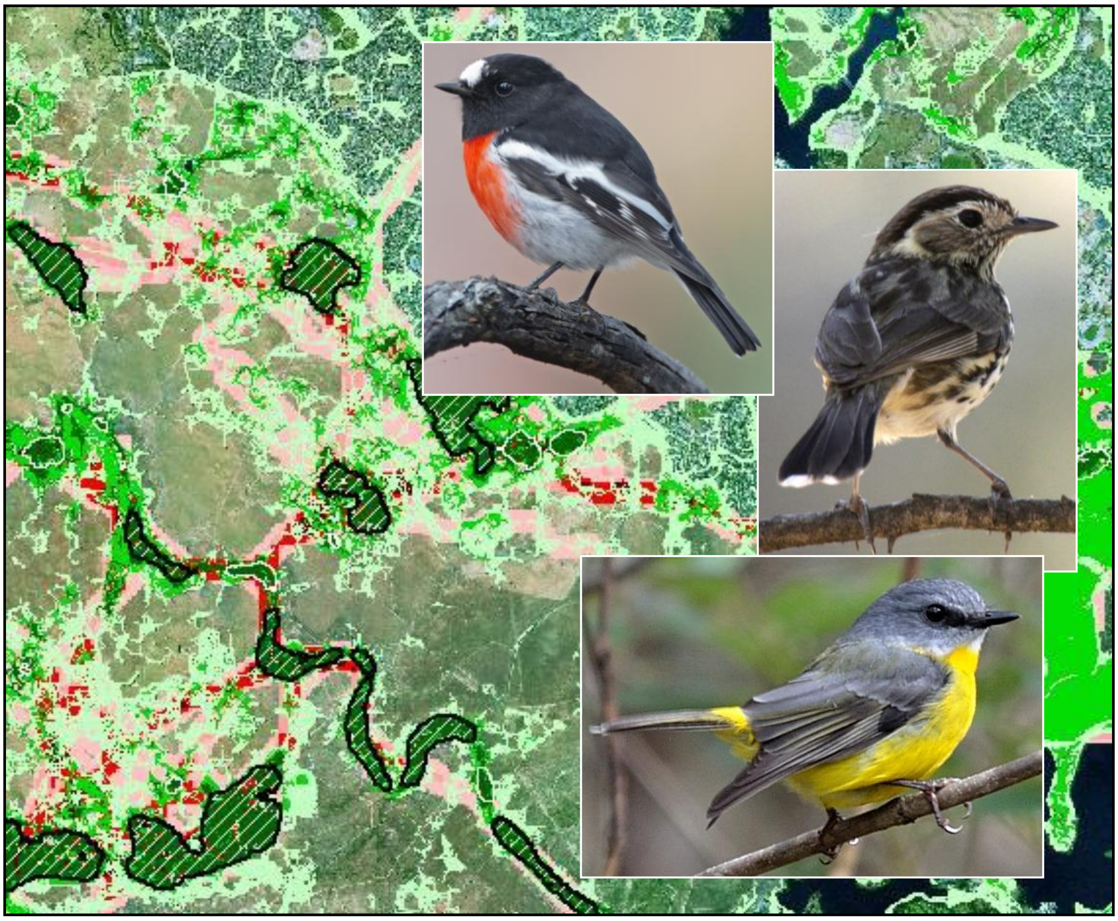

FINE SCALE MODELLING OF FAUNA HABITAT AND CONNECTIVITY VALUES IN THE ACT REGION

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Front cover: Map of modelled habitat, local and regional links for generalist species undertaken as part of this study and the following bird photos; Scarlet Robin (JJ Herison), Speckled Warbler (Aviceda) and Yellow Robin (James Niland), sourced from Wikimedia Commons).

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Executive Summary

This project utilised the best available data, modelling techniques and tools to model fauna habitat and connectivity values in the Australian Capital Territory (ACT) at a fine scale. This was a recommendation from the 'Ecological connectivity for climate change in the ACT and surrounding region' report by Manning *et al.* (2010) from the Fenner School of Environment and Society, The Australian National University.

In recognition of the important role of paddock trees, in providing stepping stone connectivity for woodland birds and small mammals, fine scale canopy mapping was undertaken using SPOT5 imagery. Tree stand density was predicted using a satellite radar-based measure of above ground biomass. These two remote sensing products were used in combination with a best available vegetation and land cover type map of the ACT region to develop models of habitat suitability for three broad fauna groups; generalists, forest species and woodland species.

Habitat patches and structural connectivity between these patches were modelled using three different Geographic Information System (GIS) based software modelling tools. All these tools utilised the least cost path modelling approach; one to model Neighbourhood Habitat Area (NHA) used to identify habitat patches; one to model local links or connectivity through stepping stones; and one to model larger scale regional connectivity between patches through the smaller local links.

A CSIRO systematic literature review found that the majority of native fauna species studied (mainly birds and small mammals) exhibit similar gap crossing and inter-patch crossing distance thresholds (Doerr *et al.* 2010). When moving between stepping stones (e.g. paddock trees) the majority of species could not cross gaps greater than ~100 m. Also many species were unable to disperse between patches of habitat (>=10 ha) separated by more than 1100 m, even where structural connectivity existed between the patches. The 10 ha size threshold was used in this study to identify habitat patches and the 100 m gap crossing threshold was used in the local links model.

The mapping products produced in this project have proven to be a valuable guide for landuse and conservation planning in the ACT. They have been used to plan revegetation and repair projects as well as to inform strategic town planning, and in the consideration of the environmental impacts of infrastructure and building projects.

1 Background

This project builds on the ‘Ecological connectivity for climate change in the ACT and surrounding region’ study commissioned by the ACT Government and undertaken by Manning *et al.* (2010) from the Fenner School of Environment and Society at The Australian National University. In their report, Manning *et al.* provide a good overview of the concept of ecological connectivity and how it has been addressed in ACT Government policy and planning. It is recommended that this project report and associated mapping outputs be used in conjunction with the technical report by Manning *et al.* A report on vegetation mapping in the Gungahlin Strategic Assessment Area by Eco Logical Australia (2011) also provides a good overview of some of the key vegetation types and their definitions in the ACT.

It is now widely recognised that habitat fragmentation is one of the biggest threats to biodiversity (Millennium Ecosystem Assessment 2005) and that maintaining and improving habitat condition and structural connectivity in the landscape is an important response to predicted climate change (Meade *et al*. 2011). Lowland vegetation is particularly fragmented in the ACT and surrounding region. Funding for this connectivity study was obtained as part of an offset package for loss of 2.6 hectares of box–gum woodland associated with the King’s Highway upgrade, on Sparrow Hill, near Bungendore NSW. Providing an answer as to how to best enhance and restore lowland woodland was thus a major impetus of the work.

There are eight species declared as threatened in the ACT for which woodlands are the main habitat. These species are all birds (ACT Government 2004). For this reason and because accurate bird data has been well collected across the ACT, this study has a focus on woodland birds and calibrates the modelling of woodland habitat against known woodland bird distributions. Recher (1999) reviewed the state of Australia's avifauna and predicted that, unless management changes substantially, the country will lose half of its terrestrial avifauna over the next century. Although this study focuses on the role of habitat and connectivity values for native birds, a review of corridor effectiveness by Gilbert-Norton *et al.* (2009) found that corridors were also important for the movement of invertebrates and non-avian vertebrates.

2 Ecological principles

The following quote from the statistician John Tukey (1962) highlights the importance of understanding the nature of ecological processes before attempting to model them across the landscape:

> Far better an approximate answer to the *right* question, which is often vague, than an *exact* answer to the wrong question, which can always be made precise.

A systematic literature review titled ‘Does structural connectivity facilitate effective dispersal of native species in Australia’s fragmented terrestrial landscapes?’ undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) collated and analysed the current state of knowledge on this question (Doerr *et al*. 2010). The findings from this review have helped to define the specific questions that need to be addressed, as well as the appropriate modelling techniques and parameters to answer these questions.

The GIS modelling techniques used in this project are based on well established ecological principles derived from the study of metapopulation biology and dynamics by (Hanski 1998) who provided the following succinct description:

> Metapopulation biology is concerned with the dynamic consequences of migration among local populations and the conditions of regional persistence of species with unstable local populations. Well established effects of habitat patch area and isolation on migration, colonization and population extinction have now become integrated with classic metapopulation dynamics. This has led to models that can be used to predict the movement patterns of individuals, the dynamics of species, and the distributional patterns in multispecies communities in real fragmented landscapes.

2.1 Habitat for settlement and dispersal

For any mobile terrestrial fauna species, habitat can fulfil two roles; habitat for settlement and habitat for dispersal (Doerr *et al*. 2011). This is illustrated schematically in Figure 1. Patch size and quality are important attributes that determine if habitat is suitable for settlement, that is, it supplies all the animal's needs for survival, such as food, shelter and nesting sites. Connectivity between the larger patches of habitat (for settlement) is facilitated via habitat for dispersal.

Realised or 'functional' connectivity is defined by actual gene flow between sub-populations and is dependent on movement potential (structural connectivity), animal behaviour and dynamics of subpopulations. Functional connectivity can be very complex and difficult to prove, where as:

> …structural connectivity contributes significantly to functional connectivity by determining movement potential. The resulting effects on population persistence are also increasingly predictable thanks to controlled research in experimental landscapes which is demonstrating that connected patches experience fewer local extinctions than isolated patches (Damschen *et al.* 2006; Brudvig *et al.* 2009), thus, structural connectivity can be directly quantified in the landscape, has predictable effects on movement potential, and is known to contribute to population persistence, making it a worthwhile focus for management (Doerr *et al*. 2011).

These two habitat types are also required for fauna species that migrate, either seasonally or in response to changed climatic conditions. The modelling approach applied in this project used this concept of habitat for settlement and habitat for dispersal.

2.2 Gap crossing thresholds

The CSIRO systematic literature review found that the majority of native fauna species studied (mainly birds and small mammals) exhibit similar gap crossing and inter-patch crossing distance thresholds (Doerr *et al*. 2010). When moving between stepping stones (e.g. paddock trees) the majority of species did not cross gaps greater than ~100 m. Also many species were unable to disperse between patches of habitat (>=10 ha) separated by more than 1100 m, even where structural connectivity existed between the patches. These thresholds are represented conceptually in Figure 2.

The 10 ha size threshold was used in this study to identify habitat for settlement and the 100 m gap crossing threshold was used to model habitat for dispersal between patches, termed 'local links'. It could be argued that a 10 ha habitat patch on its own would not support sustained settlement, but the Doerr *et al.* findings suggest that these patches do provide a temporary settlement function. This function may be restricted to the supply of food and shelter while animals are moving between larger and/or more connected patches that do provide long term settlement opportunities.

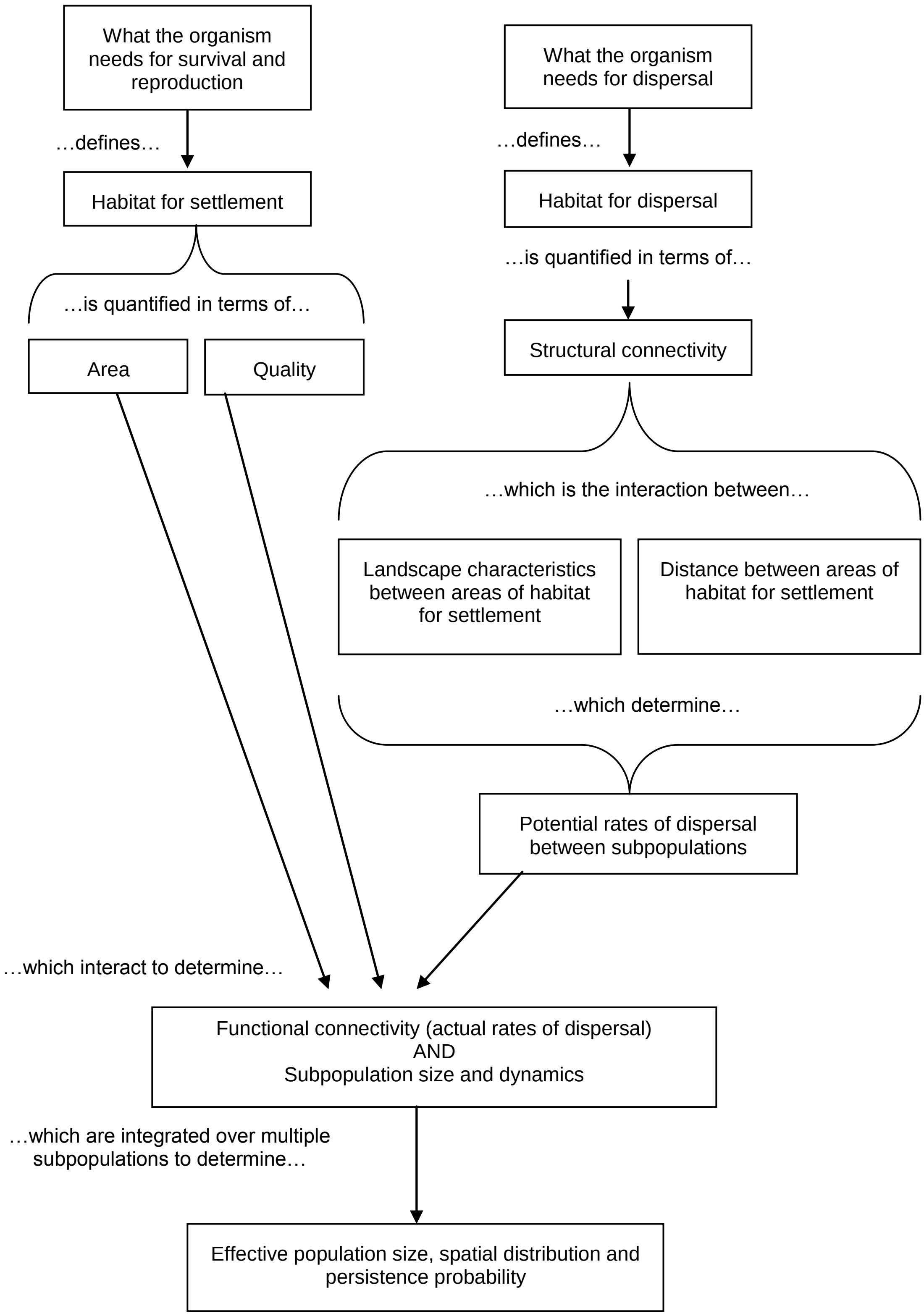

Figure 1 A schematic illustration of the role of habitat for settlement and habitat for dispersal from Doerr *et al*. (2011)

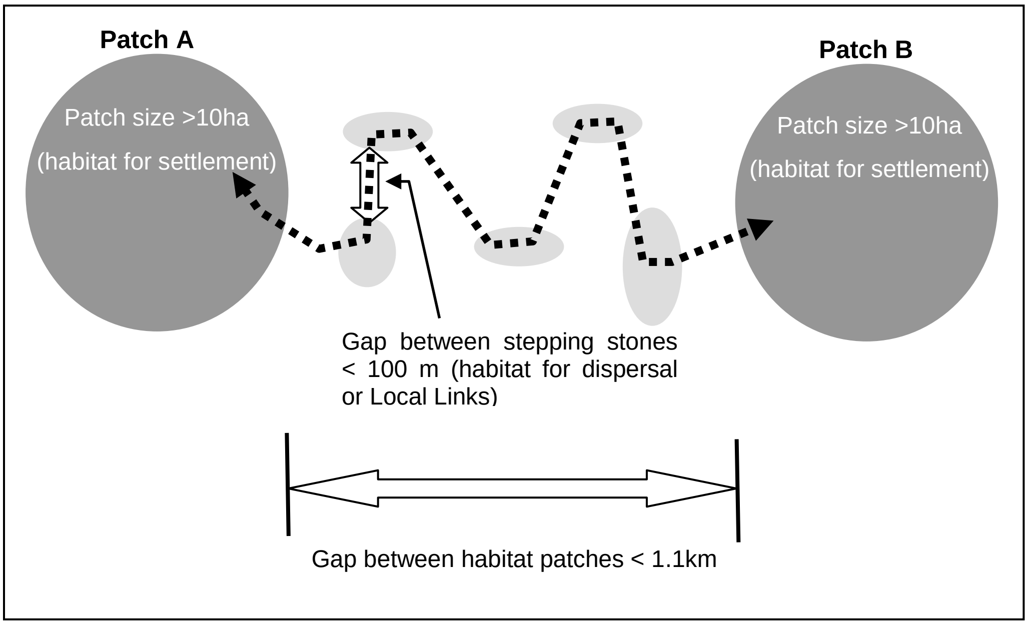

Figure 2 Graphical illustration of average gap crossing thresholds identified in the systematic review by Doerr *et al.* (2010). The darker patches represent habitat for settlement while the smaller light-grey patches show habitat for dispersal and may consist of either individual paddock trees or small patches (<10 ha)

2.3 Habitat condition modelling

Doerr *et al*. (2010) and other studies have also shown that the following vegetation attributes influence the suitability of vegetation for habitat, for settlement, and for dispersal.

2.3.1 Vegetation Structure

Woody vegetation provides the main structural element for both settlement and dispersal habitat. Older, larger trees have been shown to be important for habitat for settlement for many woodland mammal and bird species (Paton and O'Connor 2009). Individual paddock trees and even smaller shrubs can play an important role as habitat for dispersal and for long term persistence, especially for declining woodland birds (Fischer & Lindenmayer 2002). In a ten year study comparing the conservation value of different kinds of revegetation, Lindenmayer *et al.* (2012) found that a range of vegetation growth types are likely to be required in a given farmland area to support the diverse array of bird species that have the potential to occur in Australian temperate woodland ecosystems.

Two elements of woody vegetation structure that influence suitability for settlement include vertical and stand density. Vertical density relates to the presence of several vertical layers e.g. tree, shrub and grass layers. Stand density relates to the density of individual trees or shrubs for a given area.

2.3.2 Vegetation Composition

For many species, vegetation composition determines habitat suitability for settlement. Potential for provision of food resources, shelter and nesting sites is often dependent on the presence of suitable flora species (Freudenberger 1999; Recher 1999).

2.4 The cost-benefit approach to modelling habitat for settlement

As well as habitat value or condition, spatial configuration of habitat will determine if it is suitable for settlement or just dispersal. Identifying potential patches of habitat that may be suitable for settlement is based on a measure of spatial configuration called the 'Neighbourhood Habitat Area' (NHA). The NHA is calculated using a 'cost-benefit approach' (CBA) which efficiently integrates the *costs* of movement by organisms across a landscape with the *benefits* of access to habitat (defined by habitat condition).

The approach is fully documented in Drielsma, Ferrier & Manion (2007) and is further explained using a worked example in Appendix 6. These modelling techniques and associated tools have been applied in many conservation planning projects across New South Wales (NSW Department of Land and Water Conservation 2002; NSW National Parks and Wildlife Service 2003; NSW Department of Environment and Conservation 2004, 2005, 2006a, 2006b; Scotts & Drielsma 2003).

3 Project objectives and deliverables

As stated in the Services Agreement for this study, the aim of the project is to provide to ACT Government agencies responsible for planning and managing land, a landscape wide connectivity analysis building on the research already undertaken by Manning *et al.* (2010). The analysis must be able to guide the conservation of ecosystem resilience by identifying areas that are key to the maintenance and improvement of landscape connectivity across the ACT and surrounding region. A key deliverable is to develop an ecosystem connectivity map for the ACT and surrounding area.

Specific tasks that must be undertaken include:

- incorporating scattered or paddock tree information into the vegetation data layer;
- re-running the nearest neighbour and links values tools at the scale in which the vegetation data has been gridded (15 m). The re-run will involve consideration of three broad vegetation structural classes: forests, woodlands and grasslands;
- undertaking a sensitivity analysis of varying sensitivity scores. This sensitivity analysis will make use of a review paper, recently produced by Veronica and Eric Doerr and Micah Davies from CSIRO Sustainable Ecosystems, of all the Australian studies on structural connectivity titled *Does structural connectivity facilitate dispersal of native species in Australia's fragmented terrestrial landscapes?* The findings in relation to species movement and barriers, critical gap distances between suitable habitat and minimum suitable patch size should be utilised;
- incorporating a much greater number of 'nearest neighbour' matches into the rerun analysis; and
- providing a means of incorporating consideration of connectivity value into restoration, planning and development decisions.

4 Methods

4.1 Study area

The original intention was to use the study area defined by the full extent of the vegetation map which followed the boundary used for the *Planning Framework for Natural Ecosystems of the ACT and NSW Southern Tablelands* (Fallding 2002) shown in Figure 3. However, the vegetation map was found to contain a spatial offset error that affected the vegetation data sourced from the NSW National Parks and Wildlife Service. In discussions with the ACT Government it was decided to reduce the study area to the region of the vegetation map that did not contain the error. The error was subsequently corrected by the authors of the Manning *et al.* (2010) study but not in time to be used for the analysis.

