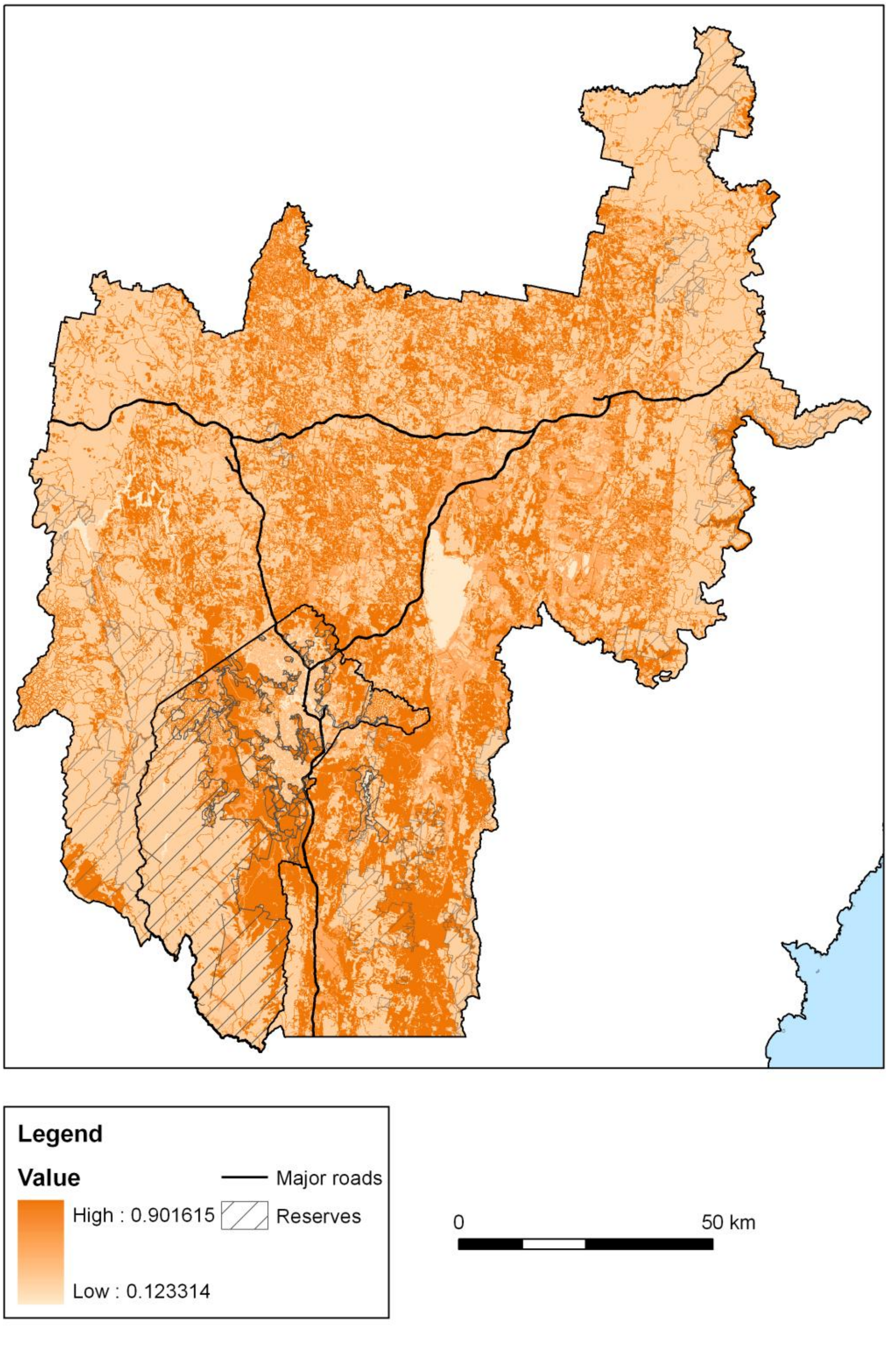

Figure 6 Map of habitat permeability (example used: model small woodland bird species analysed at the 90m grid scale).

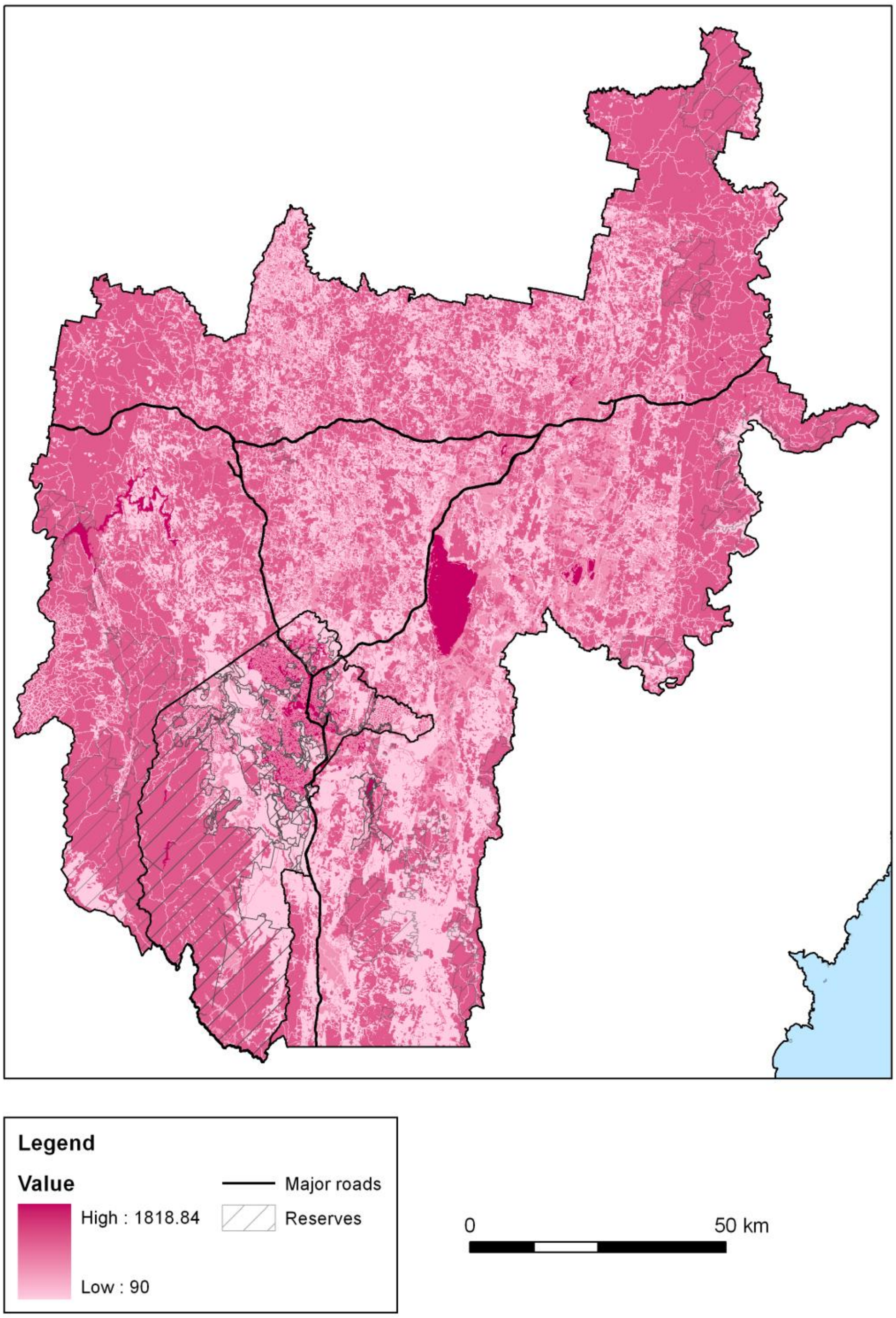

Figure 7 Map of movement costs measured as effective distance (example used: model small woodland bird species analysed at the 90m grid scale).