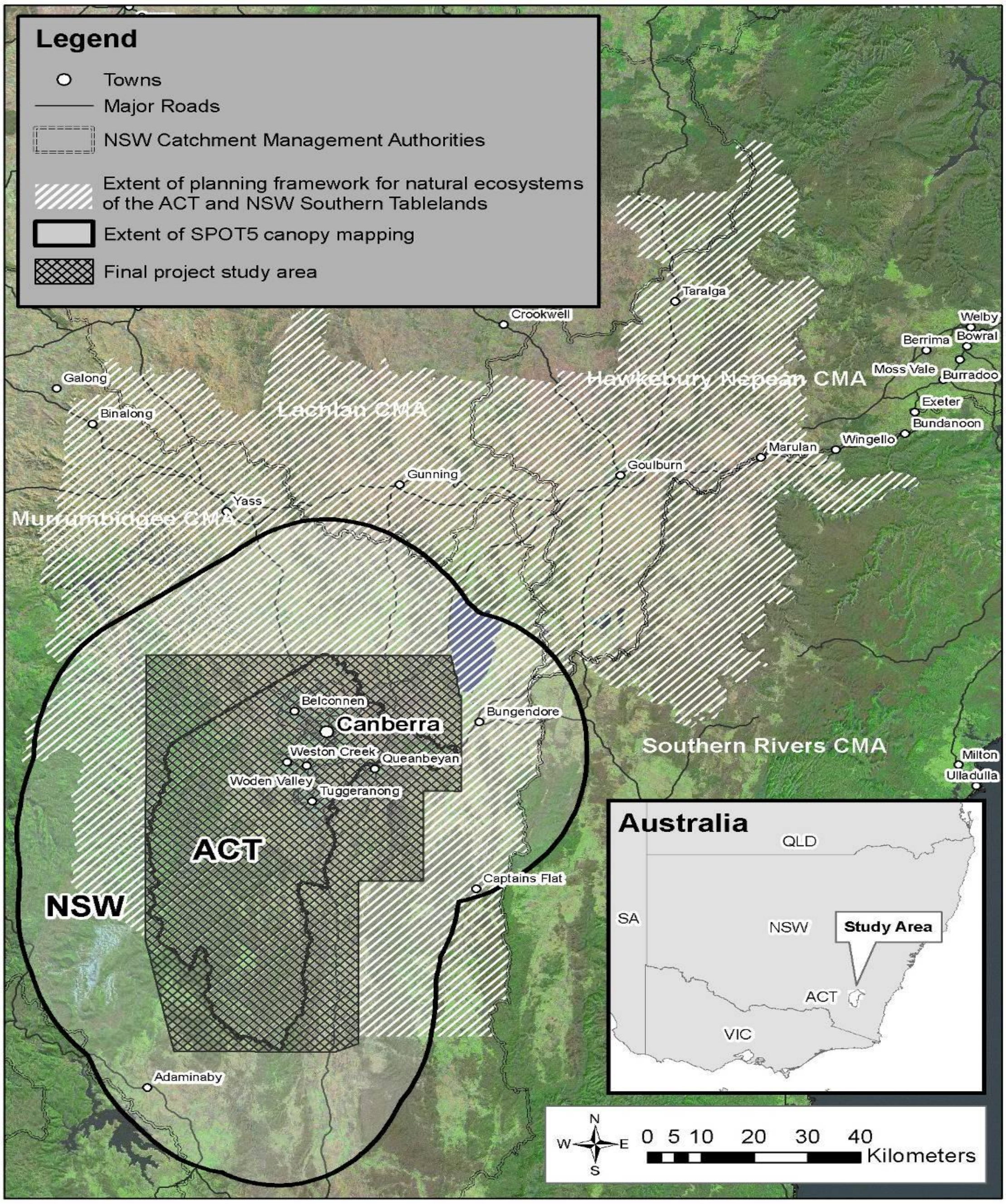

Figure 3 Map of study areas

The raster modelling techniques used to identify potential habitat and connectivity values are all based on the ‘least cost path’ concept which assumes that native fauna are more likely to travel via the path of least resistance, or least cost, when moving through the landscape. Cost is assumed to be proportional to the suitability and condition of habitat which is also affected by spatial configuration or habitat fragmentation. To identify potential wildlife corridors, hundreds of thousands of these least cost paths are calculated through habitat in the landscape. Areas of habitat with the most paths going through them are predicted to have good connectivity values and represent potential wildlife corridors.

The following three figures illustrate the computer automated method used to calculate the least cost paths using a hypothetical landscape containing habitat of varying value for the Superb Blue Wren.

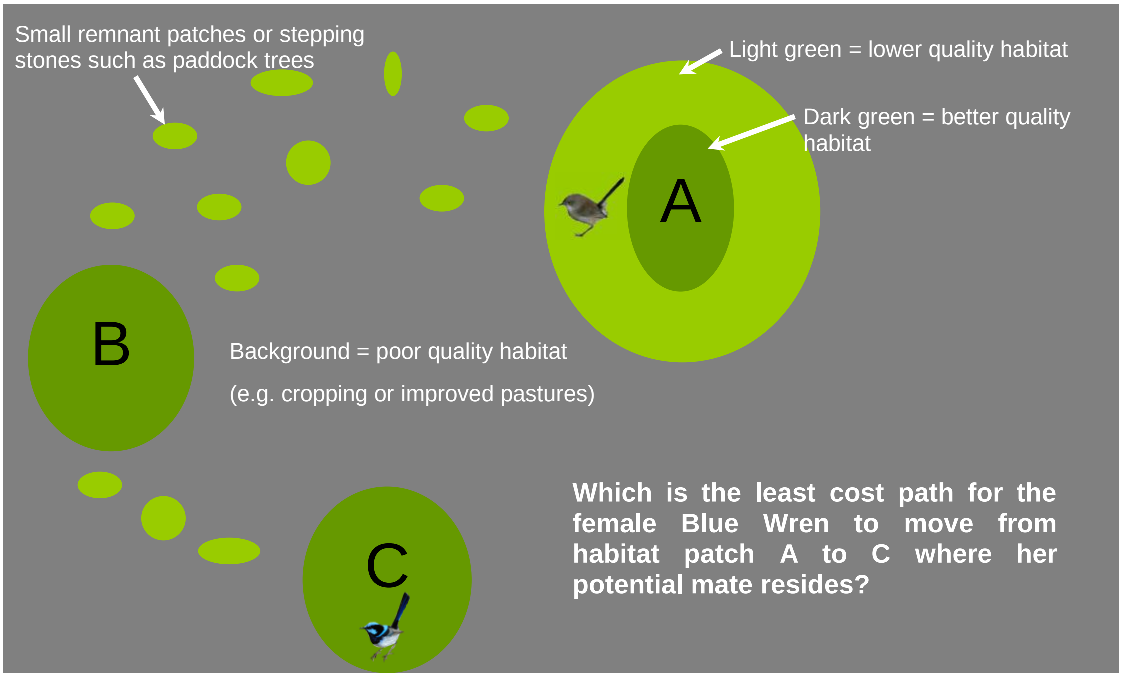

Figure 4 A simple representation of habitat to illustration the concept of the ‘least cost path’

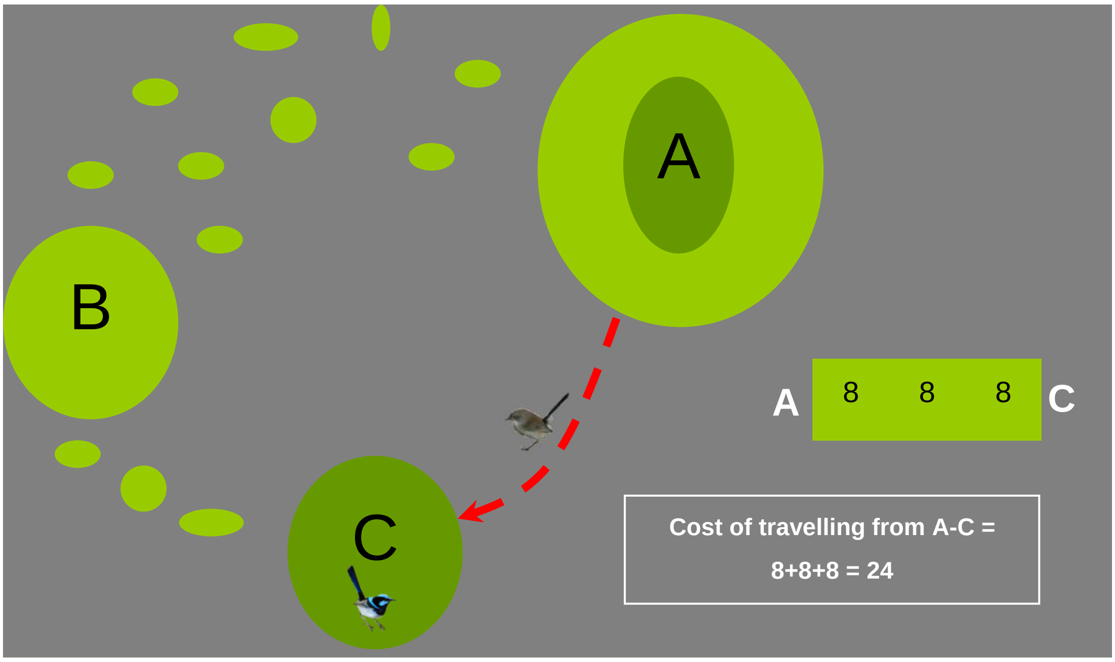

Figure 5 The accumulated relative cost of travelling through the more hostile non-habitat equals 24

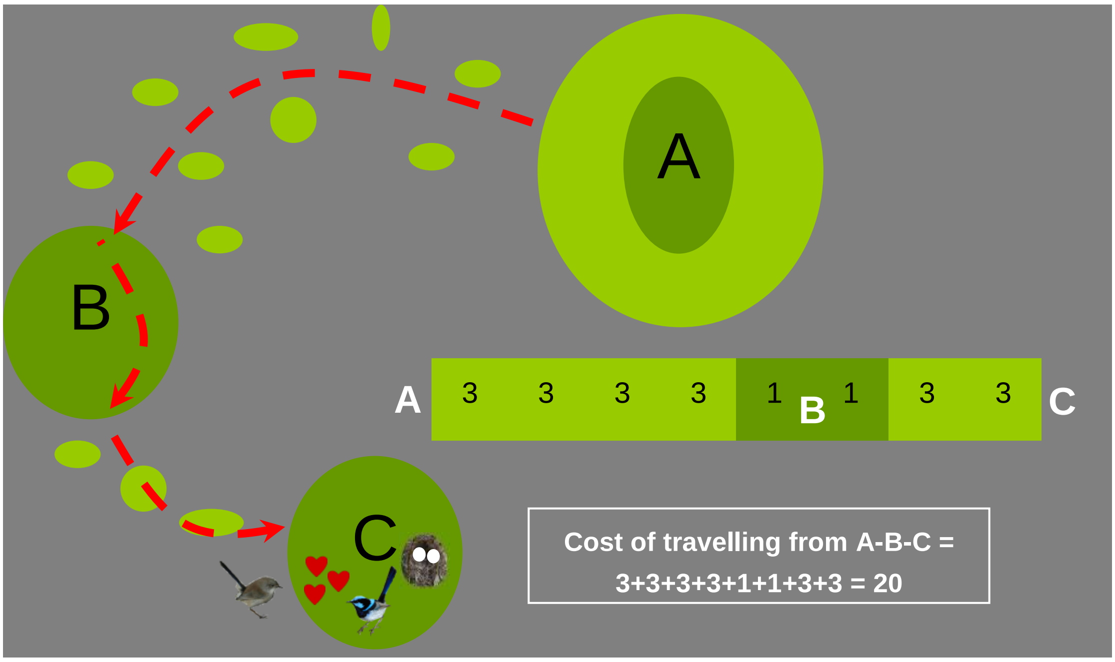

Figure 6 The least cost path is the one via habitat patch B (A-B-C) with an accumulated cost of 20 compared to the accumulated cost of 24 going the shorter but more costly path through hostile habitat (A-C). Having successfully negotiated the least cost path the female wren settles in patch C, successfully raising the next generation

On a more technical note, the modelling methods can be grouped into the following five main modelling tasks:

1. Modelling habitat condition.
2. Modelling habitat for settlement (patches >10 ha).
3. Modelled habitat colonisation potential
4. Modelling habitat for dispersal (local links through stepping stones).

5. Modelling habitat for connectivity between habitat for settlement (regional links).

More detailed technical specifications and methodologies used to undertake these modelling tasks are documented in Appendix 1.

4.2 Task 1: Modelling habitat condition

Habitat condition or suitability was modelled for the following three broad faunal functional groups:

1. Generalist species
2. Forest species
3. Woodland species.

There were three main spatial data inputs into the models:

1. Broad vegetation types and land cover
2. Fine scale woody vegetation canopy model
3. Modelled woody vegetation stand density.

4.3 Task 2: Modelling habitat for settlement (patches >10 ha)

A Neighbourhood Habitat Area (NHA) analysis (Drielsma, Ferrier and Manion 2007; Hanski 1999) was applied to the habitat models to predict the level of habitat resource available at each site (grid cell). A cut-off was applied to this model (top 20% of values) to produce islands of high habitat value. Once converted into a polygon GIS layer the area of each island could be calculated. Patches >=10 ha in size were identified as potential habitat for settlement while those patches <10 ha, and all other habitat was considered habitat for dispersal. Appendix 6 provides a worked example of the NHA calculation.

4.4 Task 3: Modelling colonisation potential

For each cell the colonisation potential is calculated by weighting the NHA value by the habitat condition value of that cell. Calculation of the NHA and habitat condition value is described above in 'Task 1 Modelling habitat condition' and 'Task 2 Modelling habitat for settlement (patches >10 ha)' above.

The objective of weighting the NHA value by the habitat condition value is to model the potential capacity of each cell to provide habitat and resources necessary for settlement for the target fauna species.

4.5 Task 4: Modelling habitat for dispersal (local links through stepping stones)

A modified version of the 'Spatial Links Tool' (Drielsma*, Manion & Ferrier* 2007) was used to model fine scale links between stepping stones (paddock trees or small habitat patches) that were found to be within 105 m proximity of each other (100 m gap crossing threshold). This modified approach has been termed the 'Local Links Tool' and is described in detail in Appendix 1.

4.6 Task 5: Modelling connectivity between habitat for settlement (regional links)

The 'Spatial Links Tool' (Drielsma, *et al.* 2007) was used to model least cost paths between habitat for settlement (habitat patches >=10ha). A visual explanation of the least cost path calculation is provided in Figure 4, Figure 5 and Figure 6. This method is based on modelling least cost paths between many random point pairs. The point pairs were restricted to only occur within habitat patches >=10ha. The main difference between the application of the Spatial Links Tool in this project and that of previous applications is that the movement cost input grid was derived from the Local Links Tool outputs.

5 Results

See Figure 22 in Appendix 4 for a map of the study area. Appendix 4 contains a full set of maps presenting the analysis results for the whole study area. The following five figures (Figure 7 to Figure 13) illustrate the results of the analysis at a fine scale based on the 'generalist' species habitat condition models.

All GIS data layers, including a short description of each, are listed in Appendix 4.

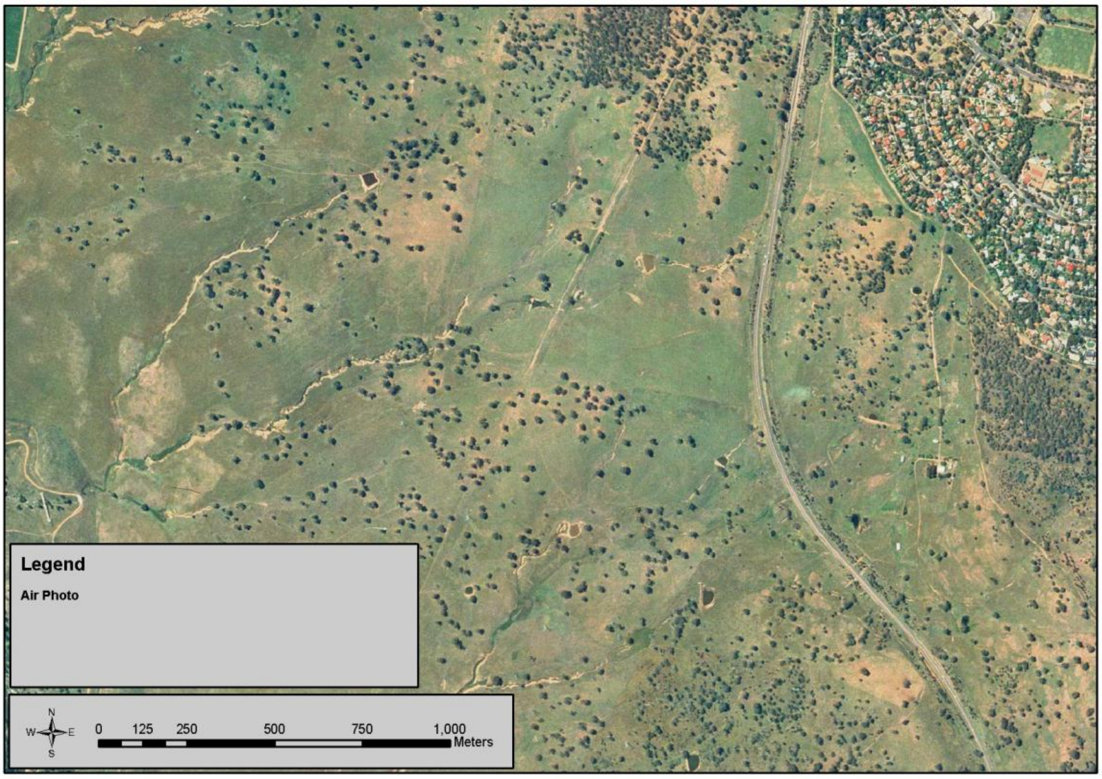

Figure 7 Air photo of a region to the west of the Mt Pinnacle Nature Reserve

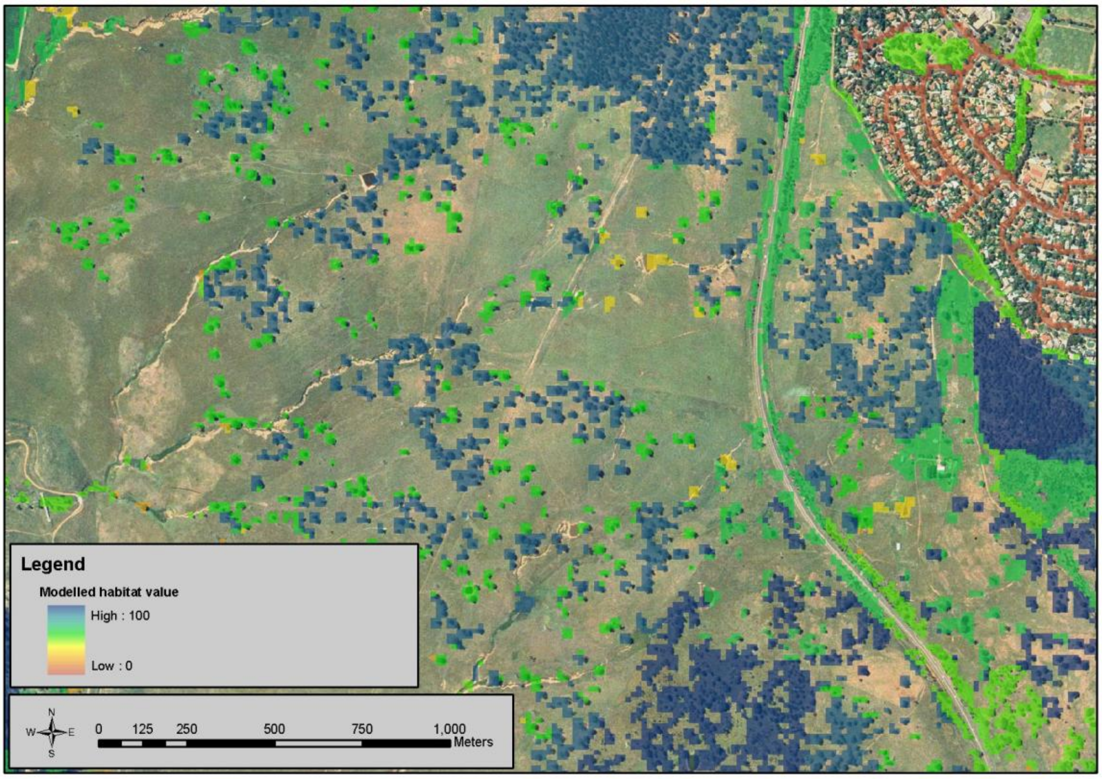

Figure 8 Modelled habitat condition for generalist species

Figure 9 Neighbourhood Habitat Area (NHA) for generalist species. High values represent locations that are well connected to high quality habitat within ~120 m proximity (17 x 17 cell window). Habitat patches are defined by NHA values (highest 20%)

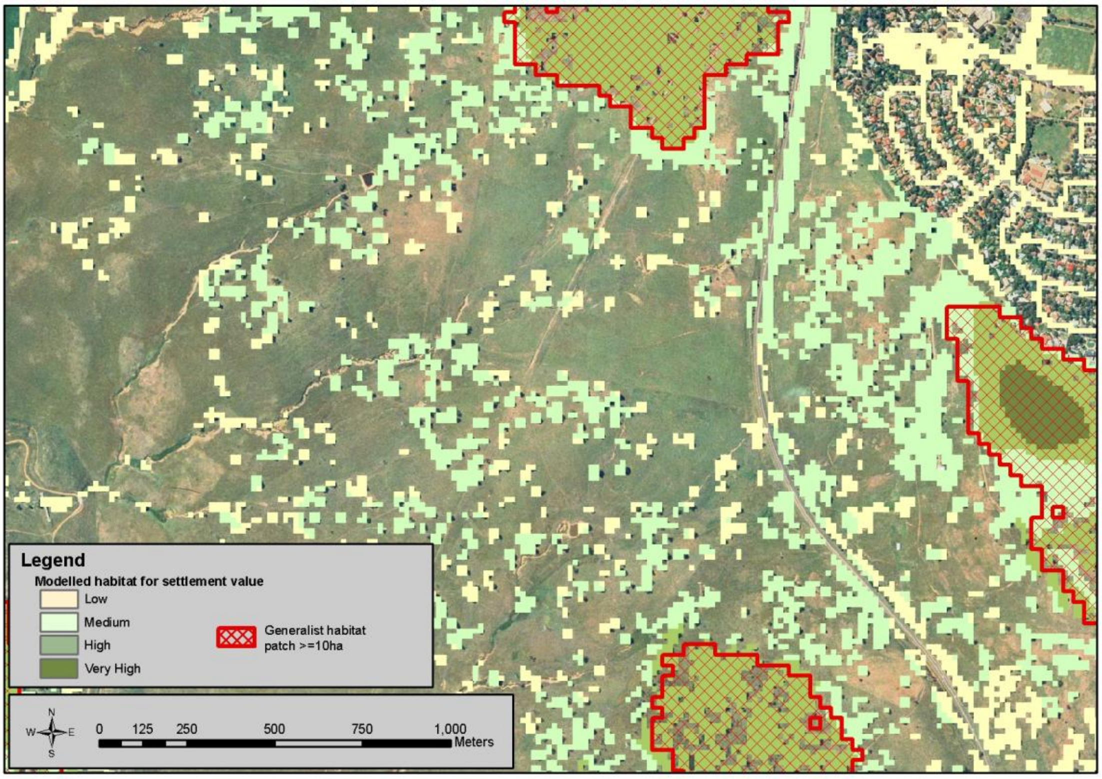

Figure 10 Modelled colonisation potential for generalist species based on Neighbourhood Habitat Area (NHA) weighted by habitat condition. High values represent locations that are well connected to high quality habitat within ~120 m proximity (17 x 17 cell window)

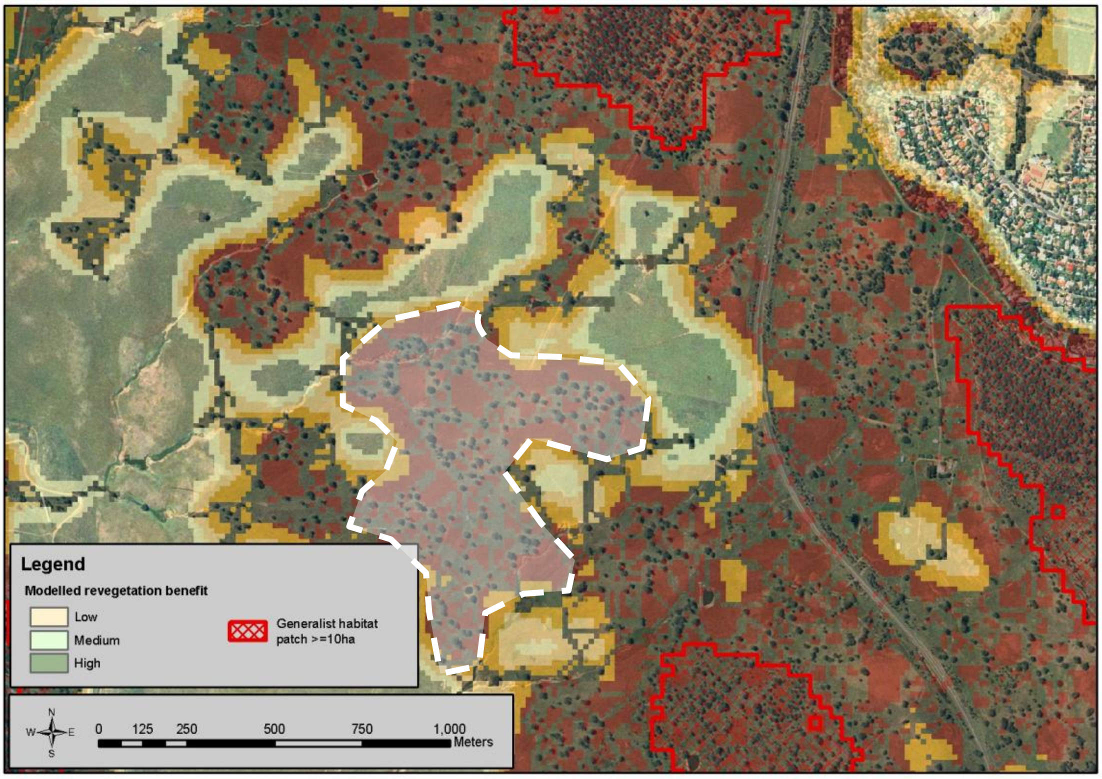

Figure 11 Modelled revegetation benefit. High values represent locations where reintroduction of appropriate native vegetation would improve habitat patch size and condition. The area identified by the white dashed line shows an example of where revegetation works could be undertaken to create a new habitat patch within 1.1 km from adjoining patches

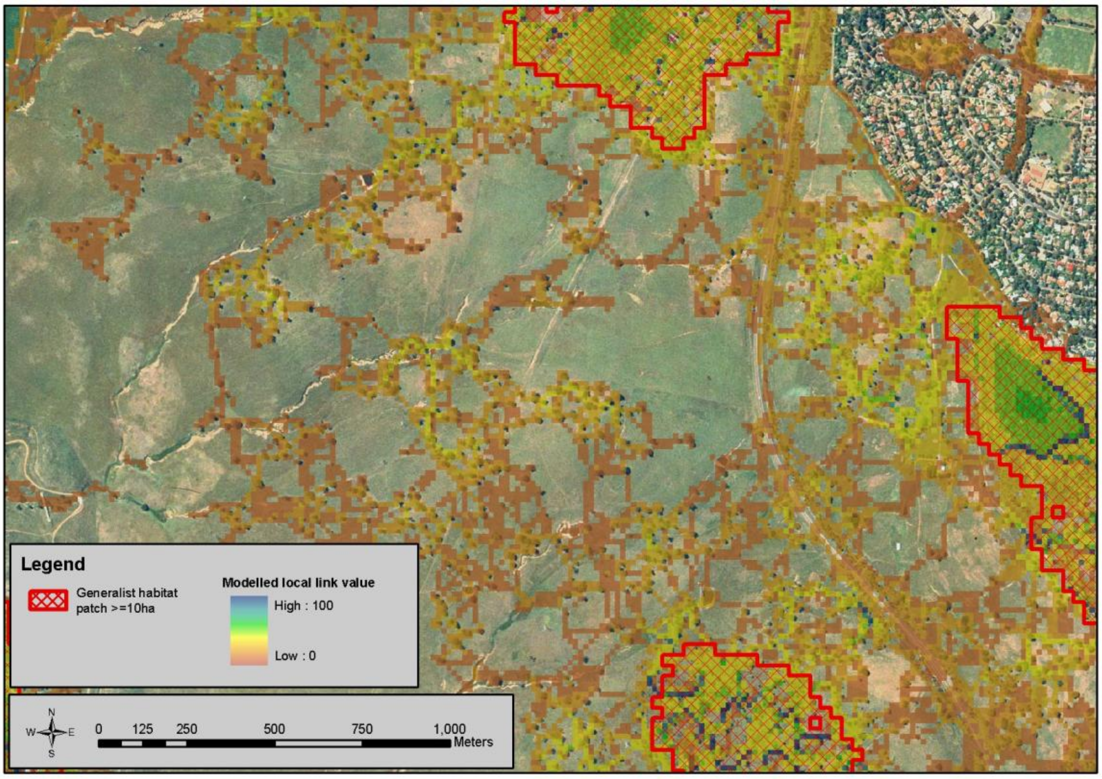

Figure 12 Modelled local link values for generalist species. Higher values represent more connected habitat (<105 m from focal cell)

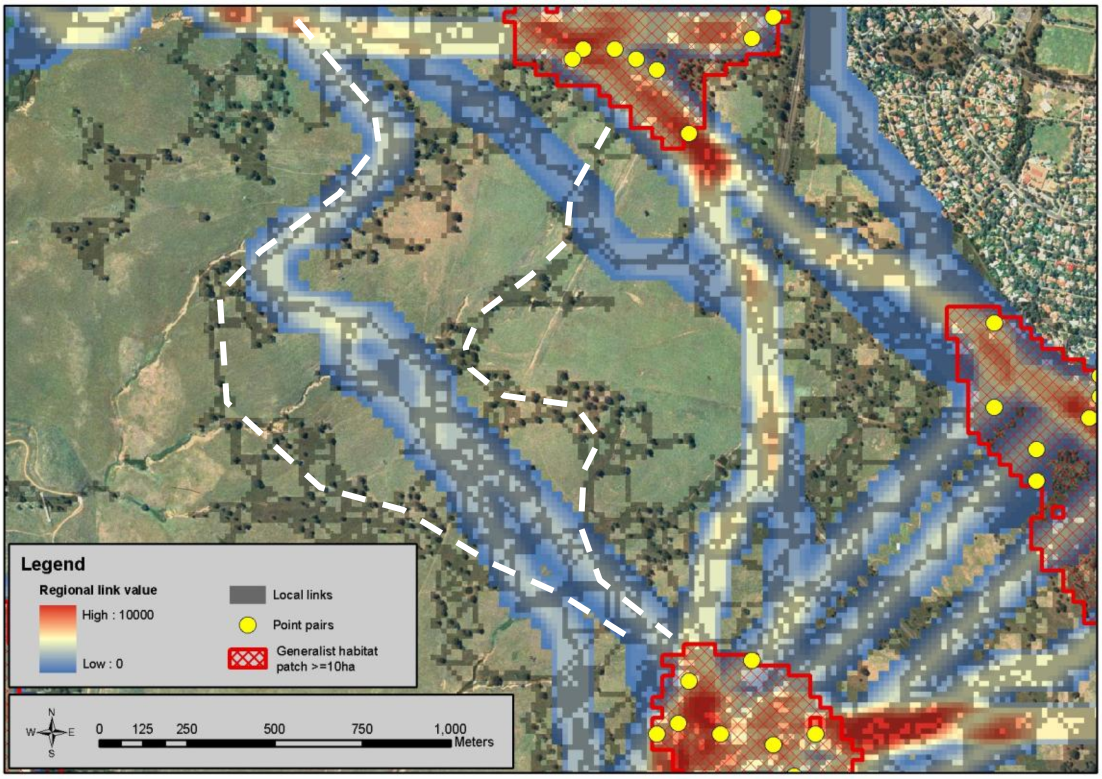

Figure 13 Regional (least cost path) links showing how the larger scale connections follow through local link paths between point pairs restricted to >=10 ha habitat patches. The dashed white lines illustrate how other paths between patches are not picked up because they do not represent the 'least cost' path

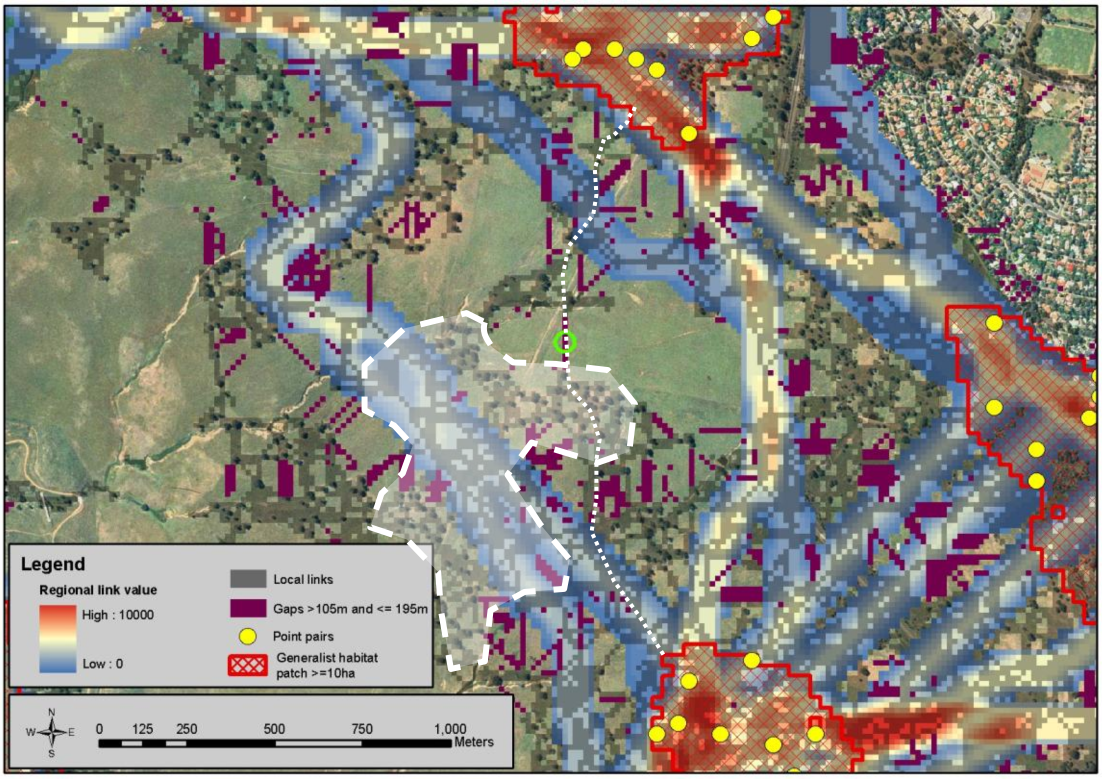

Figure 14 This figure includes identified gaps (purple cells) between habitat cells that are >105 m and <= 195 m apart. These gaps represent locations where connectivity may be enhanced with the addition of one (or more) stepping stone trees to 'close the gaps'. The small dashed white line illustrates how the addition of a stepping stone tree (in the green circle) could create a new link between habitat patches. The polygon defined by the large dashed line is taken from Figure 11 and demonstrates how new habitat patches can be created by enhancing existing low habitat quality patches that currently exist within 1.1 km of high quality patches

6 Discussion

6.1 Guide for use in supporting planning decisions

The habitat and connectivity models described in this report can be used to guide two types of planning activities: 1) assessing the value and context of existing habitat; and 2) undertaking restoration activities to maximise local and regional connectivity values.

6.1.1 Activity 1: Assessing the value and context of existing habitat

Habitat value and its regional context can inform planning decisions when used to assess the potential impacts of habitat loss due to proposed changes in landuse. A review of corridor effectiveness by Gilbert-Norton *et al.* (2009) found that natural corridors facilitated more animal movement than man-made corridors. Native remnant vegetation has also been shown to play an important role as habitat and structural connectivity for Australian native birds (Taws 2007; Paton & O'Connor 2009).

The most relevant data layers and maps for considering the value and context of habitat are:

1. Colonisation potential – which is a combination of habitat value and spatial context; (Figure 9) and
2. Regional links – which defines the least cost paths, utilising where possible functioning local links between generalist species habitat (Figure 12 and Figure 32).

If there is a reason for a particular focus on forest or woodland habitat (for example an interest in the impact of a proposal on a particular species that is a habitat specialist) then it is possible to also utilise colonisation potential for either woodland or forest habitat, and regional corridors for links between woodland habitat.

The following are key questions to consider.

Will the proposed landuse:

1. result in loss of areas of high colonisation potential? If so, will the proposal
    - o impact on a habitat patch >100 ha; or
    - o reduce a habitat area to < 10 ha; or
    - o impact on a habitat patch of 5 -– 10 ha that could be important to establishing and maintaining a 10 ha habitat patch every 1.1 km along a regional or local link?;
2. result in gaps in key regional connectivity locations of >100 m between habitat trees?;
3. result in canopy gaps of >100 m between local links connecting habitat patches identified as having high colonisation potential?

Any of the above type of losses should be avoided for landscape connectivity value to be maintained.

6.1.2 Activity 2: Undertaking restoration activities to maximise local and regional connectivity values

The aim of many habitat restoration activities is to enhance or improve habitat and connectivity values.

The most relevant data layers and maps for guiding restoration are:

1. Revegetation Potential – this is a context grid which gives higher weight to cleared areas that are most connected to habitat. It is a guide to those areas where planting or regeneration activities would do most to improve the spatial configuration of existing habitat (Figure 34);
2. Neighbourhood Habitat Area – which can be viewed in relation to particular vegetation types (natural temperate grassland, lowland woodland, riparian, montane/subalpine woodland or Callitris woodland) or in relation to the location of the highest value patches (large size/configuration, best condition);
3. Regional Links – which map the key linkage pathways;
4. Local links – which map the extent of unbroken (<100 m gap) canopy; and
5. Local links (195 m) only – which identify current breaks in canopy cover, which could be repaired through minimum planting effort. (Theoretically the establishment of one paddock tree in the middle of a 195 m gap would close that gap).

The key restoration objectives are:

1. To fill canopy gaps of >100 m in key linkage areas, especially when connecting habitat patches >=10 ha that are within 1.1 km of each other. Key linkage areas can be characterised by high regional links values;
2. To create habitat patches >10 ha every 1.1 km in the vicinity of areas of high regional link value. The most effective method to create a habitat patch >=10 ha in size is to build on existing patches, preferably >5 ha and <10 ha in size;
3. To increase the extent or improve the condition, habitat complexity and or spatial configuration of habitat of high colonisation potential;
4. To improve local dispersal potential between habitat patches by using the local links model, based on a gap crossing threshold of 195 m; to identify where there may be opportunities to introduce extra habitat stepping stones, such as individual paddock trees or small habitat patches; and to 'close the gaps' between existing stepping stone habitats.

6.2 Limitations and Recommendations

As with all modelling exercises, the models are an approximate representation of the real world and should always be used in conjunction with site-based assessment (validation) before final planning decisions are made.

There are several assumptions inherent in the models and the input data that should be kept in mind when using the models. These assumptions are discussed below.

6.2.1 Habitat models

The SPOT5 satellite-based woody tree canopy mapping does not provide any information about tree 'structure', often determined by the growth stage of those trees which have been found to be important for many woodland birds (Clarke *et al.* 2009). It was hoped that the above ground biomass index would address this limitation, but it was found to be more sensitive to tree density rather than tree size, defined by diameter at breast height (DBH) measure. This limitation could be overcome by more detailed assessment and mapping of isolated paddock trees using high resolution air photo interpretation, and/or field-based surveys.

The original intention was to model habitat and connectivity over a larger area but this aim was modified to cover only the ACT region due to errors in the vegetation community mapping. These errors have since been corrected by Dr Janet Stein from the Fenner School of Environment and Society at the Australian National University and this opens up the opportunity to extend the modelling over the area defined by the *Planning Framework for Natural Ecosystems of the ACT and NSW Southern Tablelands* (Fallding 2002).

The threshold for defining 'habitat for settlement' could be tested using field-based bird surveys and movement observations. Some of the subjectivity inherent in the determination of an NHA cut-off that defines a 'patch' could be removed by using a standardised habitat value measure such as the 'Effective Habitat Area' (EHA). The EHA for each grid-cell is calculated by expressing the NHA for the cell as a proportion of the maximum NHA that could be achieved if all of the region's vegetation still remained in pristine condition, and then multiplying this proportion by the area of the grid-cell.

The modelling undertaken in this project did not attempt to assess target fauna population viability. A more sophisticated approach using the 'rapid evaluation of metapopulation persistence' (REMP) methods, which utilise the same component analytical techniques, could be undertaken to predict metapopulation capacity of the ACT region and for predicting occupancy patterns within this landscape (Drielsma & Ferrier 2009).

6.2.2 Least cost path (LCP) modelling approach

The focus of the modelling techniques used in this study is on connectivity in a fragmented landscape and as a result the techniques are not suited to measuring connectivity values in continuous vegetation. The latter could be undertaken using the same modelling tools and input data, but modelled at larger scales and using a more traditional approach to identifying the point pairs to use in the least cost path (regional links) analysis. This involves restricting the point pairs to fall in grid cells with higher habitat condition values and modelling the least cost paths between these.

The extra paths identified in Figure 13 (using dashed lines) demonstrate how the regional links least cost path approach does not find every potential path, just the 'least cost' path between point pairs. One recommendation is that the modelling technique used to model the regional paths is modified to identify every possible path between point pairs and a value is assigned to that path that reflects the 'cost' associated with using that path. Paths that are more direct and utilise higher condition habitat would receive higher values than less direct paths through poor condition habitat.

If the regional links analysis was performed again, the authors would recommend including point pairs in habitat patches that are <10 ha in size as well as the larger >=10 ha patches. This would aid in identifying which of the smaller patches were candidates for revegetation activities with the aim of increasing the size of these patches.

It is also recommended that the ACT region be assessed in terms of the broader regional context using a larger scale spatial links analysis such as that undertaken for the NSW State Biodiversity Strategy (Drielsma *et al* 2012, NSW Office of Environment & Heritage, *in prep and 2012*) and as part of deriving the 'Landscape Value Mapping' (Drielsma *et al.* 2009).

Several studies have also highlighted some issues with the application of the least cost path analysis method to model structural connectivity (Beier, Majka & Spencer 2009; Beier, Majka & Newell 2009; Sawyer *et al.* 2011). Sawyer *et al.* (2011) made the following key recommendations (in their Appendix S2) to improve the way least cost path modelling is undertaken. This project attempted to address as many as these as was practically possible given time and resource restrictions. How this was achieved is outlined below.