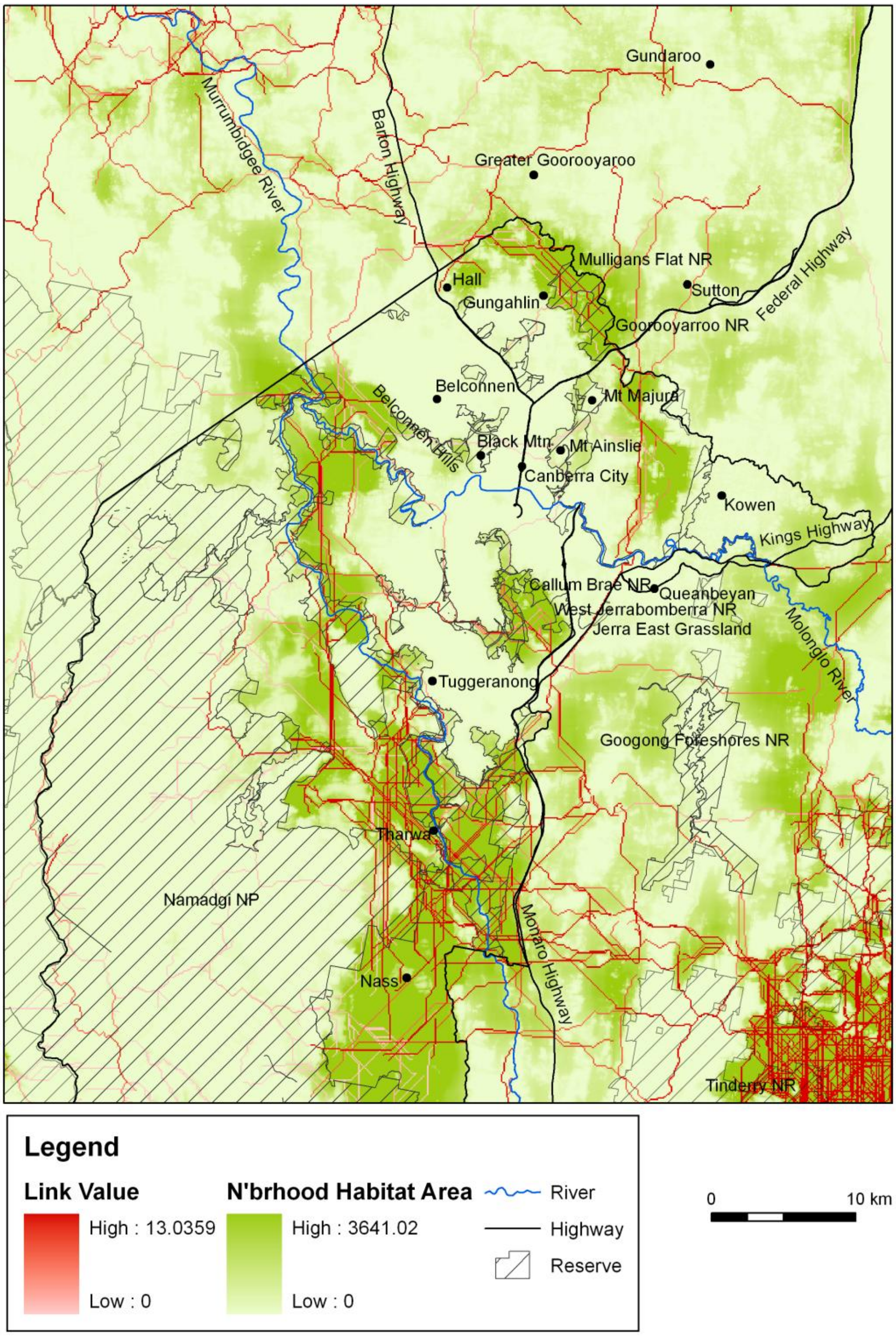

Figure 8 Map (ACT scale) for model small woodland bird species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

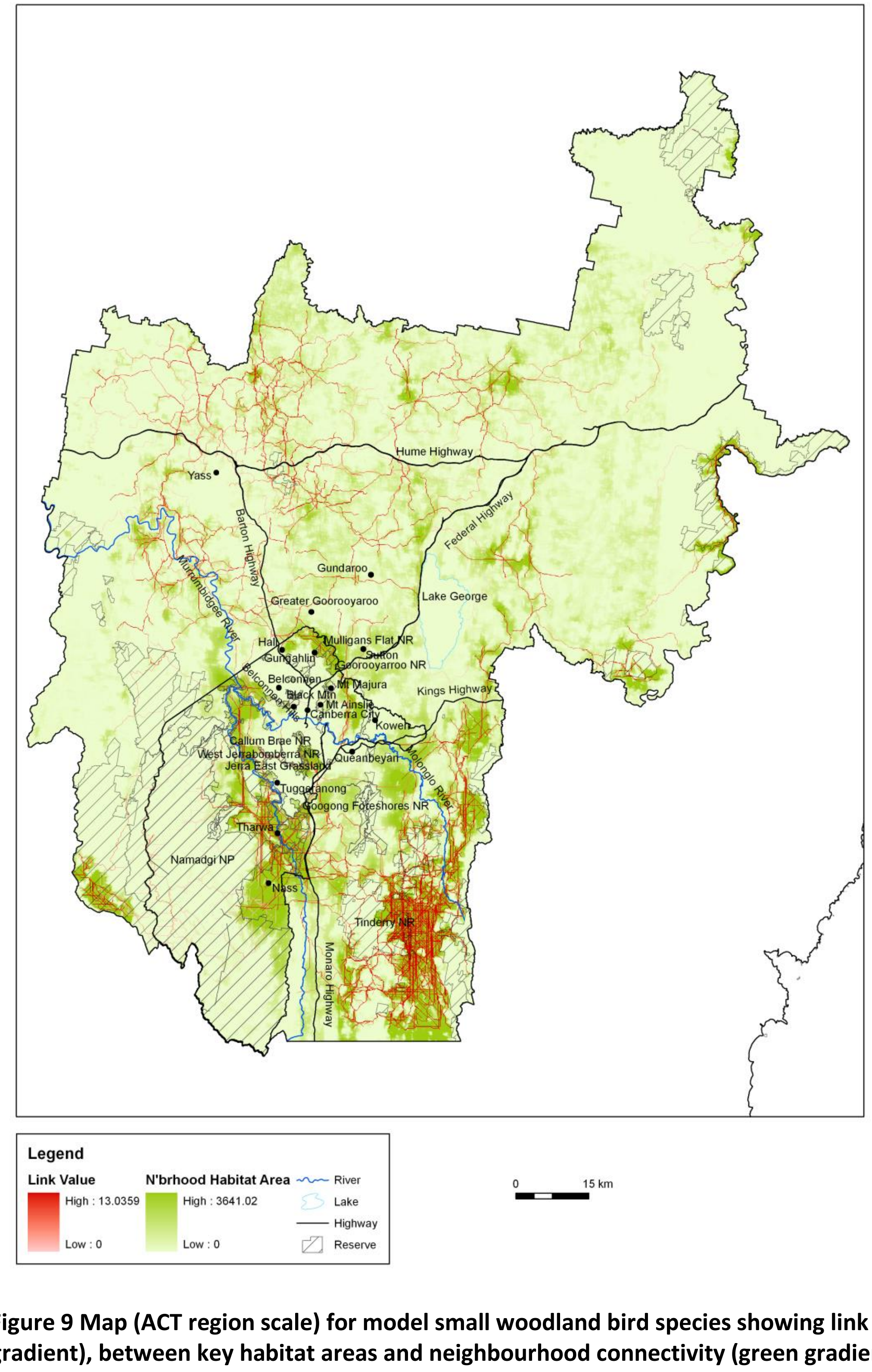

Figure 9 Map (ACT region scale) for model small woodland bird species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