6.2.3 Summary of recommendations

a) *Source patches should accurately represent populations of interest.*

This was addressed by using data from bird survey records to calibrate modelled habitat condition.

b) *Included variables should reflect species (not researcher) view of landscape.*

As far as possible the input data used to model habitat condition was chosen based on known correlations between vegetation measures and habitat use. These include factors such as vegetation structure (density) and species composition or vegetation type. The use of bird survey records to calibrate the models was undertaken as a response to this recommendation and it is hoped that as a result the models more accurately reflect the species view of the landscape.

c) *Study grain should reflect perception of species in landscape.*

The decision to use fine scale canopy mapping data sets was made in response to the small scale (100 m) of the gap crossing thresholds identified in the systematic review by Doer *et al.* (2010). Also the important role that paddock trees play in providing connectivity and habitat resources, highlighted by numerous woodland bird studies (Paton & O'Connor 2009), meant that fine scale woody vegetation mapping was required to detect paddock trees.

d) *Researchers should optimise cost schemes with empirical data and perform model validation.*

The term 'cost schemes' refers to the method of modelling the 'cost' of movement (of an animal) through different parts of the landscape and is the main input used to calculate the least cost paths through the landscape. Model validation was not undertaken as part of this project. The ACT Government has recognised that this is an important exercise, and is currently contracting the CSIRO to undertake a validation of the modelled surfaces.

e) *Researchers should perform standardised sensitivity analysis and model selection.*

Time restrictions meant that sensitivity analysis could only be undertaken for one parameter, that of gap crossing threshold. Two gap crossing thresholds were modelled, 105 m and 195 m.

f) *One-pixel wide least cost path should not be final output of LCP analysis.*

The regional links LCP analysis produced paths one pixel wide which were then 'smoothed' to produce wider paths that still reflected the underlying path value, determined by the number and weight of least cost paths going through each grid cell.

This project demonstrates how combining fine scale satellite-based vegetation mapping products with ecological process models, based on metapopulation biology theory, can predict fauna habitat and connectivity values across large areas for a relatively low cost. It is hoped that these fine scale spatial modelling products will provide a valuable resource for informing all regional planning and site-based landuse decisions in the ACT.

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Appendix 1 Modelling methods

Appendix 1 outlines the technical methodology used in this study that can be grouped into the following five main modelling tasks:

1. Modelling habitat condition.
2. Modelling habitat for settlement (patches >10 ha).
3. Modelling habitat colonisation potential.
4. Modelling habitat for dispersal (local links through stepping stones).
5. Modelling habitat for connectivity between habitat for settlement (regional links).

1.1 Task 1: Modelling habitat condition

Habitat condition or suitability was modelled for the following three broad faunal functional groups:

1. Generalist species
2. Forest species
3. Woodland species.

There were three main spatial data inputs into the models:

1. Broad vegetation types and land cover
2. Fine scale woody vegetation canopy model
3. Modelled woody vegetation stand density.

1.1.1 Broad vegetation type and land cover

As discussed in Section 2 'Ecological Principles', vegetation composition is a key predictor for many bird and mammal species. The Fenner School gave its permission to use the vegetation community and landuse map compiled as part of the Manning *et al.* (2010) study. This map was generated by combining best available maps into a single seamless map and classification. Recent, more detailed, vegetation mapping has been undertaken in the Gungahlin Area (Schweikle and Baines 2010; Eco Logical Australia 2011), so this was used to update the Manning *et al*. study. Figure 24 (Appendix 4) shows the 'map of maps' or source data used in the composite vegetation/landuse map shown in Figure 25.

For each of the three faunal functional groups a habitat suitability score (out of 100) was assigned to each vegetation/land cover class (Table 2, Appendix 2). These suitability values were partly informed by similar weightings used in Manning *et al.* (2010). Using these weightings in combination with other data sets meant that they defined the maximum habitat quality value. This was then modified by weightings produced in the other data sets.

1.1.2 Fine scale woody vegetation canopy model

Due to the fine scale of the analyses and the identified importance of scattered paddock trees, the NSW Office of Environment and Heritage was contracted to undertake fine scale woody vegetation canopy mapping for the study area (Roff and Davies 2011). This mapping was undertaken at an extremely fine scale (5 m resolution) which was resampled to 15 m resolution to match the scale of the vegetation and landuse map. A 'maximum' function was used in the resample, which means if a 15 m^2 pixel contained one or more 5 m^2 pixels, then it was assigned a value of one indicating the presence of woody vegetation, while 15 m^2 pixels without any canopy mapped were assigned to zero. The final mapping product is shown in Figure 23 (Appendix 4).

1.1.3 Modelled woody vegetation stand density

There were several limitations of the woody vegetation canopy mapping that prompted the use of another remote sensing product. Firstly the canopy mapping contained some misclassification errors where pasture was misclassified as woody vegetation, probably due to the influence of moisture on the reflectance signature received by the SPOT5 satellite. The second limitation relates to the lack of information on vegetation structure. For example, the canopy mapping did not discriminate between dense regrowth (or woody shrubs) and old growth stands. Also there is a large amount of internal variation in stand density, within the broad vegetation communities in the vegetation/landuse map.

To overcome these limitations two satellite imagery derived measures of stand density were investigated: Foliage Projected Cover (FPC) derived from Landsat imagery (Armstron *et al.* 2004); and Above Ground Biomass (AGB) derived from the Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band Synthetic Aperture Radar (PALSAR) imagery (Lucas *et al.* 2010).

Three vegetation condition survey data sets were collated where woody vegetation structural measures such as stand density and tree stem diameter (DBH) were measured (Zerger *et al.* 2007; Gibbons *et al.* 2008; NSW Department of Land and Water Conservation 2002). The spatial distribution of these three data sets is shown in Figure 31. Figure 17 shows the relationship between average stem basal area measured at the survey sites and the AGB. This graph was used to derive four AGB classes for mapping which were used to identify a correlation between AGB and tree density (average stem count/ha). Figure 18 shows the results of a comparison between FPC and AGB measures. This comparison found that AGB was better at predicting tree density (stems/ha) than the FPC measure. The FPC model failed to detect trees in around one quarter of the survey sites that contained positive tree density measures. For this reason it was decided that the AGB index would be more suitable to use as surrogate for vegetation structure (stand density).

The AGB data was resampled from its original resolution of 50 m down to 15 m and then smoothed using an average 3x3 filter. The map in Figure 26 (Appendix 4) shows these four AGB classes in the study area.

1.1.4 Using bird survey data to calibrate habitat models

Some bird species have been found to be more sensitive to habitat fragmentation than others and the populations of these species are often in decline. These declining birds, as well as species considered to be good indicators of habitat condition, have been identified and described as ‘birds to watch out for’ by Taws (2007) for the ACT and south-east NSW.

Over 10 000 records of these bird species were extracted from the NSW Wildlife Atlas that included the majority of records from the ACT Wildlife Atlas. It was not possible to incorporate all ACT Wildlife Atlas records because of the issue of duplicating sites already in the NSW Wildlife Atlas. The records in the ACT Atlas mainly consist of the woodland monitoring and incidental records of the Canberra Ornithologists Group. The 10000 bird records were intersected with the AGB dataset. Figure 20 shows the proportion of total records for each these species found to occur in the AGB classes and Figure 21 shows the proportion of bird records occurring in broad vegetation/landuse classes. From this analysis two species were chosen to determine the weightings assigned to the AGB classes for the woodland and forest habitat models:

- The Speckled Warbler preferred more open environments (see Figure 20 and Figure 21) and was chosen to represent the woodland habitat type.
- The Eastern Yellow Robin showed a strong preference for high tree density forested areas (see Figure 20 and Figure 21) and was chosen as the species most dependent on forest habitat.

For the generalist species models, equal weighting was assigned to all AGB classes that represented native vegetation (at varying levels of tree density).

Table 3 and

Table 4 (Appendix 2) present the results of this analysis which were used to assign weightings to derive the three broad habitat models.

Table 1 List of bird species investigated to calibrate habitat model, described as 'birds to watch out for' by Taws (2007)

Common Name	Family	Scientific Name
Speckled Warbler	Acanthizidae	*Chthonicola sagittata*
Horsfield's Bronze-Cuckoo	Cuculidae	*Chalcites basalis*
Hooded Robin	Petroicidae	*Melanodryas cucullata*
Pallid Cuckoo	Cuculidae	*Cacomantis pallidus*
Dusky Woodswallow	Artamidae	*Artamus cyanopterus*
Superb Parrot	Psittacidae	*Polytelis swainsonii*
Diamond Firetail	Estrildidae	*Stagonopleura guttata*
Restless Flycatcher	Monarchidae	*Myiagra inquieta*
Double-barred Finch	Estrildidae	*Taeniopygia bichenovii*
Brown Treecreeper	Climacteridae	*Climacteris picumnus*
Jacky Winter	Petroicidae	*Microeca fascinans*
Scarlet Robin	Petroicidae	*Petroica boodang*
White-winged Chough	Corcoracidae	*Corcorax melanorhamphos*
White-throated Treecreeper	Climacteridae	*Cormobates leucophaea*
Eastern Yellow Robin	Petroicidae	*Eopsaltria australis*

1.1.5 Building the final habitat models

The following algorithm was used to build the final habitat models:

{If not native in vegetation/landuse map (*MASK=1 in Table 2*)

then;

[use vegetation/landuse weighting (*in Table 2*)]

else (is native in vegetation/landuse map)

$$\left(\frac{\text{((vegetation/landuse weighting x 2) x (AGB weighting) x (canopy mask))}}{300} \right) \text{X 100}$$

The canopy mask consisted of zero (no canopy mapped) or one where canopy was mapped. The vegetation community weighting contributed to 2/3 of the final habitat score while the AGB weighting made up the remaining 1/3. This decision to give the vegetation community mapping more weight in the model was made after feedback from a presentation to ACT Government representatives and members of three community groups involved with the management of the Pinnacle, Mt Painter and Aranda Bushland. Members of these groups have a very good level of local knowledge of the ecological values of the Belconnen hills landscape restoration area, including habitat use by woodland birds.

The final habitat model maps are shown in Appendix 4 (Figure 28, Figure 29 and Figure 30).

1.2 Task 2: Modelling habitat for settlement (patches >10 ha)

A Neighbourhood Habitat Area (NHA) analysis (Drielsma 2007; Hanski 1999) was applied to the habitat models to predict the level of habitat resource available at each site (grid cell). A cut-off was applied to this model (top 20% of values) to produce islands of high habitat value. Once converted into a polygon GIS layer the area of each island could be calculated. Patches >=10 ha in size were identified as potential habitat for settlement while those patches <10 ha, and all other habitat was considered habitat for dispersal. See Appendix 6 for a worked example of the NHA calculation.

1.2.1 Parameters used in NHA analysis

a) *Permeability*

The ‘permeability’ grid surface is the inverse of ‘cost’, that is, areas with high permeability present a low cost to fauna movement. Permeability is calculated using

Equation 1.

$$\frac{([\text{Cond Grid}] - \text{min hab condition})}{(\text{max hab condition} - \text{min hab condition})} \times (\text{max perm} - \text{min perm}) + \text{min perm}$$

Equation 1 Calculation of permeability from the Habitat Condition grid where ‘min perm’ and ‘max perm’ is equal to the minimum and maximum permeability based on the minimum and maximum1/α values, or average distance travelled through areas of lowest and highest habitat condition (see below).

b) *One on alpha (1/α)*

The 1/α parameter defines the average distance that an animal can travel through an area given the habitat condition of that area. See Appendix 6 for a more detailed explanation of this parameter. In this analysis for a window size of 17 x 17 cells a minimum 1/α value (for non-habitat areas) was assigned 105 m reflecting the 100 m gap crossing threshold between stepping stones and a maximum 1/α (for highest quality habitat) of 1100 m reflecting the 1.1 km distance threshold for movement along stepping stone corridors.

c) *Neighbourhood area analysis window*

The size of the analysis window determines the ‘area of influence’ for the calculation of the NHA measure assigned to the focal (central) cell. A size of 17 x 17 cells was chosen. This includes habitat cells that are within a distance of 120 m to 170 m from the focal cell and represent an area of 6.5 ha. This window size was chosen as it was operationally tractable (calculation of NHA took ~9 hrs) and encompasses all habitat within the 100 m gap crossing threshold.

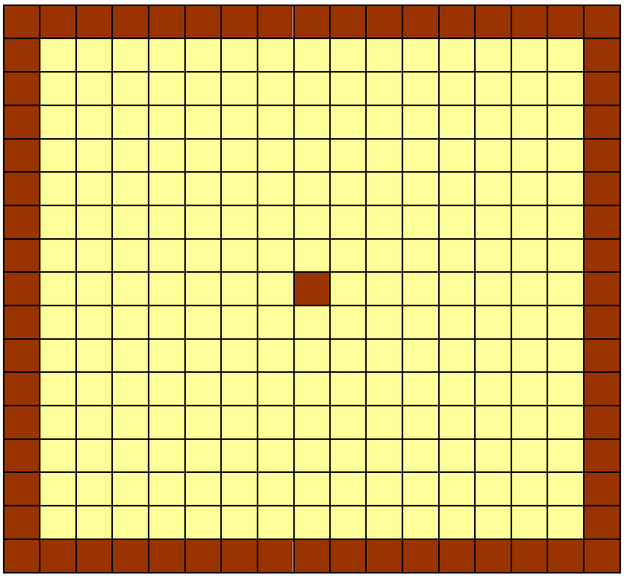


Figure 15 Illustration of the configuration of the 'Neighbourhood Area' analysis window. Each cell represents a 15 m X 15 m grid cell, the 17 cells x 17 cells window equates to an area of ~6.5 ha. The distance between the central cell and the edge cells ranges from 120 m (closest edge cell) to ~170 m (to the corner cell)

1.3 Task 3: Modelling colonisation potential

For each cell the colonisation potential is calculated by weighting the NHA value by the habitat condition value of that cell. Calculation of the NHA and habitat condition value is described above in ‘Task 1 Modelling habitat condition’ and ‘Task 2 Modelling habitat for settlement (patches >10 ha)’ above.

The objective of weighting the NHA value by the habitat condition value is to model the potential capacity of each cell to provide habitat and resources necessary for settlement for the target fauna species.

1.4 Task 4: Modelling habitat for dispersal (local links through stepping stones)

A modified version of the ‘Spatial Links Tool’ (Drielsma, Manion & Ferrier 2007) was used to model fine scale links between stepping stones (paddock trees or small habitat patches) that were found to be within 105 m proximity of each other (100 m gap crossing threshold). This modified approach has been termed the ‘Local Links Tool’. This modified method can be described in the following four stages:

1. First, the movement ‘permeability’ is calculated in the same way as it is for the NHA model. Inputs include the habitat condition model and one on alpha (1/α) distance.
2. Second, a least cost path is calculated from the focal cell to every cell within the analysis window that has a non-zero habitat value, that is, cells with habitat.
3. For each path generated, a path ‘value’ is calculated using a distance decay function applied to the path’s accumulated cost, and this accumulated path value is assigned to all cells in the path.
4. Steps 2 and 3 are repeated for every grid cell containing a positive habitat value in the study area.

Each cell in the output grid accumulates the values of every path passing through it that has an accumulated cost less than a specified threshold. The threshold cost is based on the accumulated cost of a path moving through seven 15 m cells (=105 m) of non-habitat. This reflects the 100 m average gap crossing threshold.

The input data and parameters are the same for the calculation of NHA outlined in 'Task 2 Modelling habitat for settlement (patches >10 ha)' above.

1.5 Task 5: Modelling connectivity between habitat for settlement (regional links)

The 'Spatial Links Tool' (Drielsma, Manion & Ferrier 2007) was used to model least cost paths between habitat for settlement (habitat patches >=10 ha). A visual explanation of the least cost path calculation is provided in Figure 4, Figure 5 and Figure 6. This method is based on modelling least cost paths between many random point pairs. The point pairs were restricted to only occur within habitat patches >=10 ha. The main difference between the application of the Spatial Links Tool in this project and that of previous applications is that the movement cost input grid was derived from the Local Links Tool outputs. The analysis stages involved in generating regional links include the following:

1. Generation of input grids including a cost surface and random points within habitat patches >=10 ha.
2. Selection of a random point pair within a specified distance threshold.
3. Calculation of the least cost path between the two points.
4. For each path generated, a path 'value' was calculated using a distance decay function applied to the path's accumulated cost and this accumulated path value was assigned to all cells in the path.
5. As more paths are found, the path 'value' for cells within the paths was accumulated until a specified number of paths was found.
6. Paths were always one cell wide, so to make them more visible an averaging filter (based on a 7 x 7 cell widow) was run over the output grid to smooth the values while retaining the relative underlying path value.

1.5.1 Parameters used in Spatial Links Tool analysis

a) Permeability grid

The local links modelled outputs were used to derive the permeability grids for the regional links analysis. The 15 m local links grids were resampled to 30 m cell resolution (based on the average of the four underlying 15 m cells) to reduce processing time. For grid cells that did not have a local links value (non-canopy and non-local links areas) the vegetation and landcover weightings were used to define permeability.

For the regional links analysis for the woodland species the local links layer was given a 10x weighting compared to the non-links cells, that is, 10 times more permeable. After review of the model output this weighting was increased to 100x for running the regional links analysis for the generalist species. This means that for the generalist species regional links models, the least cost paths are more restricted to the output from the local links model.

b) Point pairs

Around 19 000 random points were generated within habitat patches >=10 ha. Habitat cells close to the edge of the patches usually had lower NHA values and this was used to restrict the points to the edge regions. The maximum distance between point pairs was 20 km and the minimum distance was 5 km.

c) Distance decay function

The value of each path is determined by applying a sigmoidal decay function to the effective distance between points based on the following parameters; i = 0.001 and ‘1/α’ = 15 000 (also illustrated in Figure 16 below). See Drielsma, Manion & Ferrier (2007) for a full description of the functions and parameters. The effective distance is calculated using Equation 2 (Appendix 6).

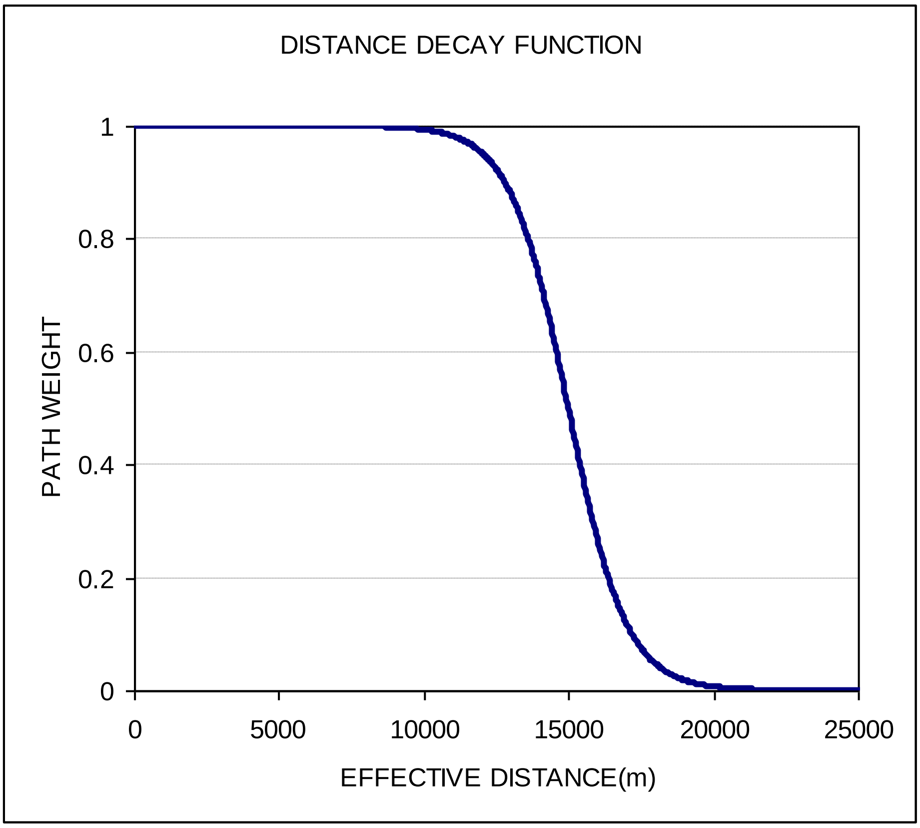


Figure 16 Graph of distance decay function used to assign the path value based on the effective distance between points in regional links analysis

d) Number of paths

For the generalist species regional links models, a total of 6 000 000 paths were modelled. For the woodland species regional links models, a total of 550 000 paths were modelled.

Appendix 2 Tables

Table 2 Vegetation composition and land cover suitability weightings

Mapping Class	Class description	Included terms	Woodland spp Suitability	Forest spp suitability	Generalist spp suitability	MASK
1	Natural Temperate Grassland	Natural Temperate Grassland	100	50	100	0
2	NTG (modelled), Native pasture	Native grassland (high prob of occurrence), native grassland (low prob of occurrence), native pasture, grassland (unspecified)	90	50	90	0
3	Lowland woodland	Partially_modified_lowland_woodland(woodland), partially_modified_lowland_woodland(open forest), partially_modified_lowland_woodland(open woodland)	100	80	100	0
4	Grassland-woodland mosaic	Box-gum woodland, grassland-woodland mosaic, moderately_modified_lowland_woodland(woodland), melliodora-blakelyi woodland, moderately_modified_lowland_woodland(open forest)	90	50	90	0
5	Substantially modified lowland woodland	Substantially modified lowland woodland, moderately_modified_lowland_woodland(open forest), secondary grassland(high prob of occurrence), secondary grassland(low prob of occurrence), secondary_grassland(moderately modified lowland woodland), secondary_grassland(partially modified lowland woodland), tableland woodland	50	30	50	0
8	Heath/shrubland	Heathland-shrubland-herbfield-rock, heathland-shrubland-herbfield-rock	90	30	90	0
10	Riparian	Riparian forest, riparian woodland, wetlands, wetlands, aquatic and fringing veg complex, Callistemon-Kunzea riparian, Casuarina riparian woodland, Casuarina woodland, viminalis riparian woodland	100	100	100	0
11	Montane / subalpine woodland	Subalpine woodland, montane woodland, woodland (non-montane/subalpine/riparian)	100	80	100	0
12	Forest	Upland montane forest, dry forest, wet forest, macrorhyncha-rossii forest,	50	100	100	0
13	Callitris woodland	Callitris woodland	100	80	100	0
14	Kunzea derived shrubland	Kunzea derived shrubland	50	5	50	1
15	Former pine plantation	Former pine plantation post-2003, former pine plantation pre-2003	5	5	5	0

Mapping Class	Class description	Included terms	Woodland spp Suitability	Forest spp suitability	Generalist spp suitability	MASK
16	Exotic plantation	Softwood production, plantation/arboretum, oleaginous fruit, exotic plantation, Plantation (Horticulture-Orchard)	5	5	5	0
17	Modified grasslands	Modified grassland/urban vegetation complex, modified pasture, exotic pasture, no data areas in natural Ecosystems Project extant vegetation cover, runway (grassed surface)	30	30	30	0
18	Native street trees	Street trees (native species > 60% street tree-count, and 20+ years)	10	10	10	1
19	Exotic street trees	Street trees (exotic, young (< 20 years) natives)	5	5	5	1
20	Cultural	Urban, residential, building, built up area, all roads and tracks (excludes pathways), runway, building complex, general industry point, transport facility point (airport, railway stations, car park, helipad, bus interchange, marina), Plantation (Horticulture-Crop, Horticulture-Vineyard)	0	0	0	1
21	Lakes/water	Lakes/water, hydro area (waterbody area, watercourse)	0	0	0	1
22	Wetlands	Wetlands	0	0	0	0
23	Open forest	Bridgesiana-dives woodland, macrorhyncha-rossii woodland, pauciflora-rubida woodland	80	100	100	0
24	Native plantation	Native plantation	30	30	30	0

Table 3 Breakdown of NSW Wildlife ATLAS records occurring in above ground biomass (AGB) classes. Highlighted rows indicate species chosen to derive the weightings for the three broad habitat models

		Proportion of total records (%) in Above Ground Biomass (AGB) classes			
Common Name	**Number of records**	**AGB 0-20**	**AGB 20-50**	**AGB 50-150**	**AGB >150**
Speckled Warbler	652	1	9	64	20
Horsfield's Bronze-Cuckoo	242	1	18	38	21
Hooded Robin	191	1	21	35	22
Pallid Cuckoo	382	2	23	31	26
Dusky Woodswallow	475	2	17	32	30
Superb Parrot	325	7	26	18	32
Diamond Firetail	255	1	19	26	35
Restless Flycatcher	215	6	18	32	37
Double-barred Finch	268	1	7	41	39
Brown Treecreeper	313	7	21	26	40
Jacky Winter	281	5	13	26	45
Scarlet Robin	758	1	9	30	49
White-winged Chough	1175	2	12	31	50
White-throated Treecreeper	2685	4	6	19	67
Eastern Yellow Robin	1413	3	6	11	78

Table 4 Proportion of NPWS Wildlife ATLAS records occurring within the four above ground biomass classes. Also the final weighting assigned to these classes for use in the woodland and forest habitat models. Note that the '<20' AGB class was assigned a zero weighting as visual inspection found that this class contained very little native vegetation

	Proportion of ATLAS records (% of total)		Weighting used in habitat models (Proportion of records rescaled between 0-100)		
AGB Range	Speckled Warbler (Woodland bird)	Eastern Yellow Robin (Forest bird)	Woodland	Forest	Generalist
<20	1	3	0	0	0
20-50	9	6	14	8	100
50-150	64	11	100	14	100
>150	20	78	31	100	100

Appendix 3 Results of analysis used to inform habitat condition model

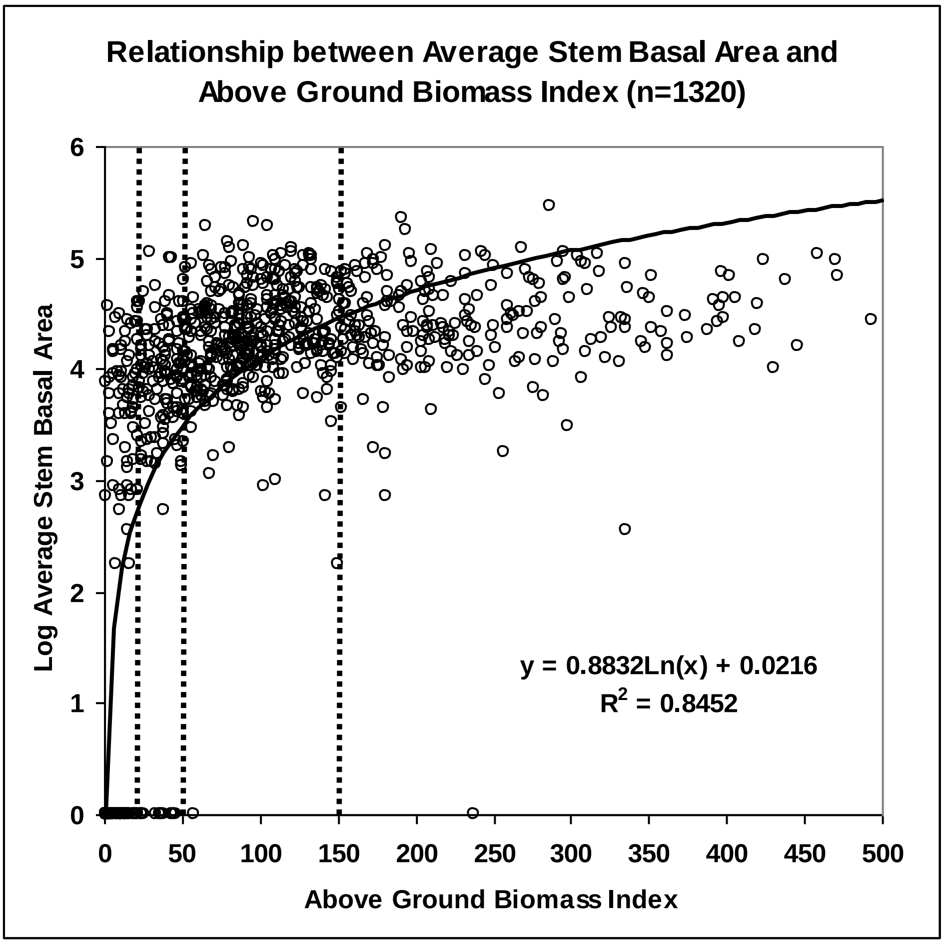


Figure 17 Relationship between above ground biomass (AGB) index and average basal area of all woody stems in survey sites. Dotted lines show the cutoffs used to define the four AGB classes

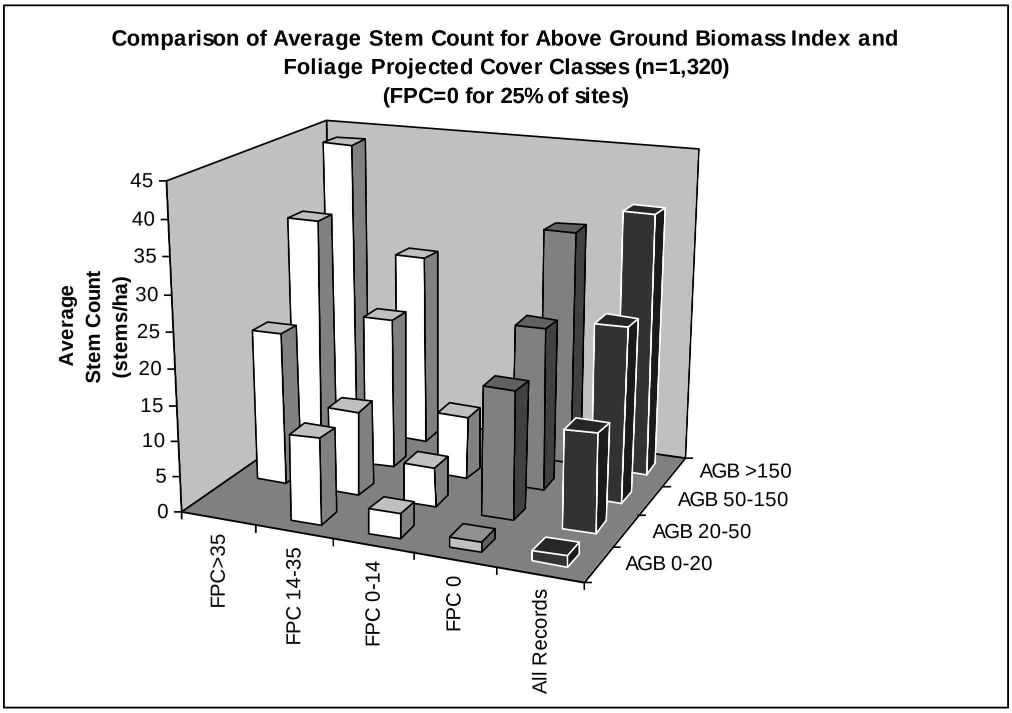


Figure 18 Graph showing the average woody stem density for bands of FPC and AGB values. Note that the majority of the survey sites where FPC=0 (shown in dark grey) contained positive stem count values

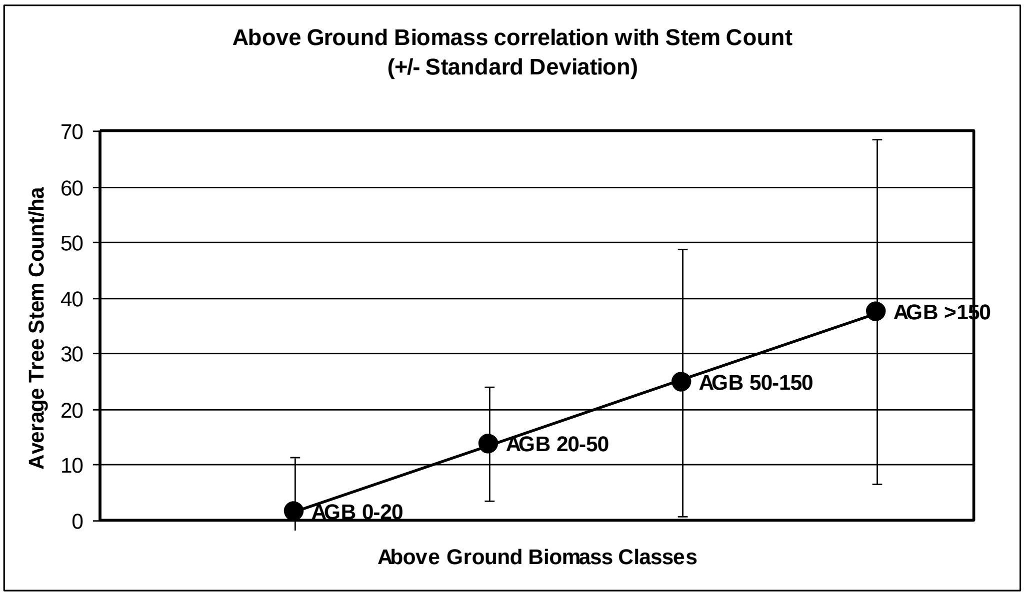


Figure 19 Graph showing correlation between average tree stem count at survey sites for each of the four above ground biomass index classes

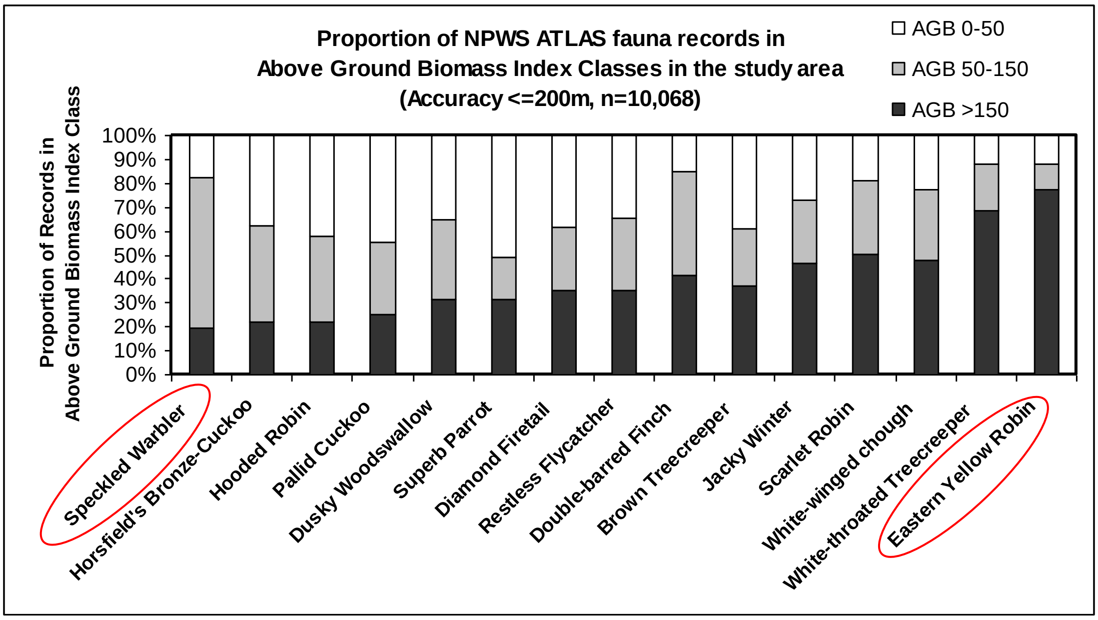


Figure 20 Graph showing the proportion of fauna records, out of the total records in study area, occurring in three above ground biomass index classes.

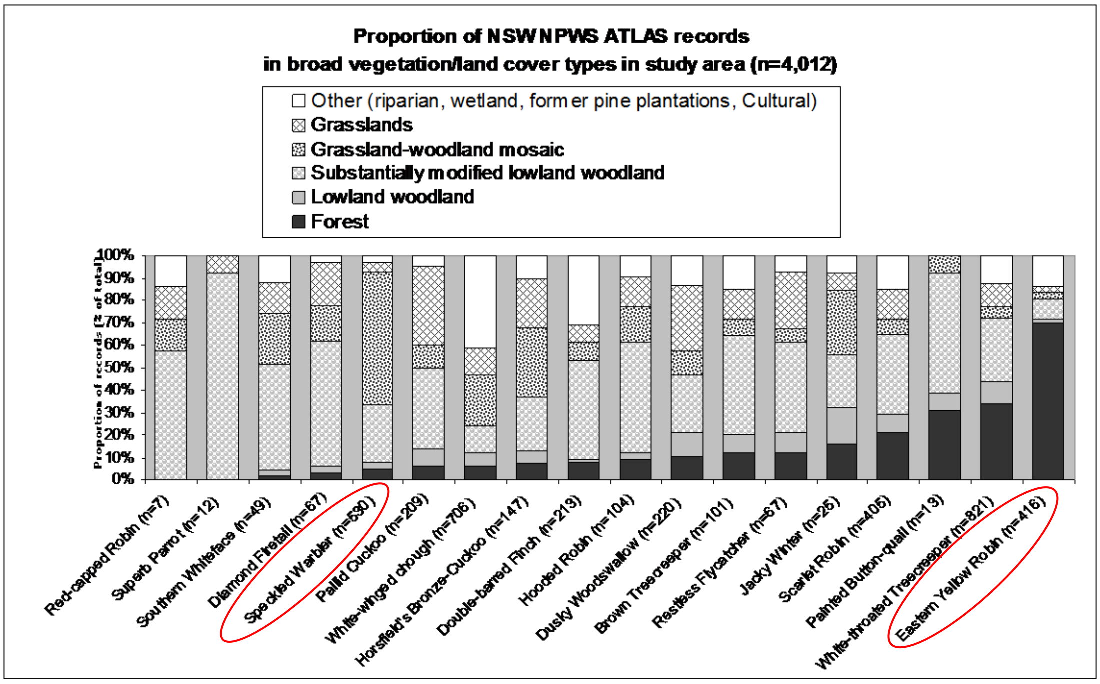


Figure 21 Graph showing the proportion of fauna records, out of the total records in study area, occurring in the broad vegetation type/landuse classes.

Appendix 4 Maps

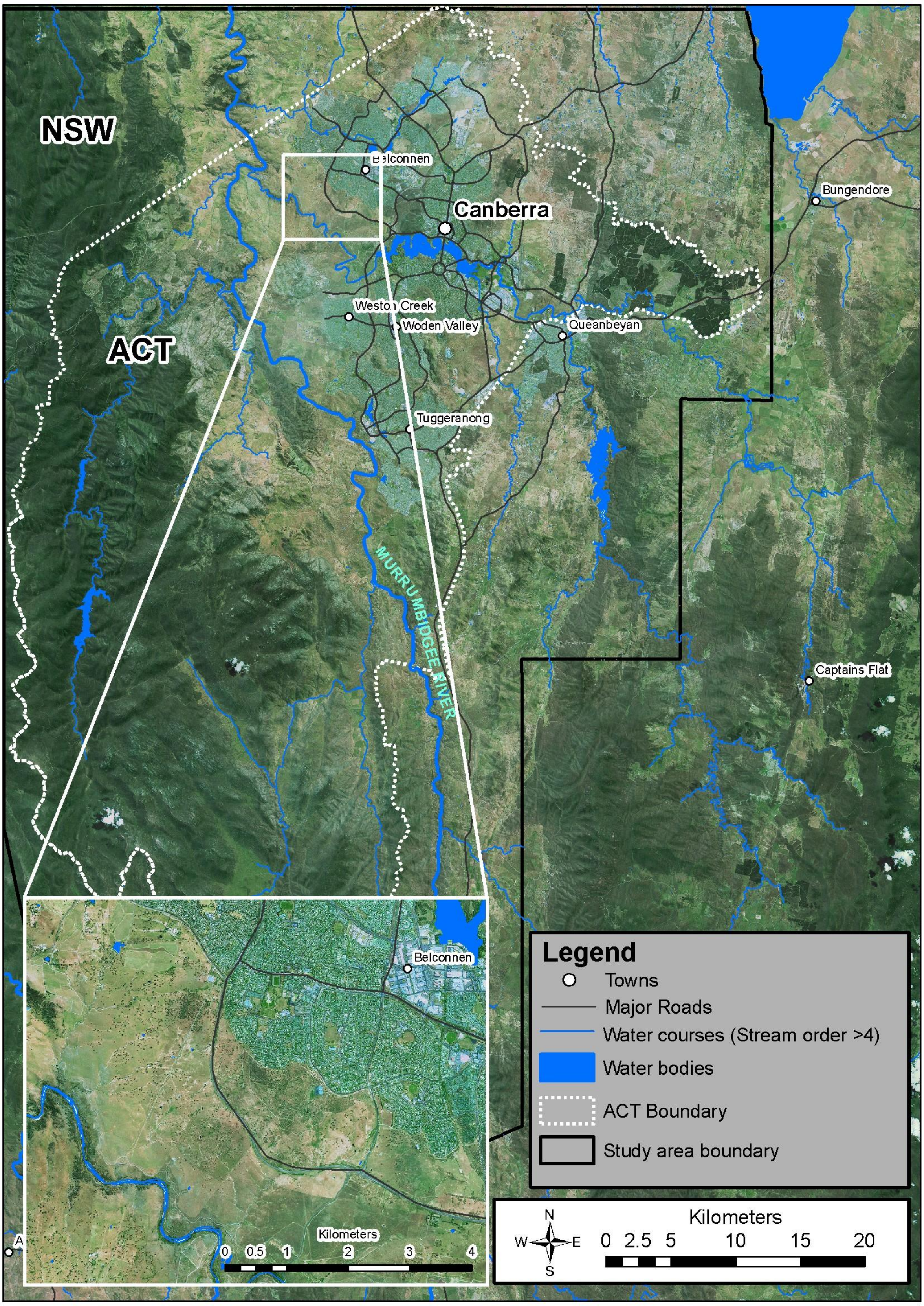


Figure 22 Map showing SPOT5 image (2008) for study area

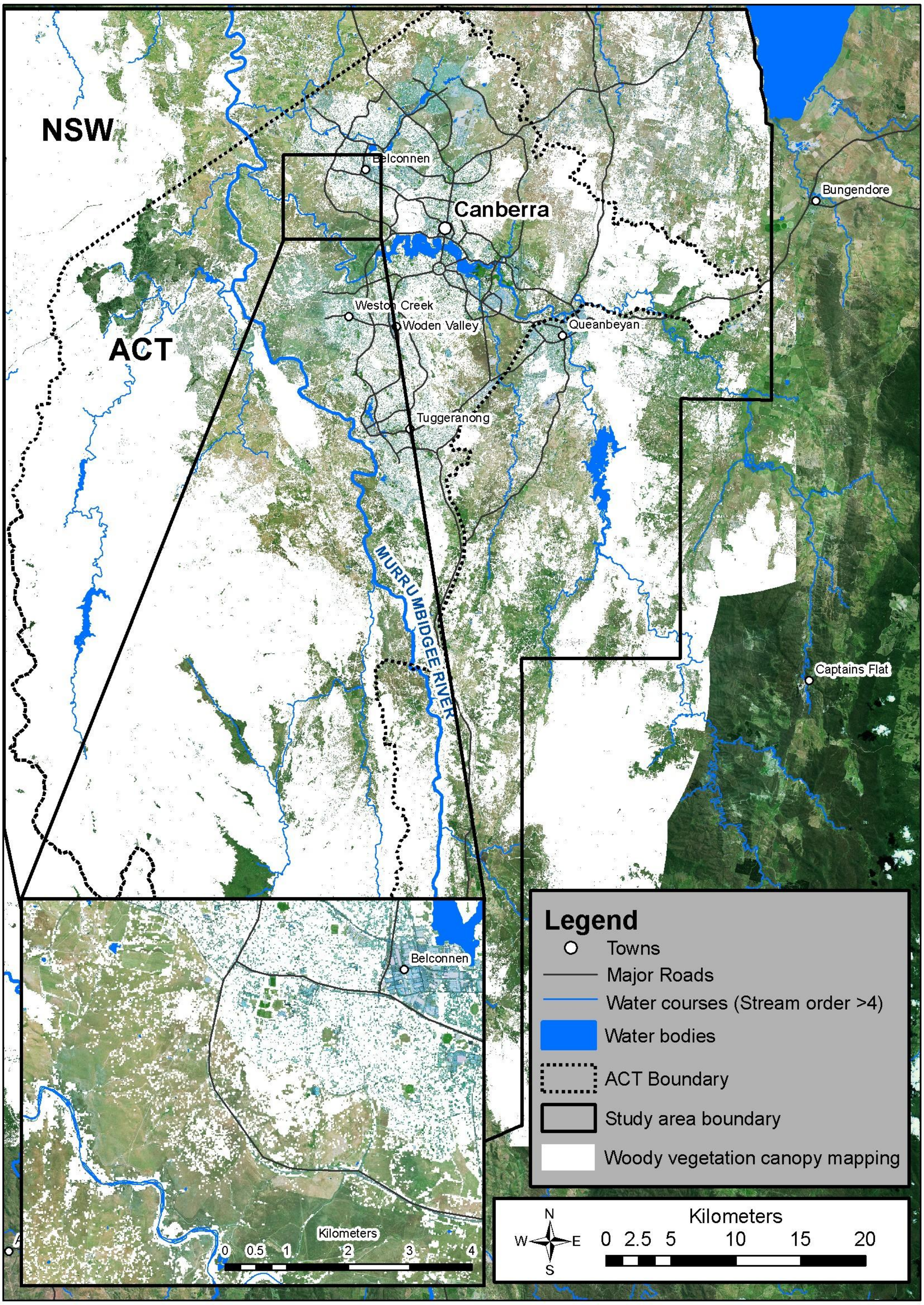


Figure 23 Map of fine scale woody vegetation canopy mapping undertaken by OEH overlaying a SPOT5 image (2008)