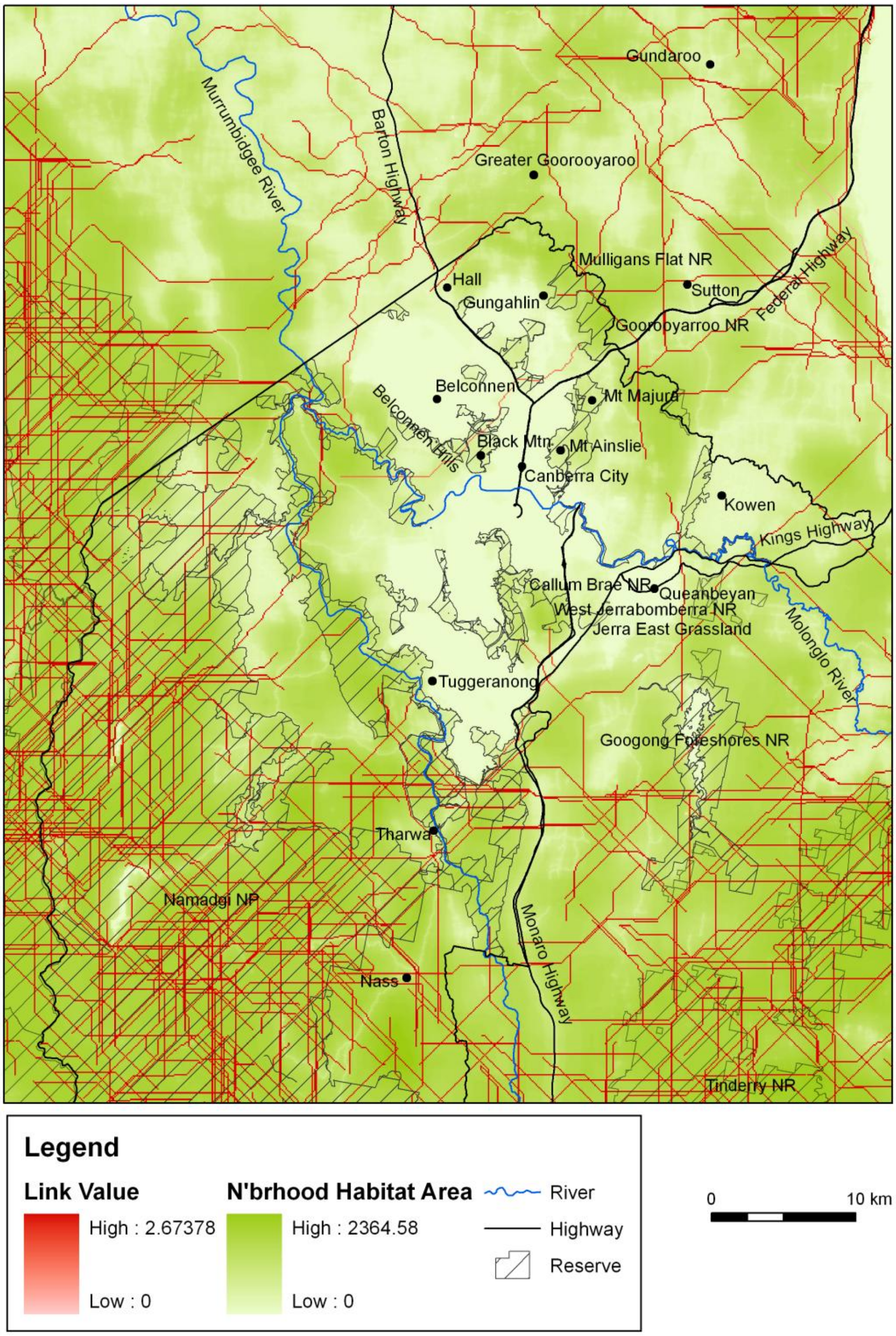

Figure 10 Map (ACT scale) for model large strongly flying bird species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

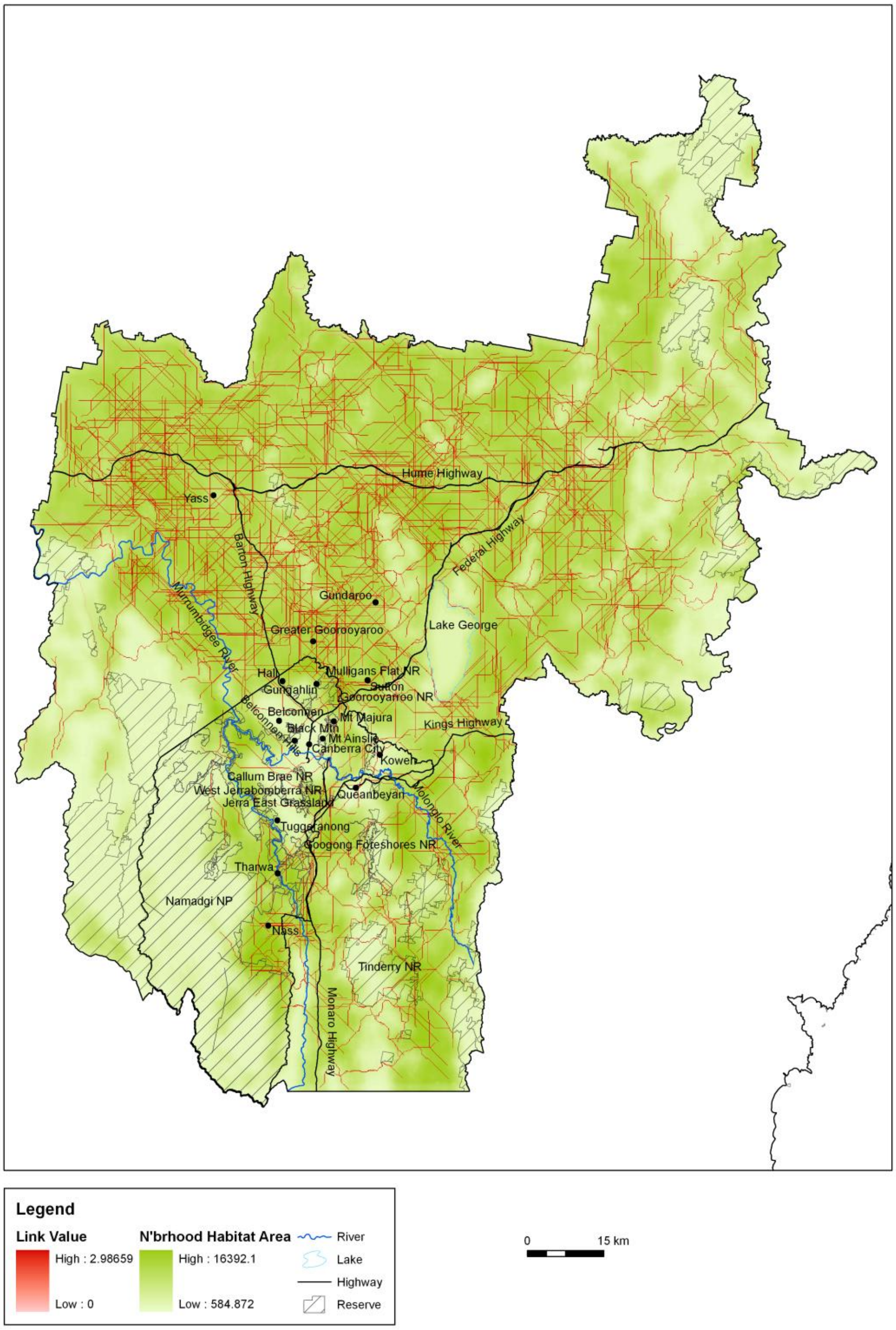

Figure 11 Map (ACT region scale) for model large strongly flying bird species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

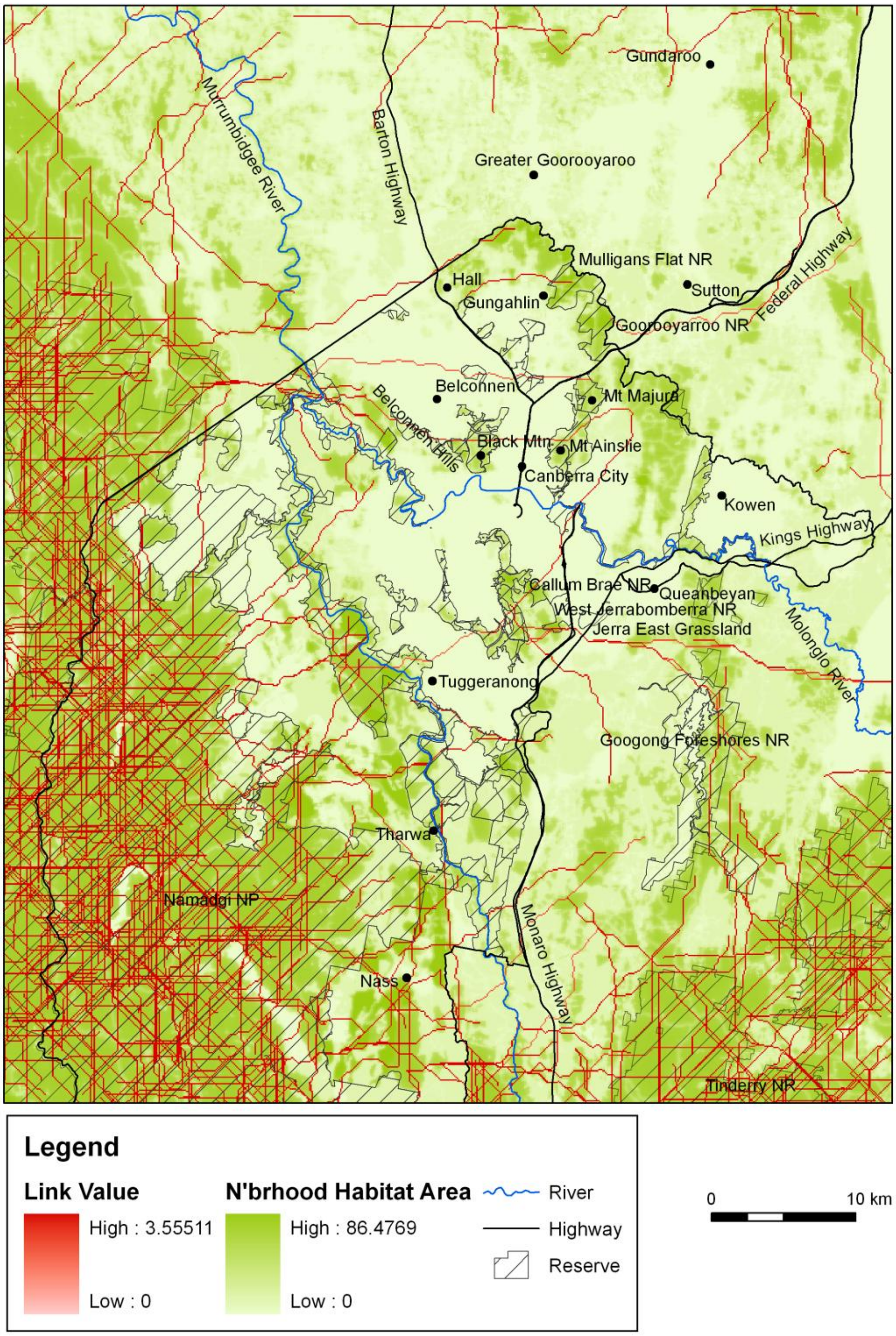

Figure 12 Map (ACT scale) for model arboreal marsupial species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