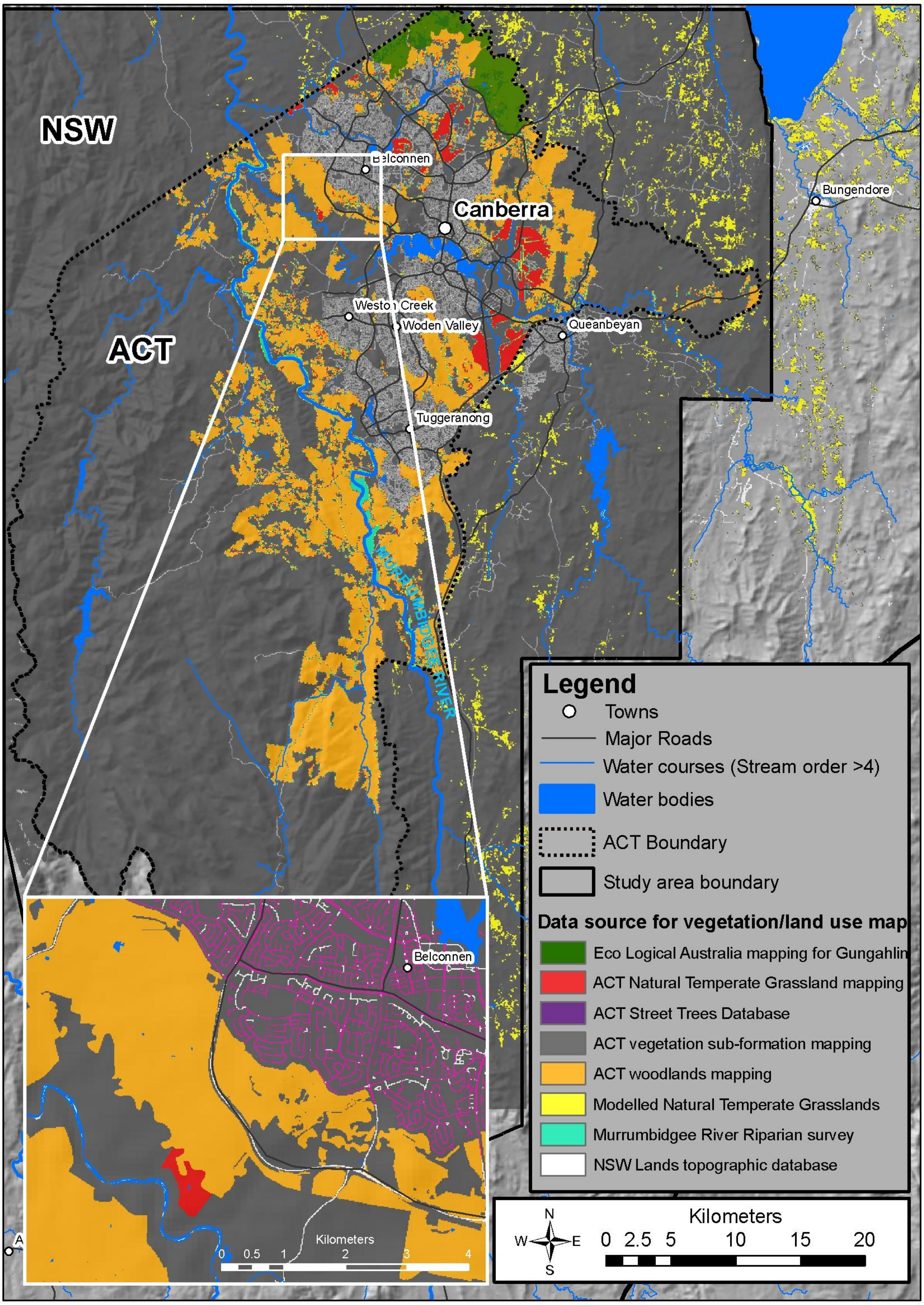


Figure 24 Data source for vegetation/landuse map

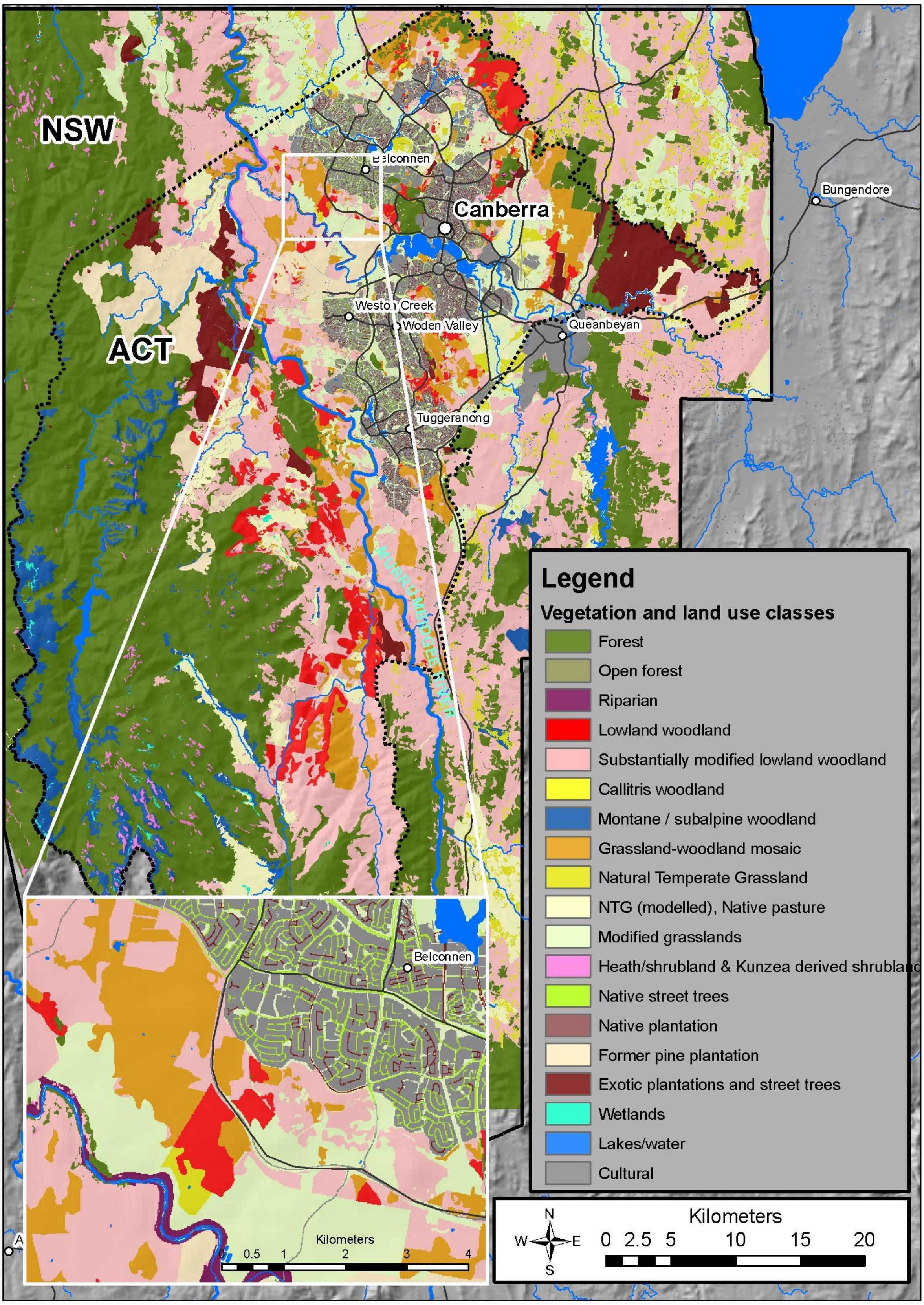


Figure 25 Map of broad vegetation and landuse classes

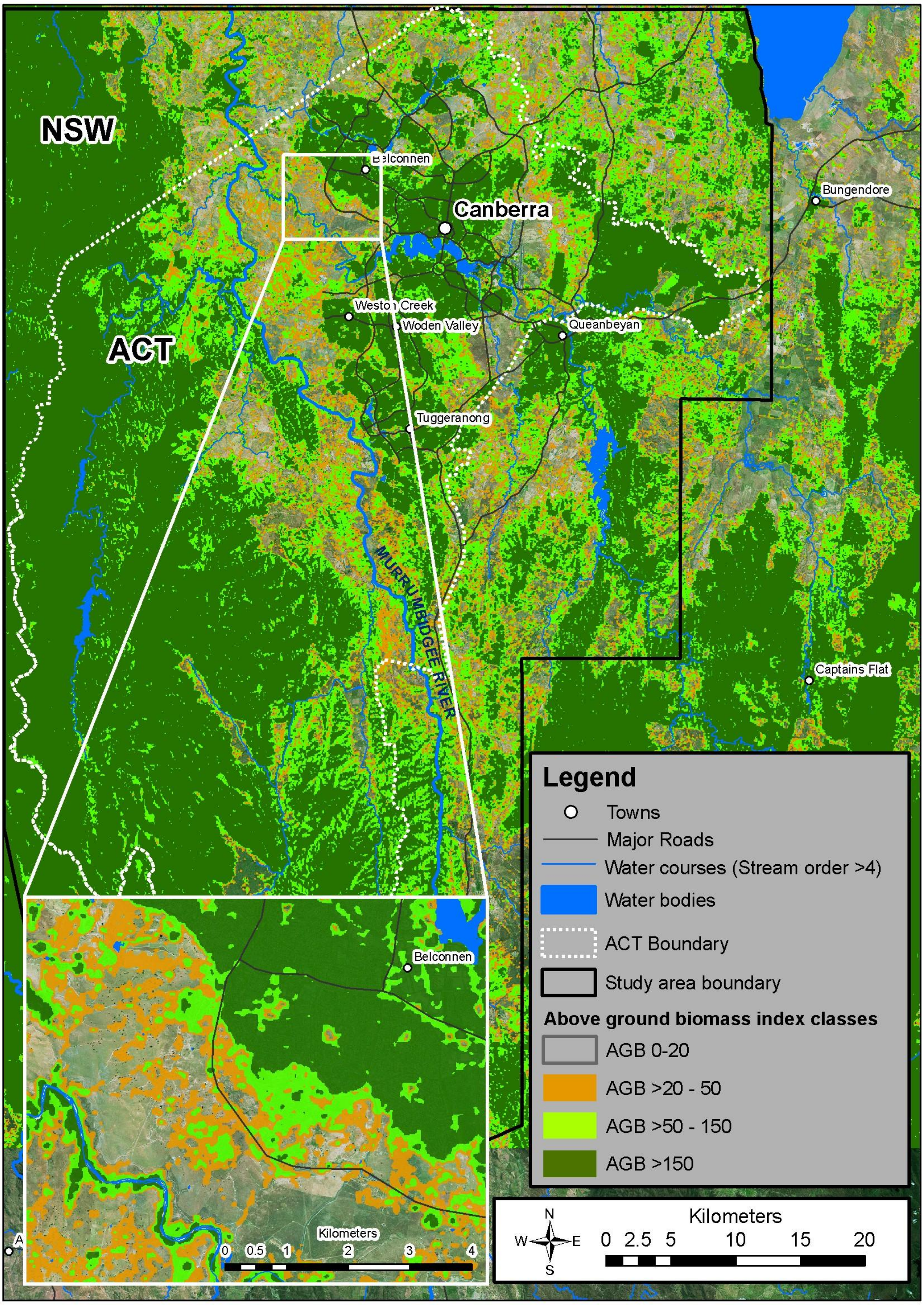


Figure 26 Map showing the above ground biomass index

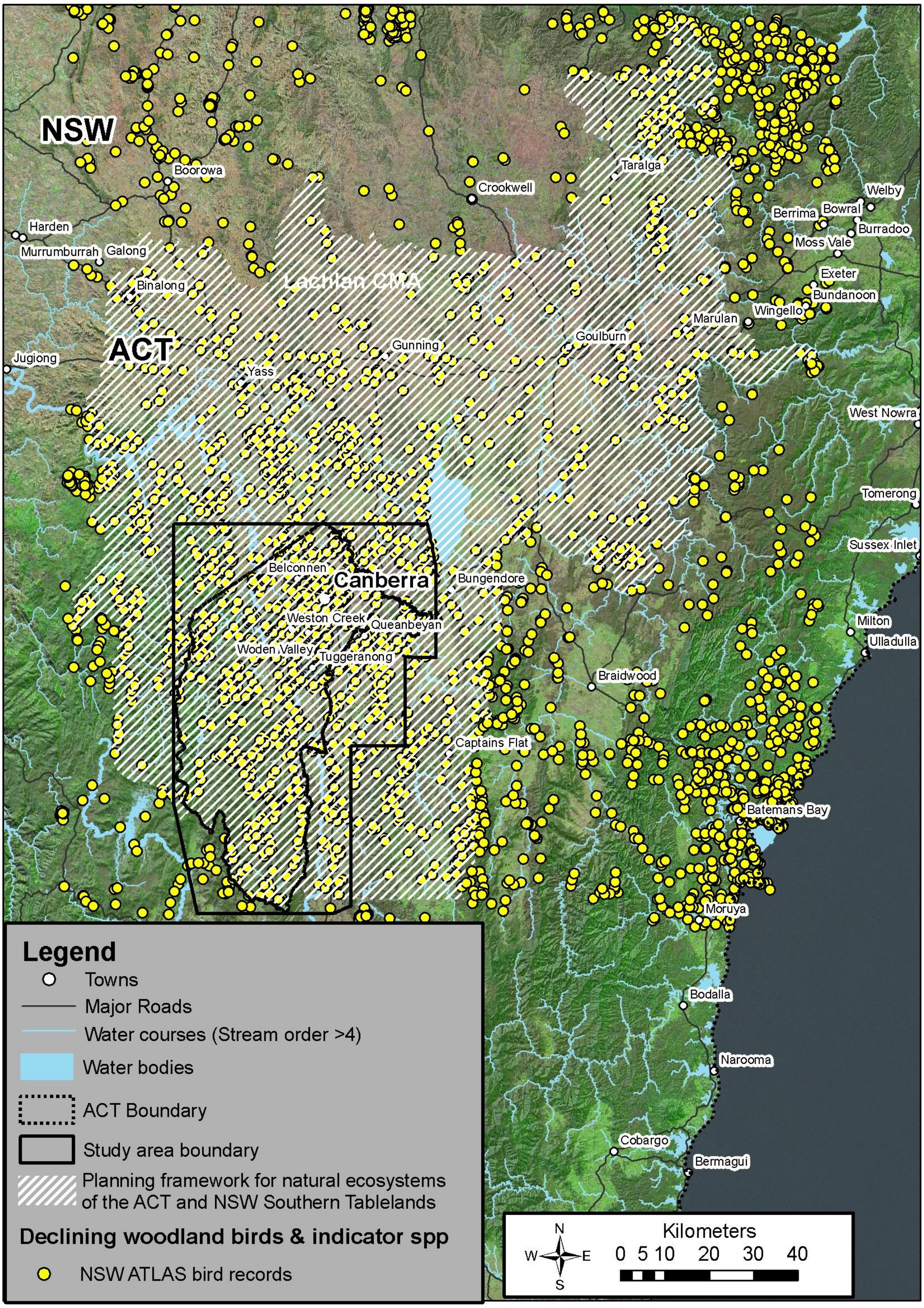


Figure 27 Map showing location of declining woodland birds and indicator species described as 'birds to watch out for' in Taws (2007)

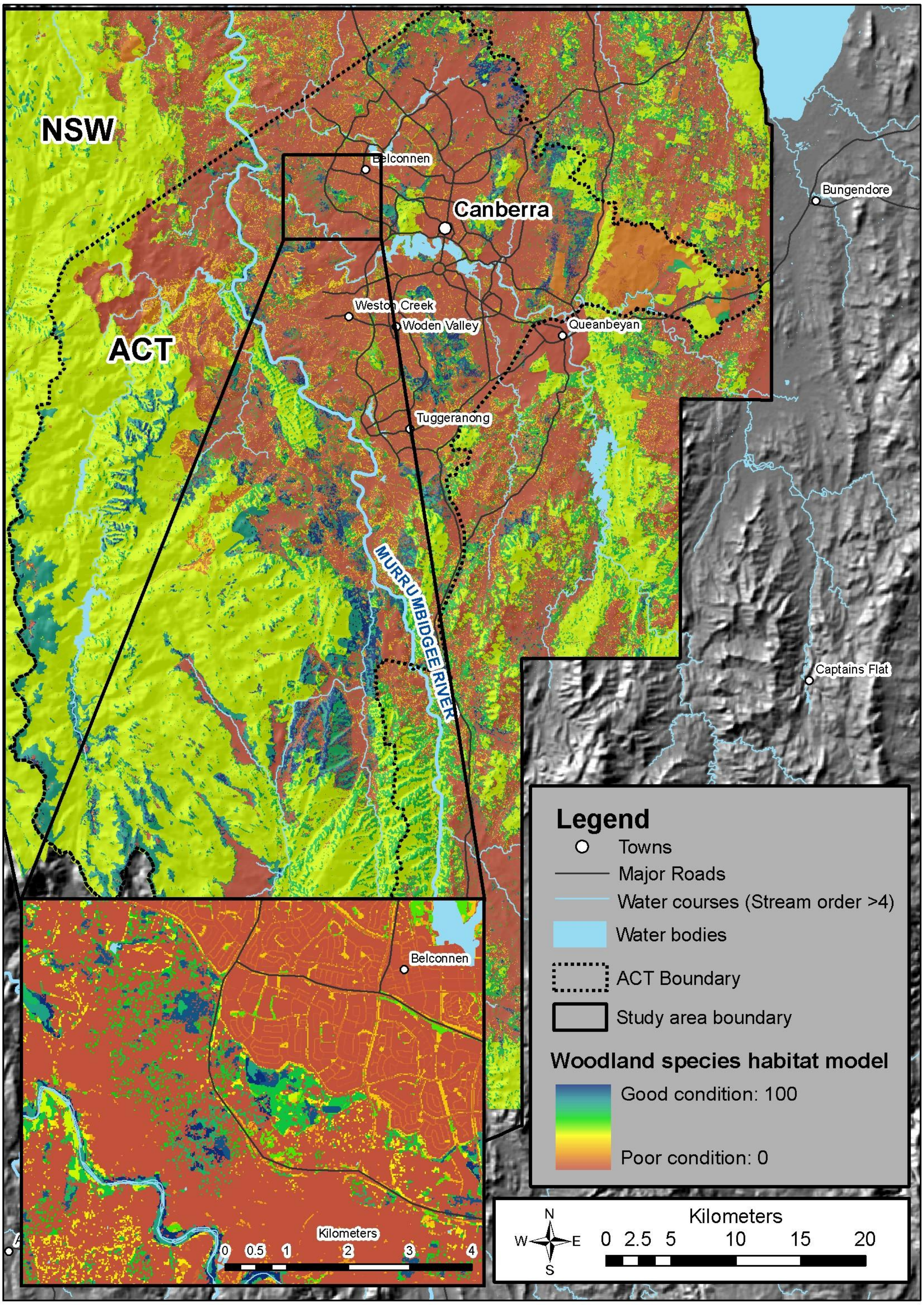


Figure 28 Map showing habitat model for woodland community fauna species

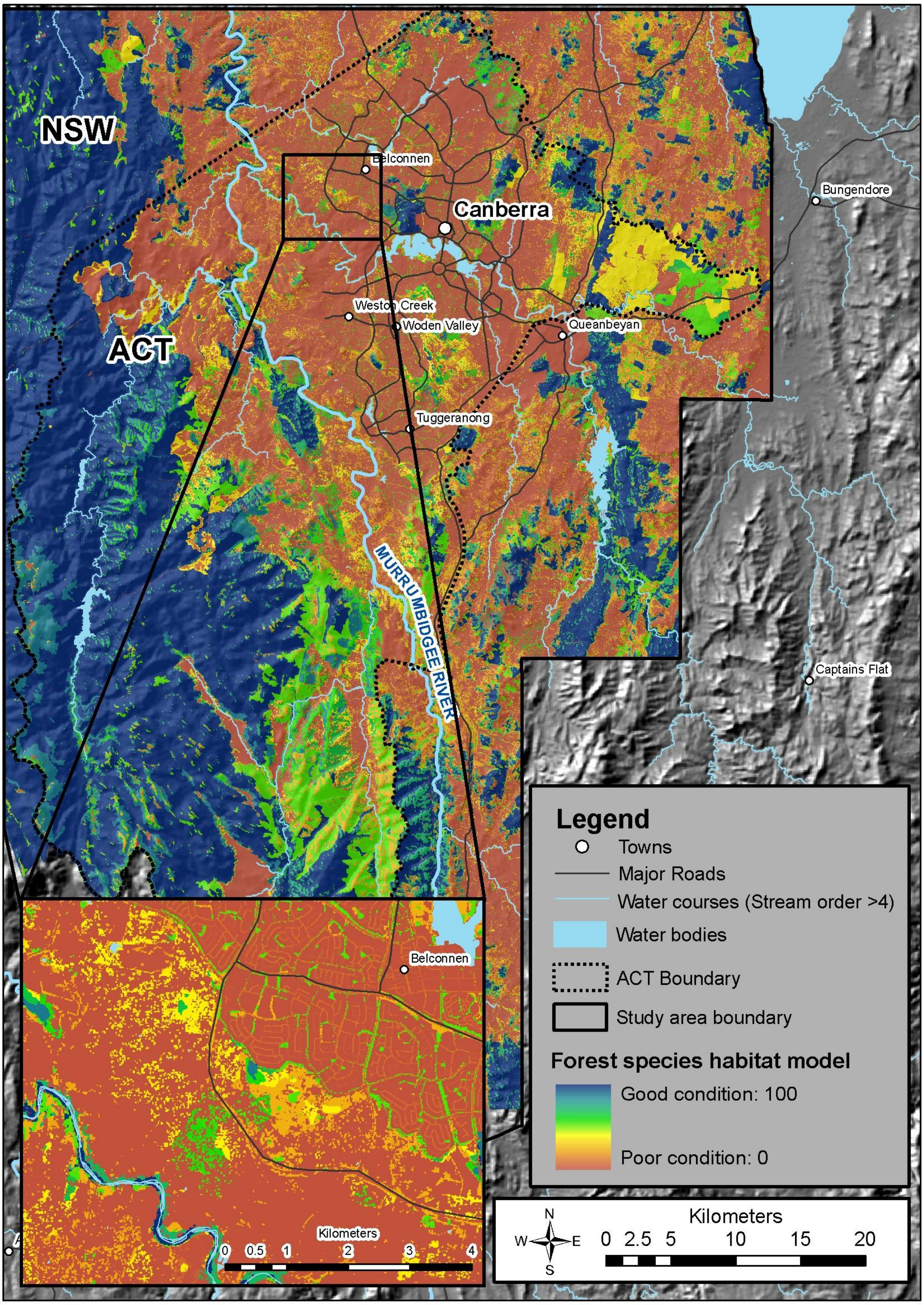


Figure 29 Map showing habitat model for Forest community fauna species

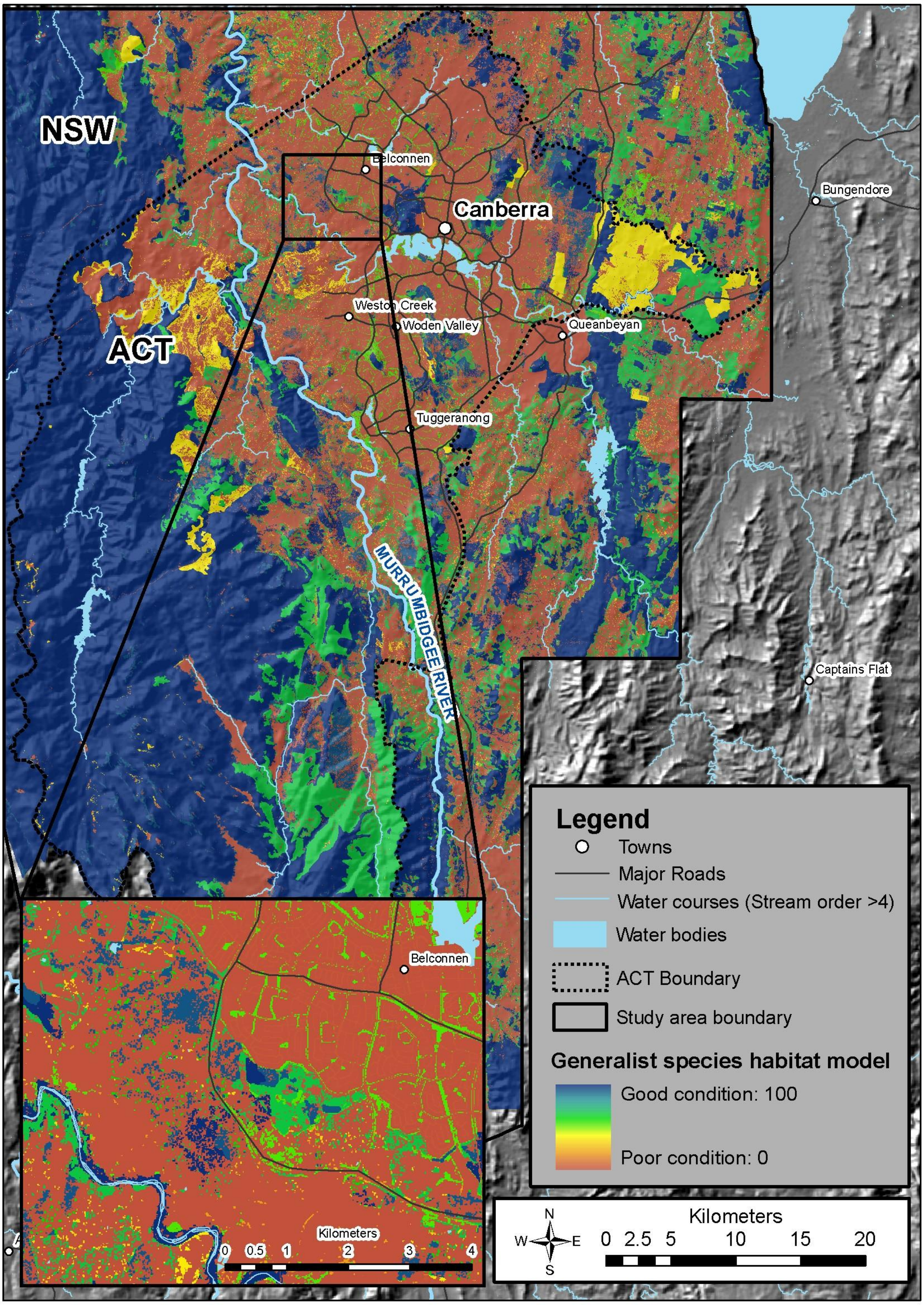


Figure 30 Map showing habitat model for Generalist fauna species

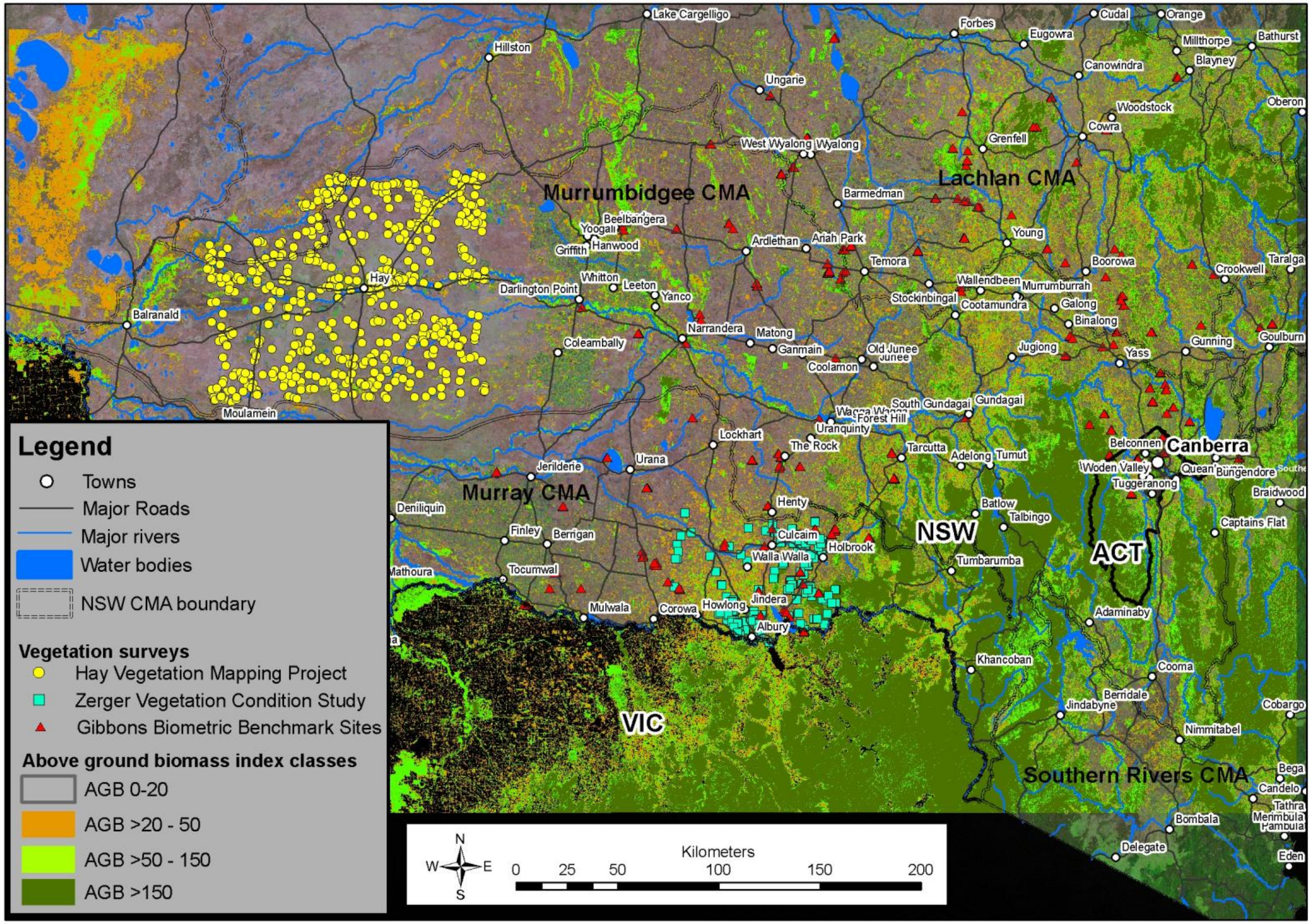


Figure 31 Map showing distribution of vegetation condition survey sites used to investigate tree stand density and calibrate the Above Ground Biomass model from the following projects: Hay native vegetation mapping project (NSW Department of Land and Water Conservation 2002); Zerger vegetation condition modelling project (Zerger *et al.* 2007); and Gibbons Biometric benchmark condition surveys (Gibbons *et al.* 2008)

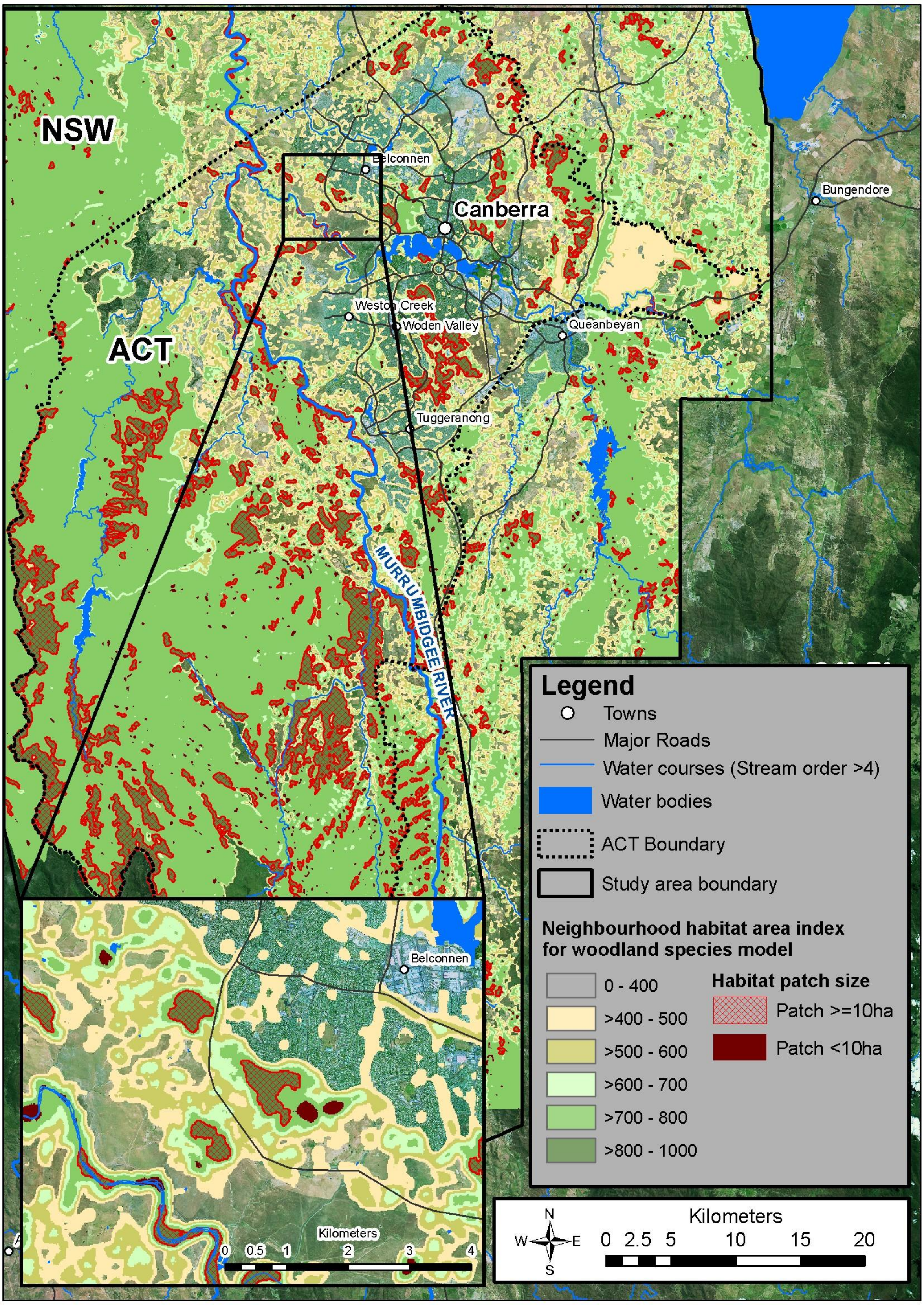


Figure 32 Map showing habitat value (neighbourhood habitat area index) for woodland species

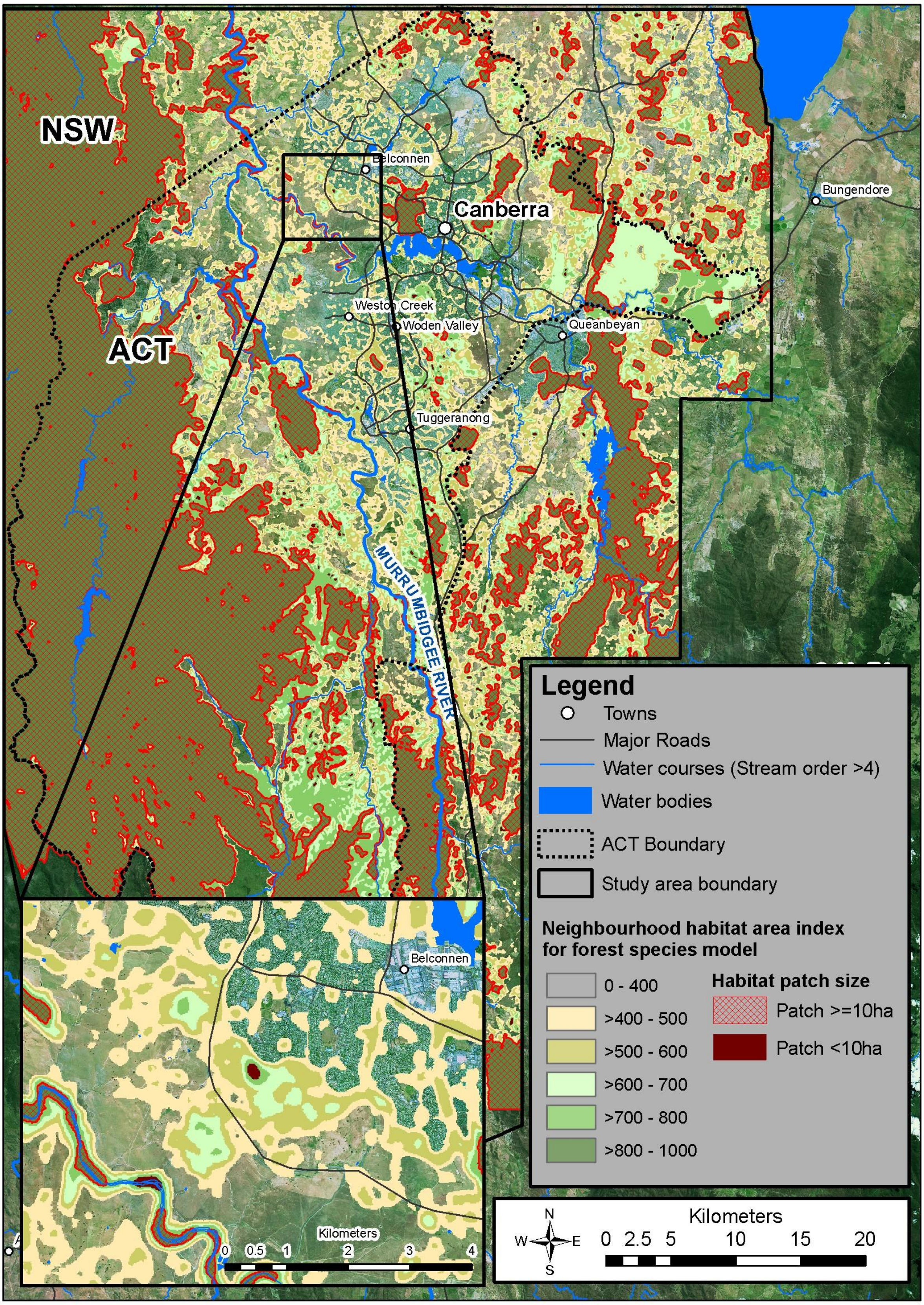


Figure 33 Map showing habitat value (neighbourhood habitat area index) for forest species

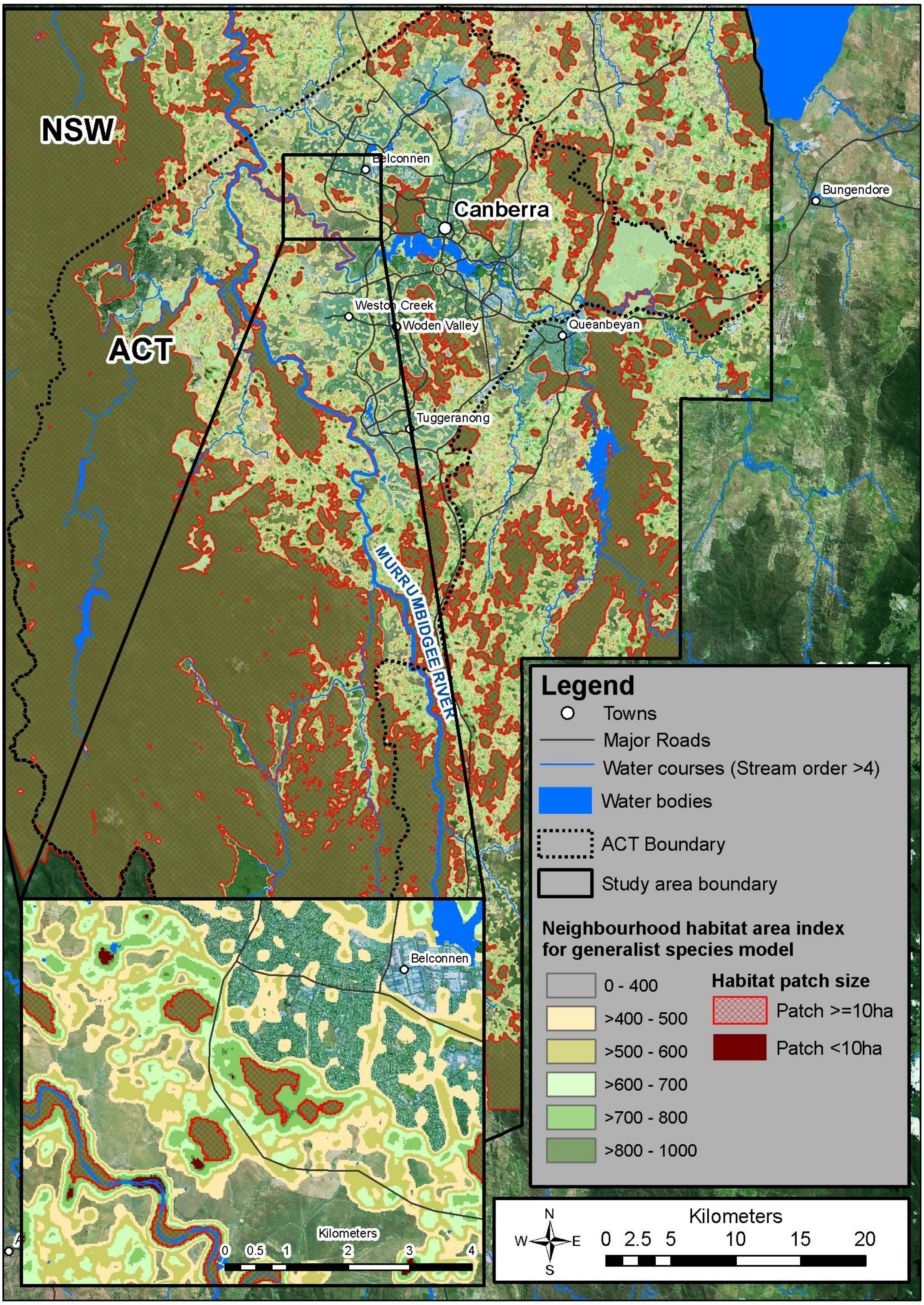


Figure 34 Map showing habitat value (neighbourhood habitat area index) for generalist species