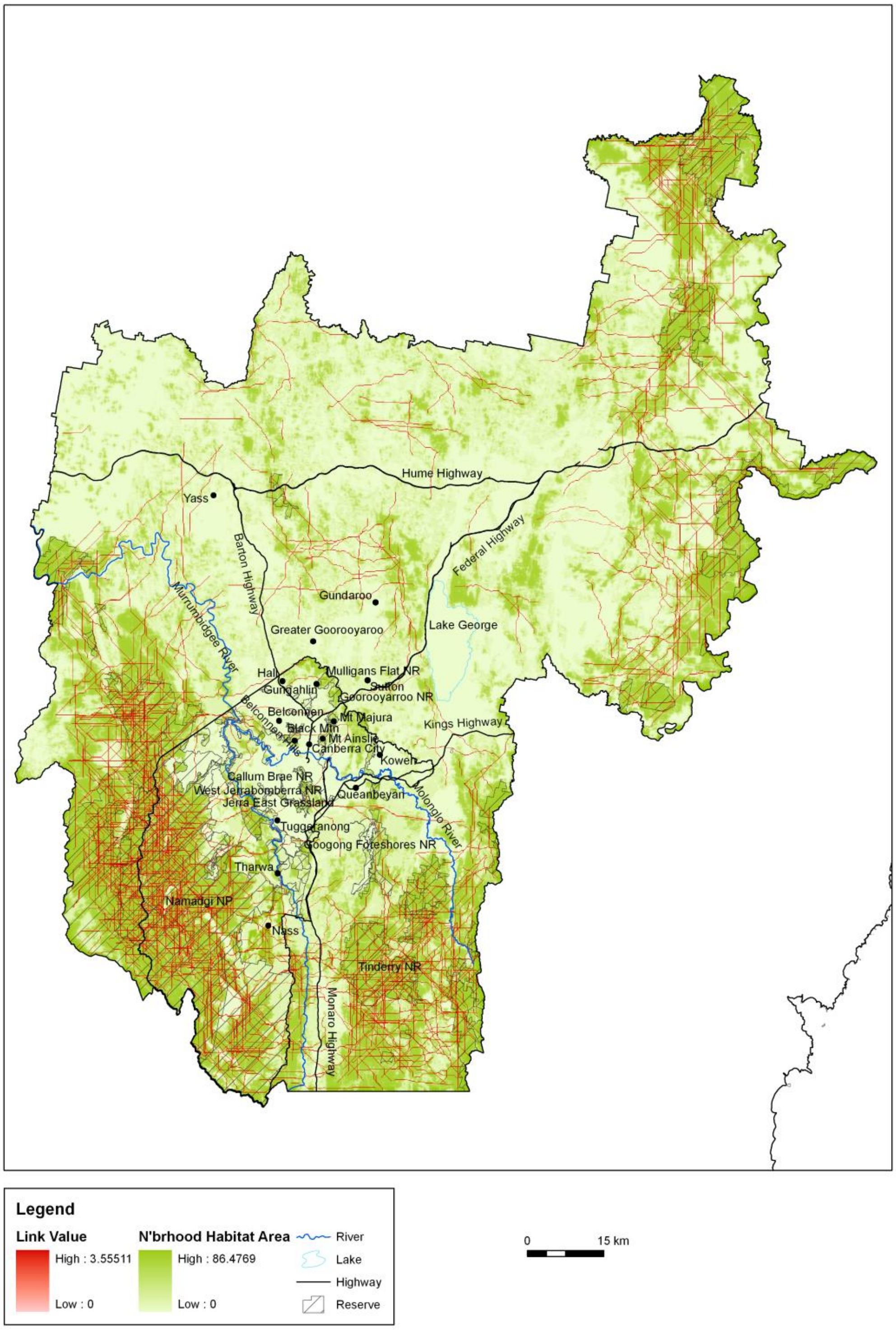

Figure 13 Map (ACT region scale) for model arboreal marsupial species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

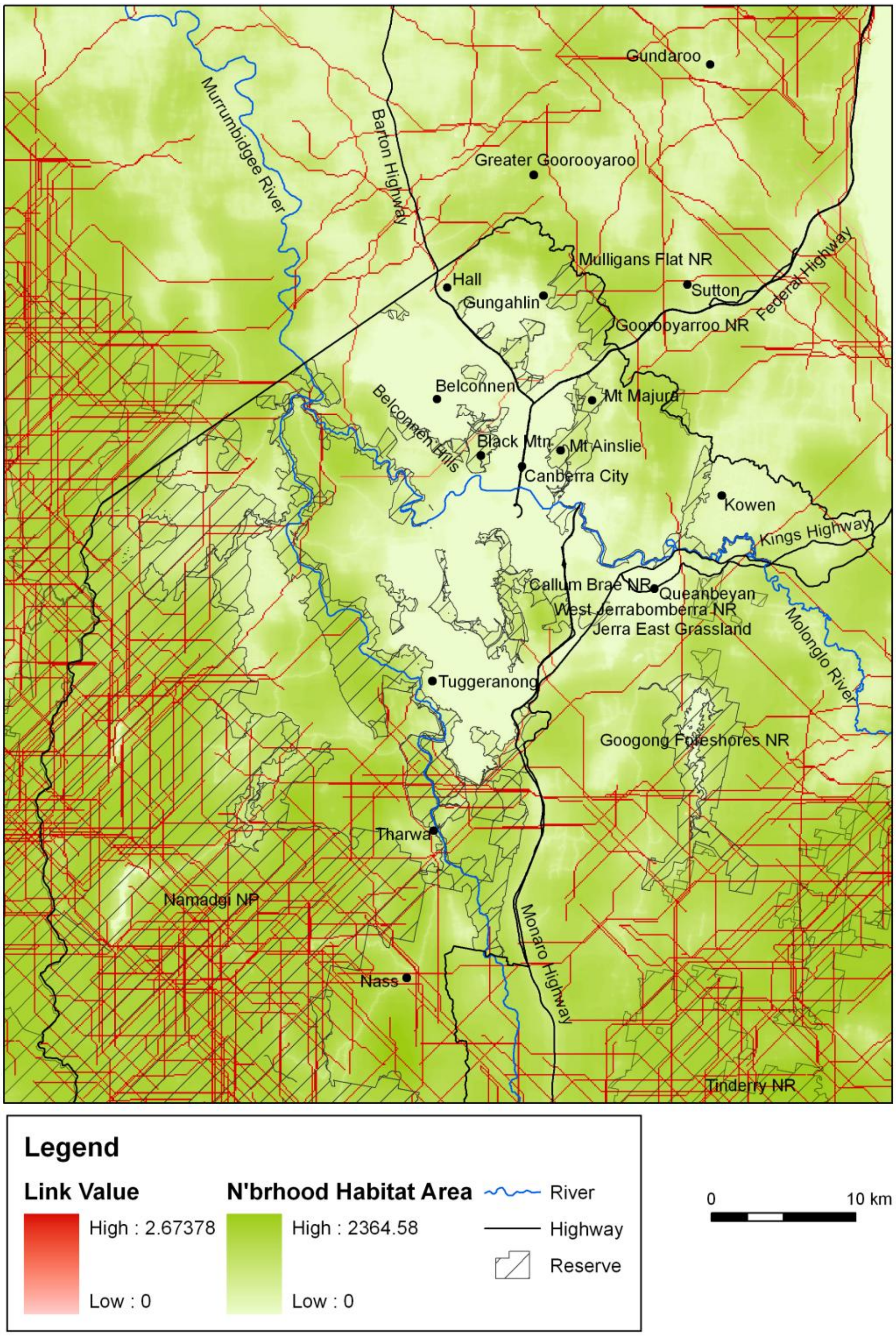

Figure 14 Map (ACT scale) for model ground dwelling mammal species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

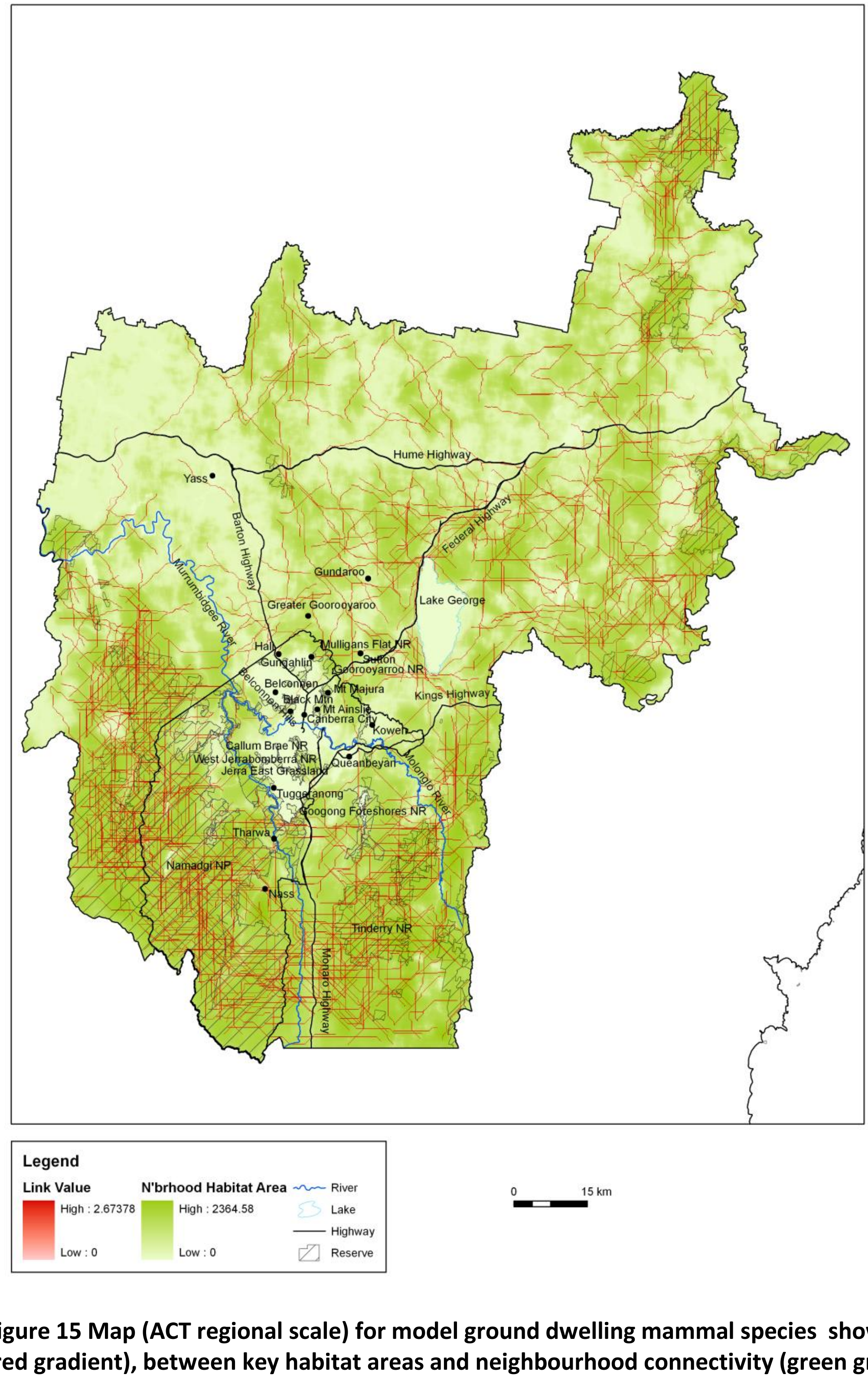

Figure 15 Map (ACT regional scale) for model ground dwelling mammal species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

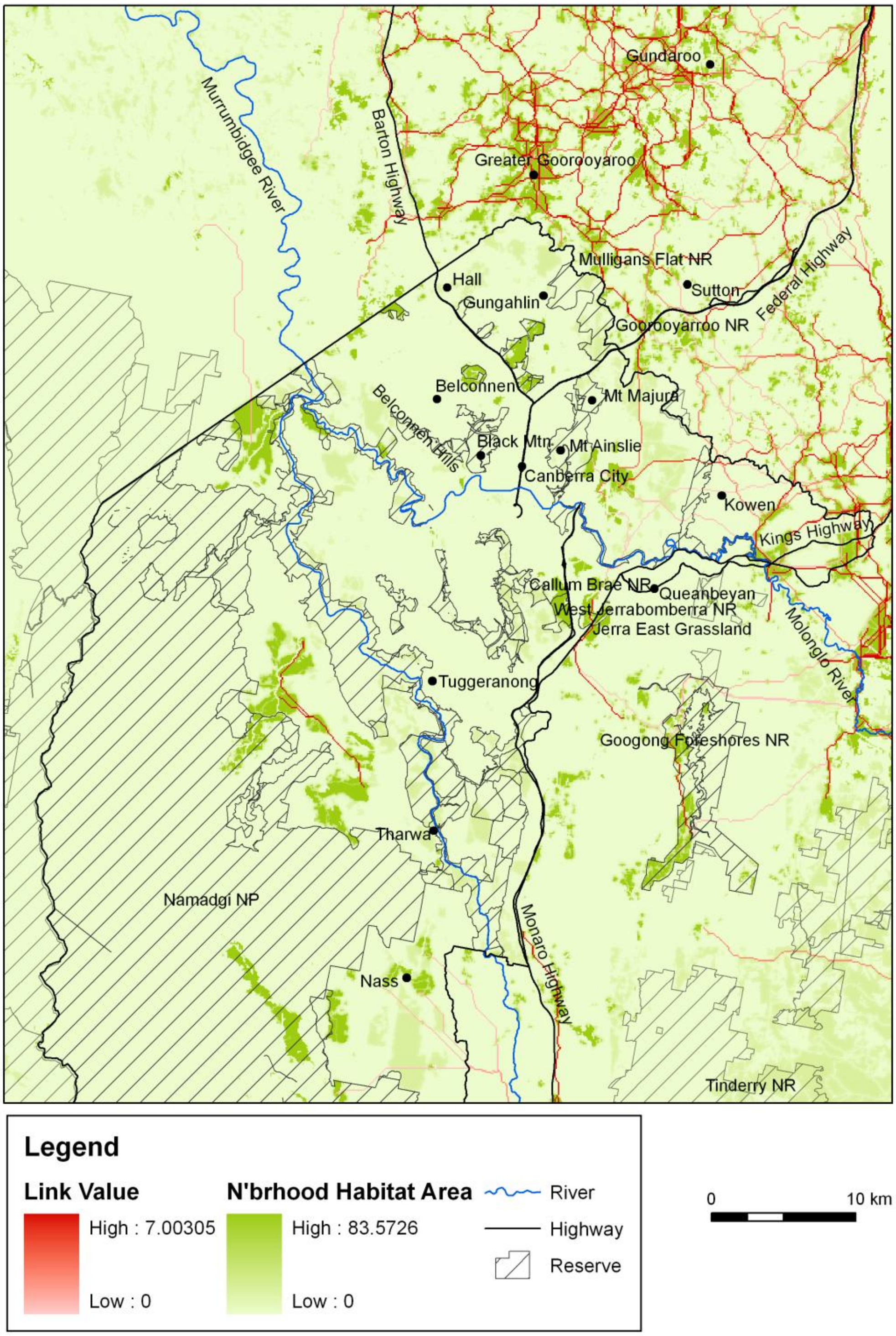

Figure 16 Map (ACT scale) for model grassland reptile species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

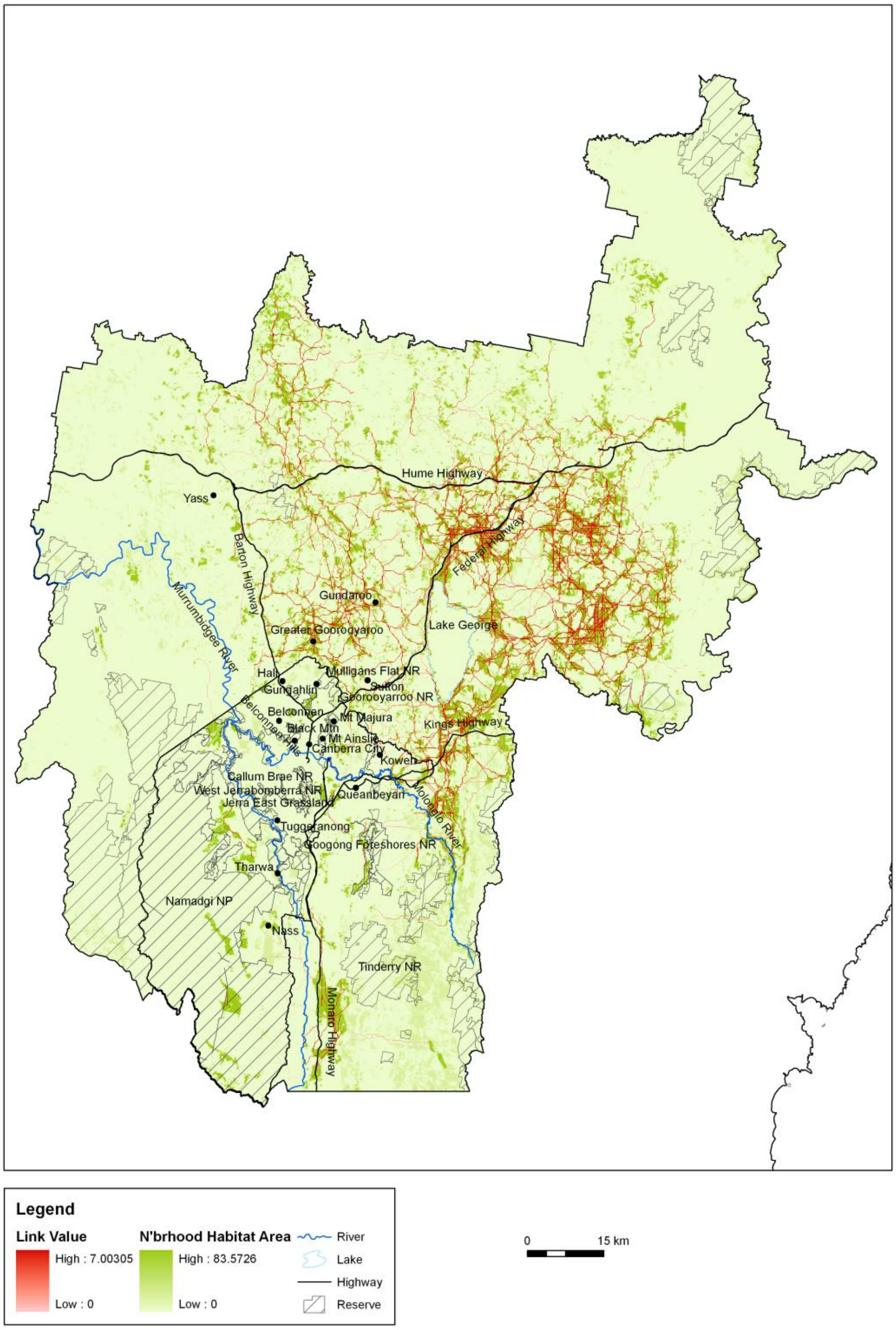

Figure 17 Map (ACT regional scale) for model grassland reptile species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

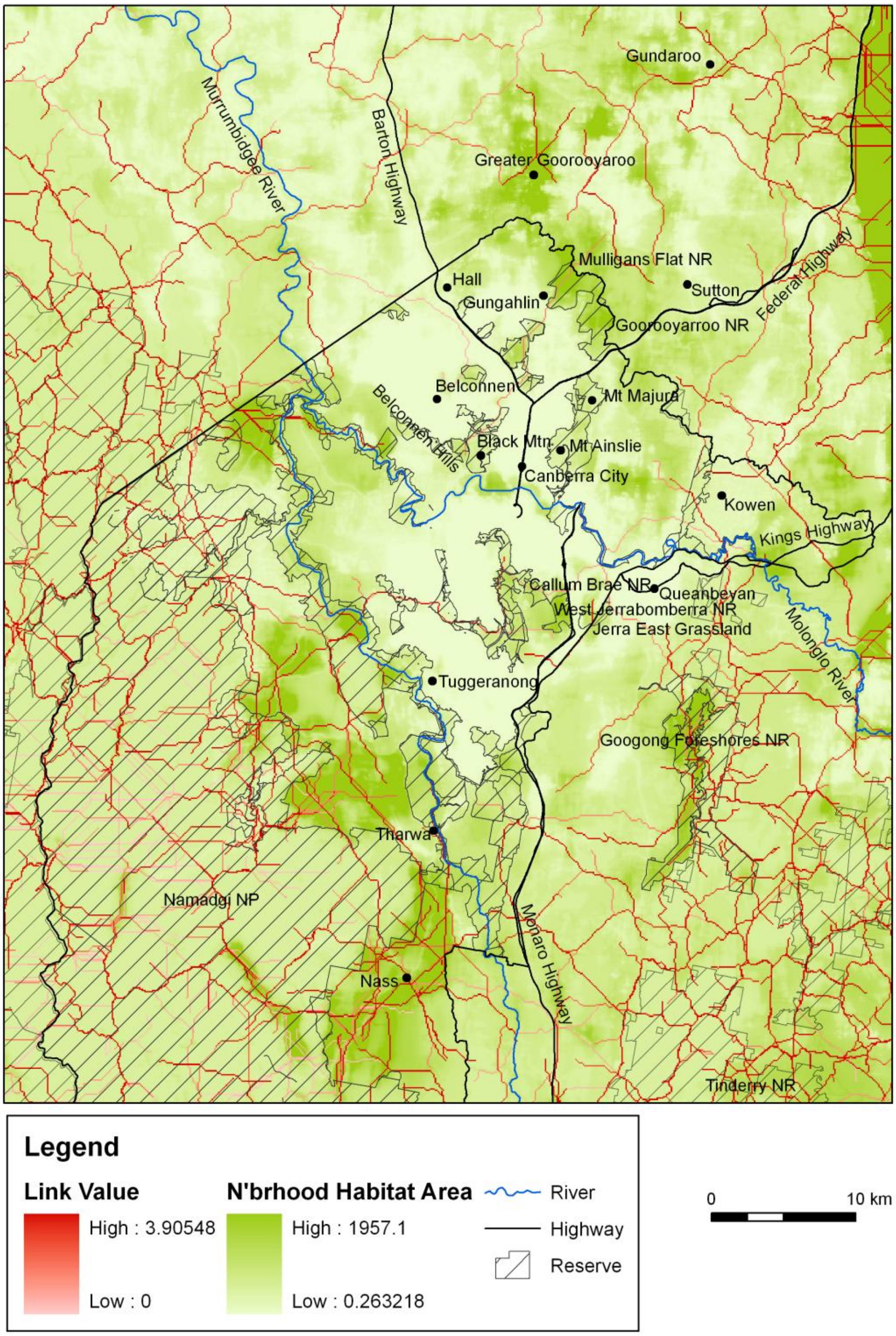

Figure 18 Map (ACT scale) for model amphibian species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

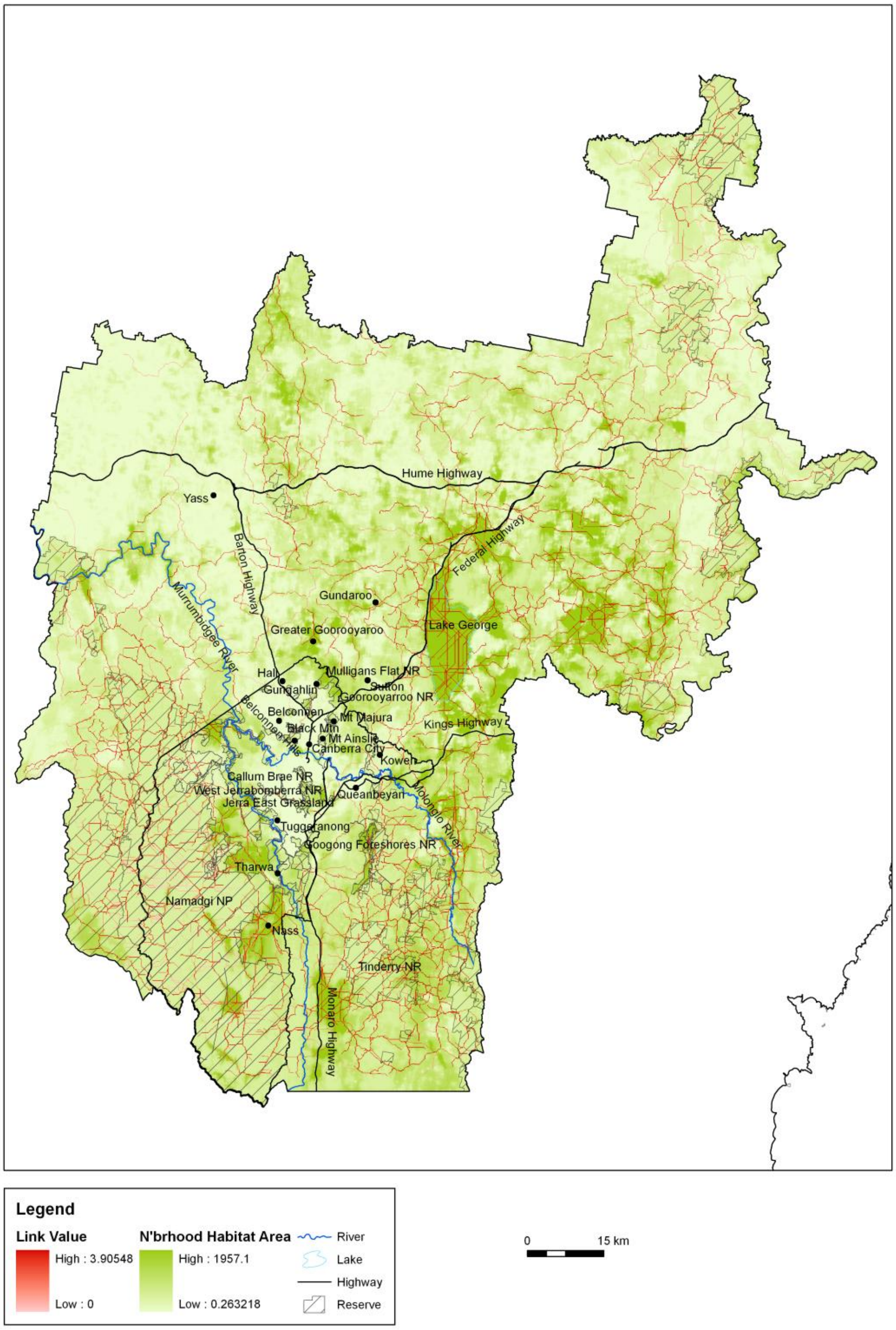

Figure 19 Map (ACT regional scale) for model amphibian species showing link value (red gradient), between key habitat areas and neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity.

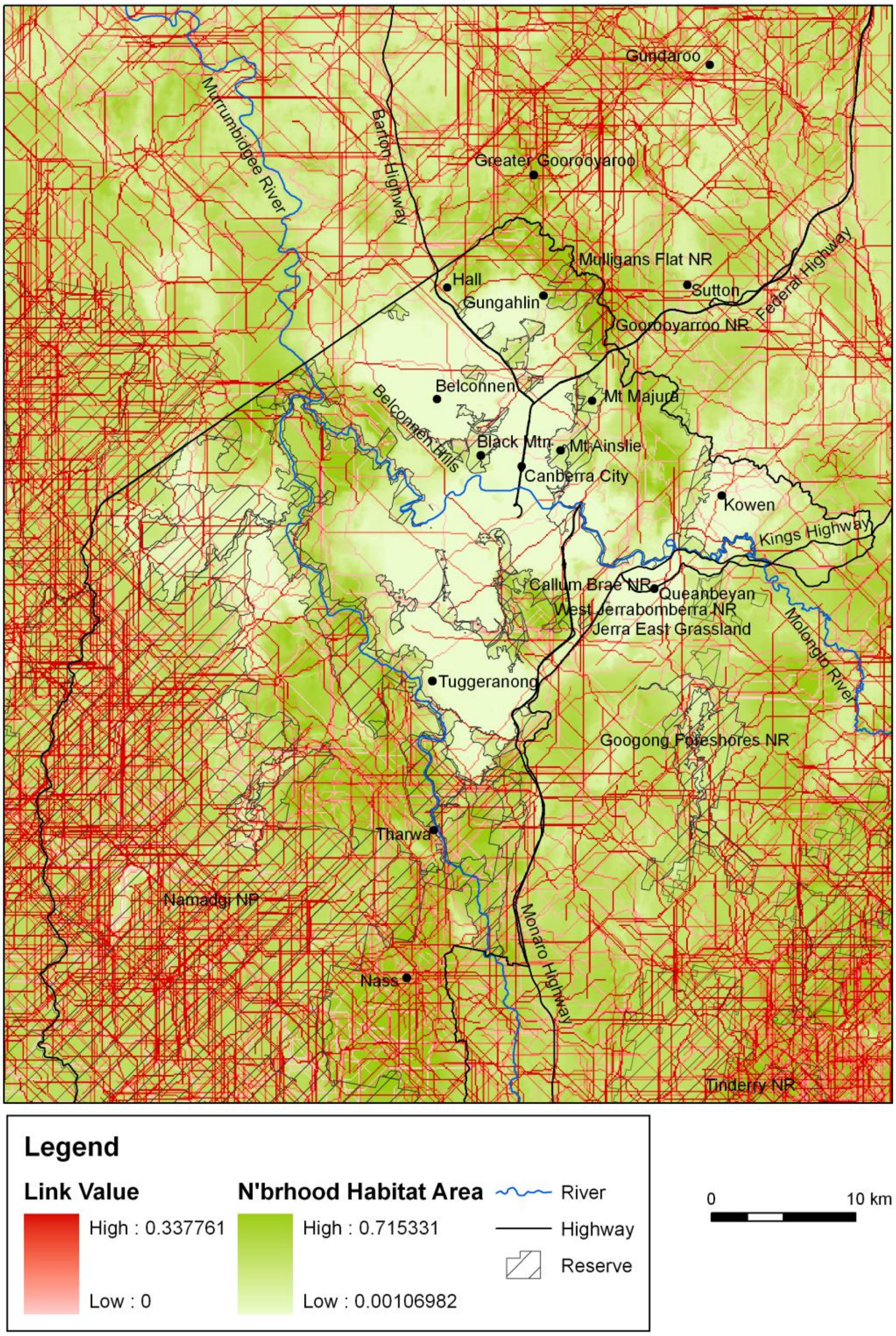

Figure 20 Map (ACT scale) for all model species showing averaged link value (red gradient), between key habitat areas and averaged neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity. Note: this data is intended to be indicative only because averaged data will, by definition, underestimate connectivity for some species, and overestimate it for others.

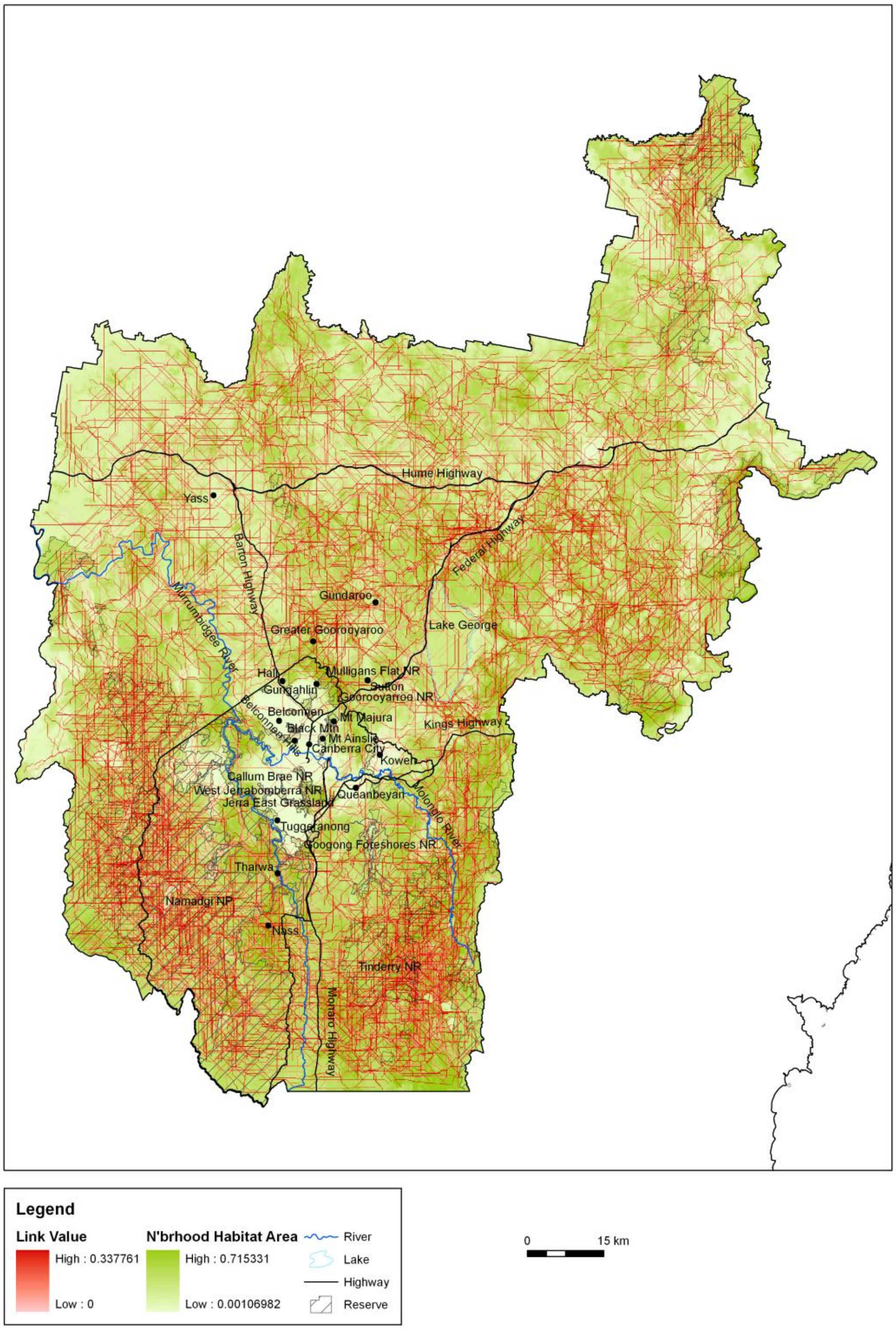

Figure 21 Map (ACT regional scale) for all model species showing averaged link value (red gradient), between key habitat areas and averaged neighbourhood connectivity (green gradient). Darker colours indicate higher link values and neighbourhood connectivity. Note: this data is intended to be indicative only because averaged data will, by definition, underestimate connectivity for some species, and overestimate it for others.

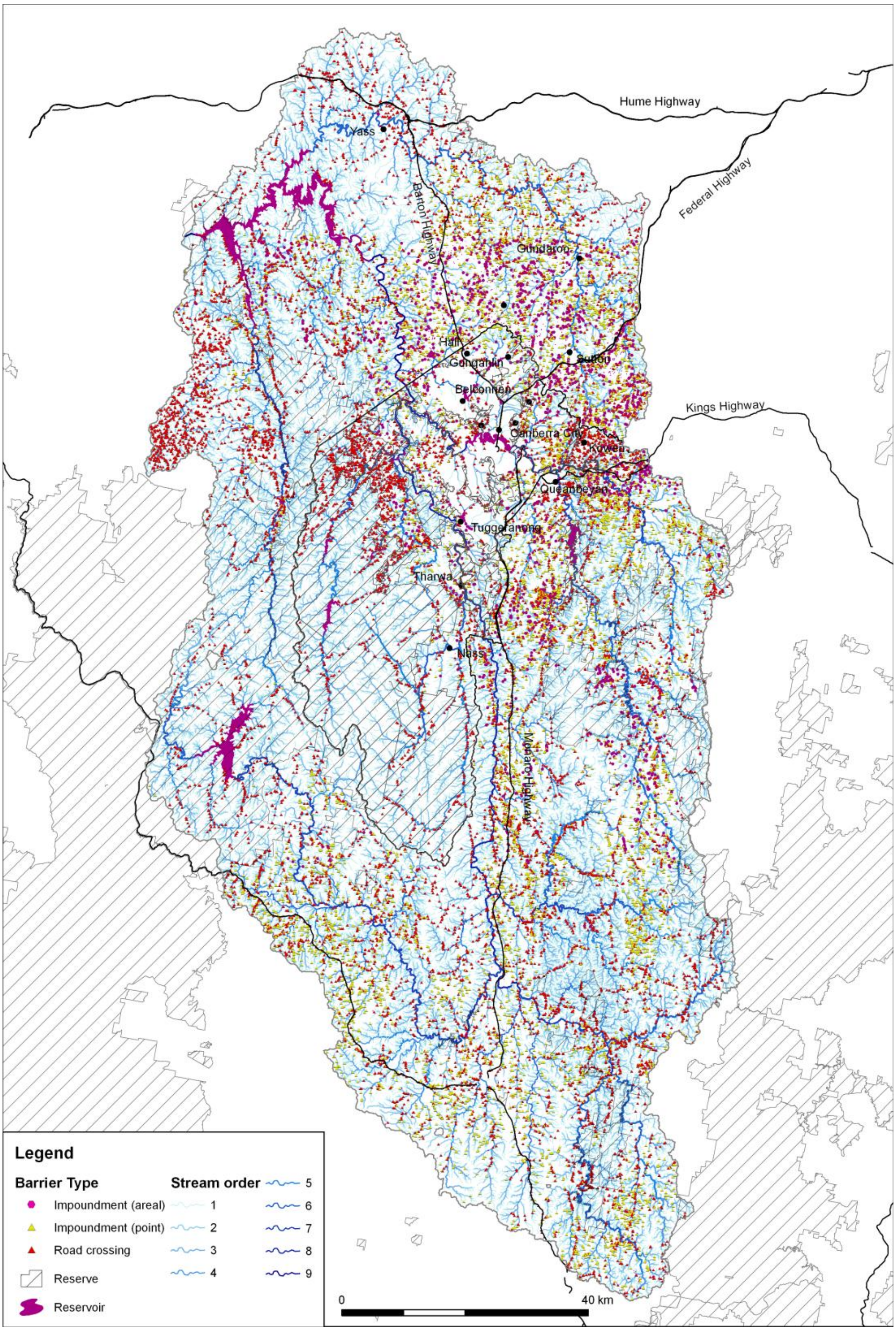

Figure 22 Anthropogenic structures potentially impeding fish passage in the Murrumbidgee River catchment upstream of Burrinjuck Reservoir

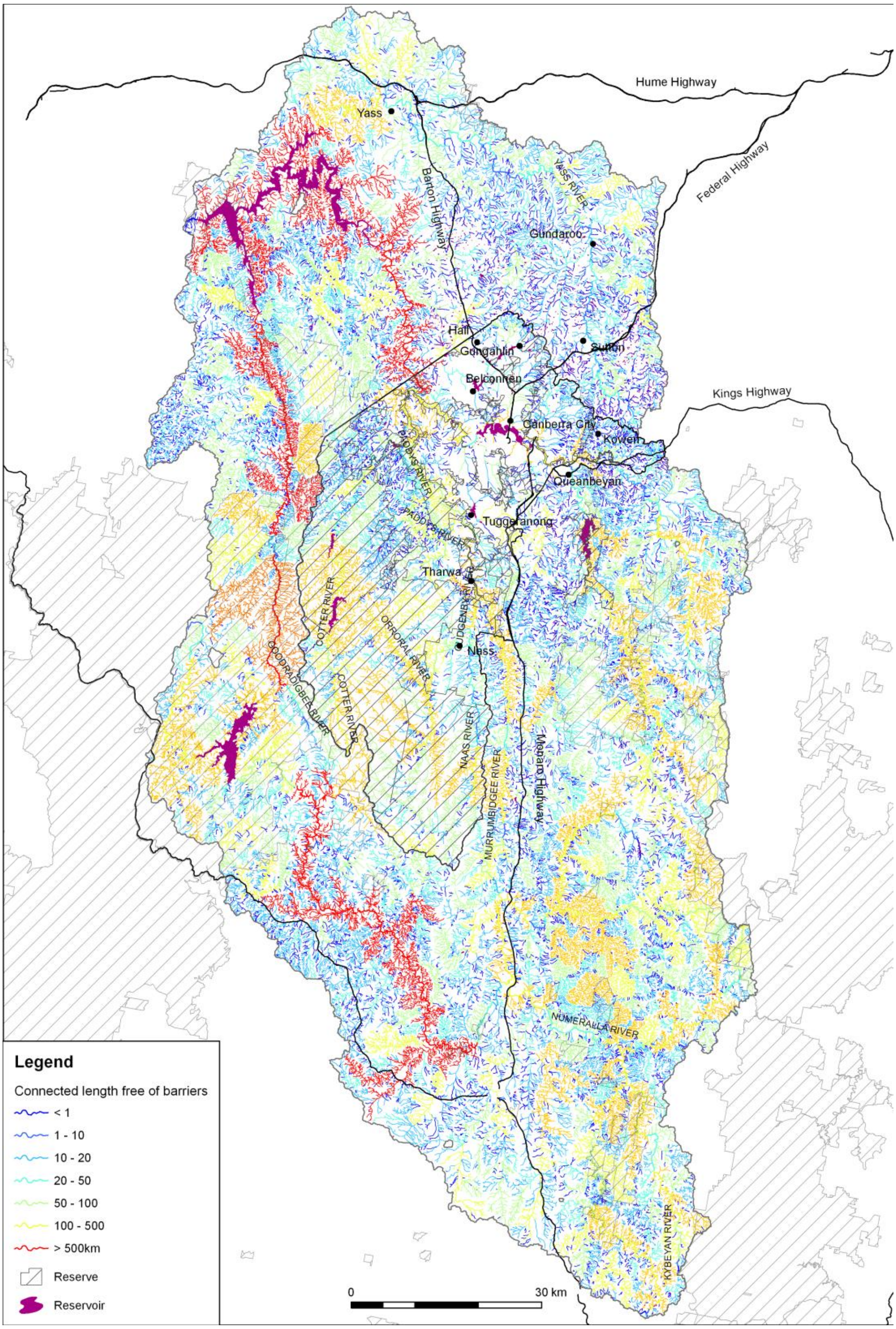

Figure 23 Length of connected channel free of anthropogenic structures that potentially impede fish passage in the Murrumbidgee River catchment upstream of Burrinjuck Reservoir

Appendix 3 – Data sources

Appendix 3 Data supplied by ACT and NSW Government agencies used to compile the gridded layer of major vegetation types and landuse categories and identify in-stream barriers.

ACT woodlands mapping December 2005

ACT Natural Temperate Grassland mapping December 2006

Murrumbidgee River Riparian survey 2008

Natural Temperate Grassland (models incorporating rainfall and slope < 4^o) (modelled by Greg Baines, ACT Parks Conservation and Lands)

ACT vegetation sub-formation mapping

Kosciusko to Coast vegetation mapping

Planning Framework for Natural Ecosystems of the ACT and Southern Tablelands extant vegetation (Fallding 2002)

NSW Lands topographic database (transportation, hydrography and cultural themes)

ACT Street Trees Database