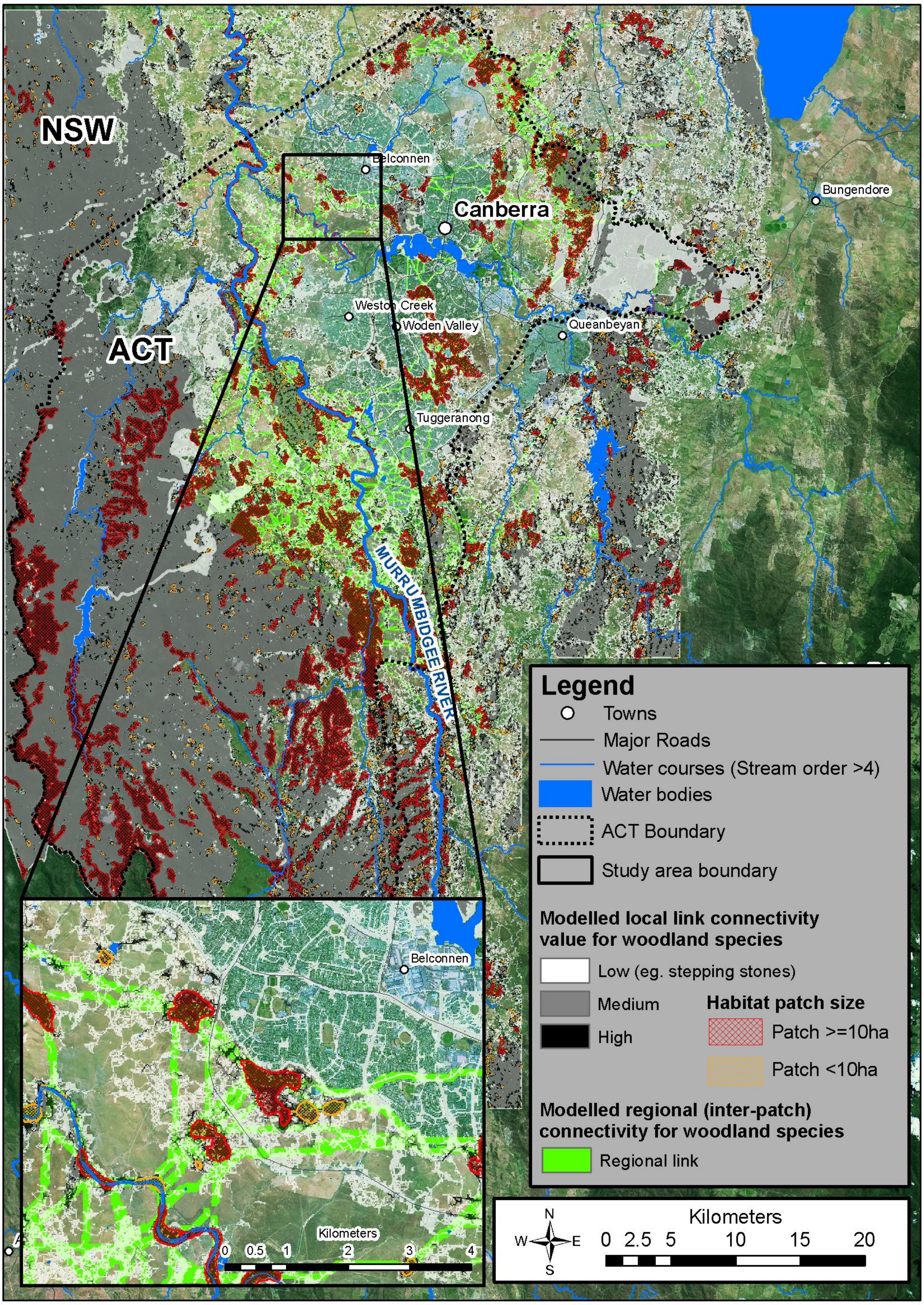


Figure 35 Map showing local and regional (inter-patch) connectivity values for woodland species

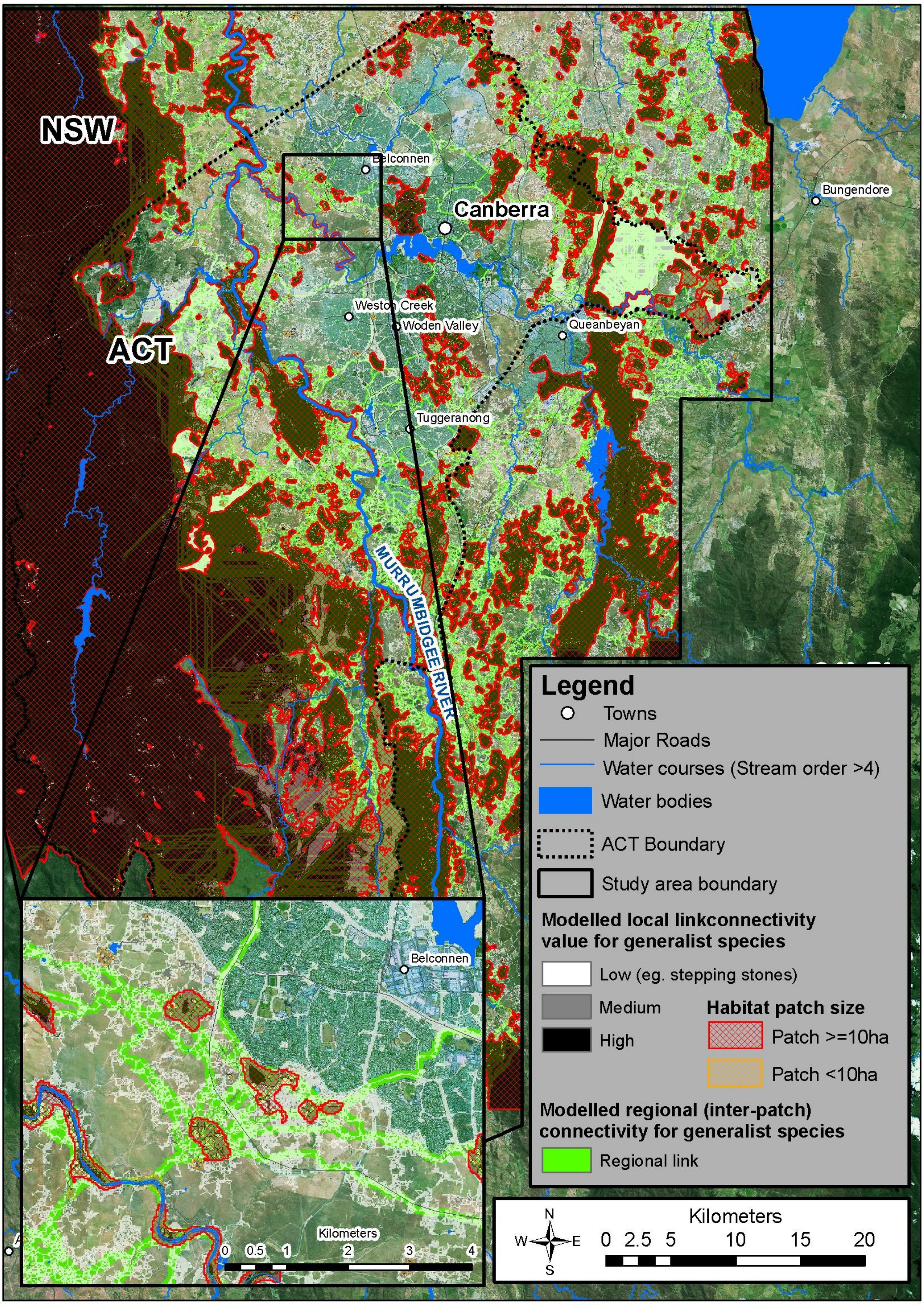


Figure 36 Map showing habitat patches, local and regional (inter-patch) links for generalist species

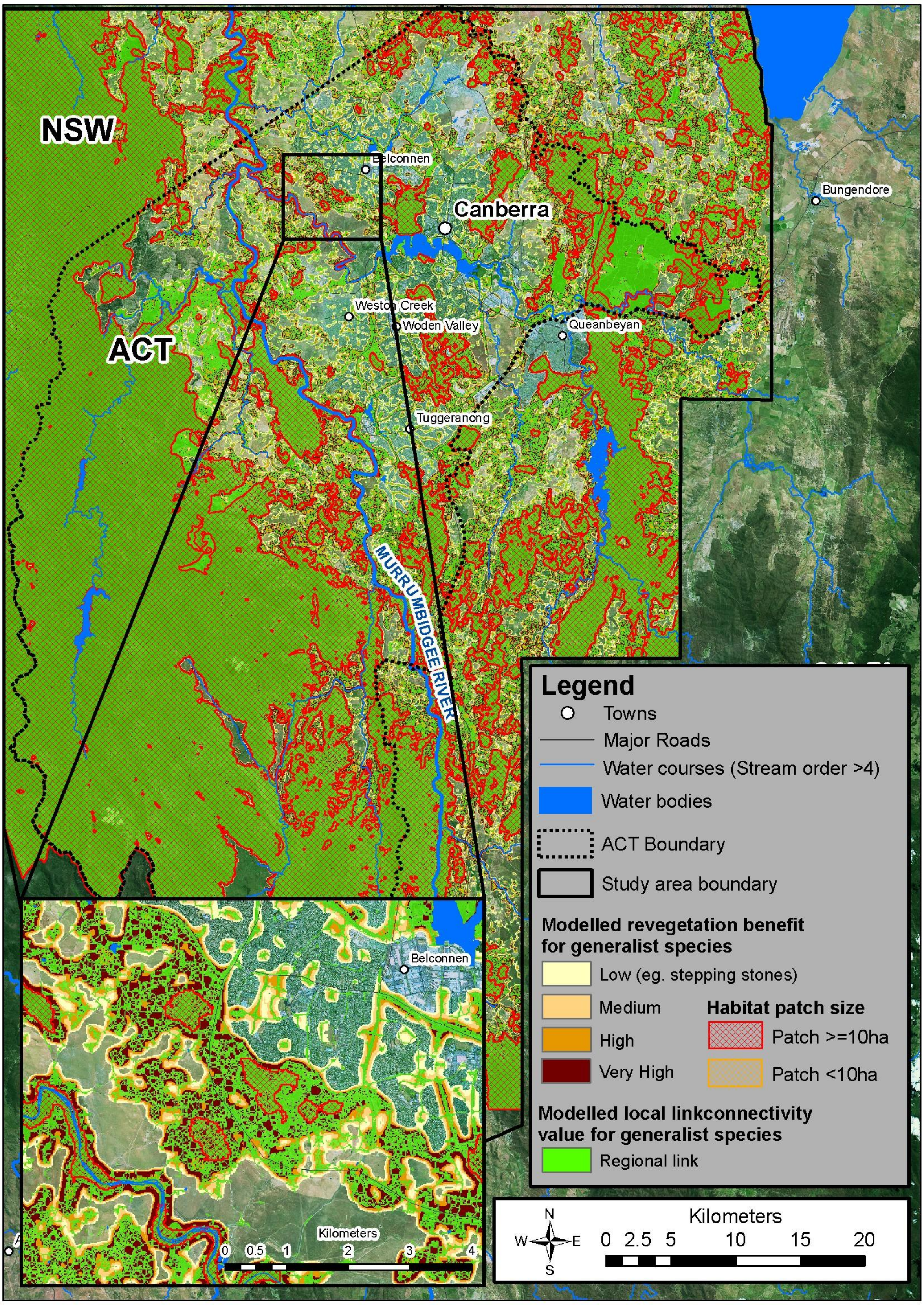


Figure 37 Map showing habitat patches and modelled revegetation benefit for generalist species

Appendix 5 GIS Data Layers

Table 5 List of GIS data layers generated in the project

Layer Name	Data Type	Description/Interpretation
INPUT LAYERS		
agb_ave33clas.lyr	Grid	Above Ground Biomass data set for NSW. Classified into four classes based on correlation with tree stem density. The grid contains a table with weightings used in modelling habitat suitability for woodland and forest.
canopy15max2.lyr	Grid	Canopy mapping based on the presence of canopy from SPOT5 mapping at 5m resolution. Presence/absence (1/0).
vegcov2up01.lyr	Grid	Updated vegetation map. Updated using new vegetation mapping for Gungahlin. See grid table for classes.
GENERALIST MODELS		**Modelled habitat for generalist species, which gives equal weight to woodlands and forest.**
gen_h.lyr	Grid	<u>Habitat model</u>: Habitat condition model for generalist species. High values represent most suitable habitat.
gen_ctx_v5i	Grid	<u>Neighbourhood habitat area</u>: Habitat 'context' i.e. cell value reflects connectivity to surround cells and their habitat value. Indicates resource availability for an animal at that cell. Values calculated for habitat and non-habitat cells. High value = high woodland habitat context value.
gen_top20pc_ctx	Polygon	<u>Habitat patches</u>: Polygons representing generalist habitat patches defined by the highest 20% of spatial context (gen_cx_v5i) values. Legend indicates patches greater than or equal to 10 ha.
gen_ctx_v5ic.lyr	Grid	<u>Revegetation potential</u>: Generalist 'revegetation' priority. This is the context grid which gives higher weight to cleared areas that are most connected to habitat e.g.. this might guide where to increase the size of a patch to improve spatial configuration.
gen_cp_v5i.lyr	Grid	<u>Colonisation potential</u>: Habitat value, or colonisation potential = spatial context (HNA) x habitat value, for the 'generalist' species, which gives equal weight to woodlands and forest. High values indicate high habitat value (colonisation potential).
gen_cor_v5i.lyr	Grid	<u>Local links – 105m</u>: Generalist 'paddock tree links' based on 105 m gap crossing threshold. High values indicate more paths were found linking higher quality habitat i.e. important for local (stepping stone) connectivity between larger high value habitat patches (habitat for settlement).
g_l_all15x7.lyr	Grid	<u>Regional links</u>: Generalist species local corridor value based on least cost paths through the local links paths. High values indicate more paths were found i.e. more important for regional connectivity between larger high value habitat patches.

Table 5 cont.

Layer Name	Data Type	Description/Interpretation
WOODLAND MODELS		**Modelled habitat for woodland species, which gives higher weight to woodland habitat features.**
wl_h.lyr	Grid	Habitat model: Habitat condition model for woodland species. High values represent most suitable habitat.
wl_ctx_v05.lyr	Polygon	Neighbourhood habitat area: Woodland habitat 'context' i.e. cell value reflects connectivity to surround cells and their habitat value. Indicates resource availability for an animal at that cell. High value = high woodland habitat context value.
wl_top20pc_ctx	Polygon	Habitat patches: Polygons representing woodland habitat patches defined by the highest 20% of spatial context (wl_ctx_v05ai) values. Legend indicates patches greater than or equal to 10 ha.
wl_ctx_v05hq_shape.lyr	Polygon	Neighbourhood habitat area – subset of vegetation types: Woodland habitat context for the following vegetation types which were given highest weighting in the woodland habitat model; Natural Temperate Grassland, Lowland woodland, Riparian, Montane / subalpine woodland and Callitris woodland. Has some patch area analysis undertaken: [AREA_P_TOT] = the total patch area (ha) for all habitat context classes. [AREA_P_CAN] = total patch size (ha) if only considering the two highest habitat values (3&4) which are those that contain the most trees.
wl_ctx_v05hq_c3c4only.lyr	Polygon	Neighbourhood habitat area – subset of highest values: Only the two highest woodland habitat context classes from [wl_ctx_v05hq_shape.lyr]. These equate to the areas with most canopy mapped. Those patches <10 ha are candidates for increasing in size – either through revegetation of trees (for those with low habitat context scores) or repairing understorey for surrounding areas if they have canopy cover i.e. polygon has a high habitat context score. Field: Area (ha).
wl_cp_v5i.lyr	Grid	Colonisation potential: Habitat value, or colonisation potential = spatial context (HNA) x habitat value. found .e. High values indicate high habitat value (colonisation potential).
wl_cor_v05.lyr	Polygon	Local links – 105 m: Generalist 'paddock tree links' based on 105 m gap crossing threshold. High values indicate more paths were found linking higher quality habitat i.e. important for local (stepping stone) connectivity between larger high value habitat patches (habitat for settlement).
wl_corv5a13i.lyr	Grid	Local links – 195 m: Woodland local links based on the 195 m threshold (13 grid non-habitat grid cells). High values indicate more paths were found, ie. more important for local connectivity between larger high value habitat patches.
gap195.lyr	Polygon	Local link – 195 m gaps (only): Extra paths found when using a gap threshold of 195m. wl_corv5a13i.lyr grid converted into a polygon where path value >0. Presence/absence (1/0).
regcor550k.lyr	Grid	Regional corridors: Regional corridors based on 'join the dots' links analysis using 550 000 paths between point pairs selected at random. Points were grouped in high value habitat patches only. High values indicate more paths were found i.e.more important for regional connectivity between patches.

Table 5 cont.

Layer Name	Data Type	Description/Interpretation
FOREST MODELS		**Modelled habitat for forest species, which gives higher weight to forest habitat features.**
for_h.lyr	Grid	Habitat model: Habitat condition model for forest species. High values represent most suitable habitat.
for_ctx_v05ai	Grid	Neighbourhood habitat area: Habitat 'context' i.e. cell value reflects connectivity to surround cells and their habitat value. Indicates resource availability for an animal at that cell. Values calculated for habitat and non-habitat cells. High value = high woodland habitat context value.
for_top20pc_ctx	Polygon	Habitat patches: Polygons representing forest habitat patches defined by the highest 20% of spatial context (for_ctx_v05ai) values. Legend indicates patches greater than or equal to 10 ha.
for_cp_v5i	Grid	Colonisation potential: Habitat value, or colonisation potential = spatial context (HNA) x habitat value. High values indicate high habitat value (colonisation potential).
for_corv05a.lyr	Grid	Local links – 105 m: Generalist 'paddock tree links' based on 105 m gap crossing threshold. High values indicate more paths were found linking higher quality habitat i.e. important for local (stepping stone) connectivity between larger high value habitat patches (habitat for settlement).
for_corv05a13.lyr	Grid	Local links – 195 m: Forest local links based on the 195 m threshold (13 grid non-habitat grid cells). High values indicate more paths were found i.e. more important for local connectivity between larger high value habitat patches.
		Regional links: Not modelled for forest species.

Appendix 6 Calculation of the Neighbourhood Habitat Area (NHA)

As previously stated, it is well established that habitat fragmentation is a primary cause of biodiversity loss. Habitat fragmentation, or loss of habitat connectivity, acts to further reduce biodiversity holding capacity of an area. Neighbourhood Habitat Area (NHA) is an ecologically meaningful measure based on metapopulation biology theory which has been developed to rapidly model potential fauna habitat values. NHA is calculated using a 'cost-benefit approach' (CBA) which efficiently integrates the *costs* of movement by organisms across a landscape with the *benefits* of access to habitat (defined by condition). The approach is fully documented in Drielsma, Ferrier & Manion (2007) and is further explained using a worked example below.

The NHA for a given raster grid-cell is influenced by the permeability of that grid cell to animal movement and this, in turn, is influenced by two parameters; average movement ability and habitat condition. The permeability surface can be modelled using a range of different methods. The example shown here uses landuse and vegetation community mapping as a surrogate for both permeability and habitat condition. Each combination of landuse classes and vegetation communities can be assigned a different value for each of these parameters.

The movement ability parameter for each landuse class determines the 'cost' for an organism to travel from the 'focal cell' (raster grid-cell) out to 'habitat' grid-cells so it can utilise that resource.

The $1/\alpha$ parameter is the average distance that an organism can travel through each landuse class/vegetation community combination. How this parameter affects permeability over distance (from a raster grid-cell) is illustrated in Figure 38. A permeability of one means there is no resistance to movement while a low permeability, 0.1 for example, results in a very high resistance or 'cost' to the organism of moving through that area.

In previous studies (e.g. Ellis *et al.* 2007) this parameter has been tailored for individual fauna species or functional groups of fauna. The simple worked example shown here uses vegetation communities as a surrogate for all biodiversity and applies a set of 'generic' parameter values to each landuse class/vegetation community combination. The $1/\alpha$ parameter is usually assigned based on expert opinion, but there is great potential to draw from the scientific literature and undertake research that improves our understanding of how biodiversity surrogates respond to different landuse classes and management actions. This type of investigation would allow these parameters to be tailored to each vegetation community and improve the modelling of dynamic ecological interactions that occur between biodiversity, habitat condition and habitat permeability.

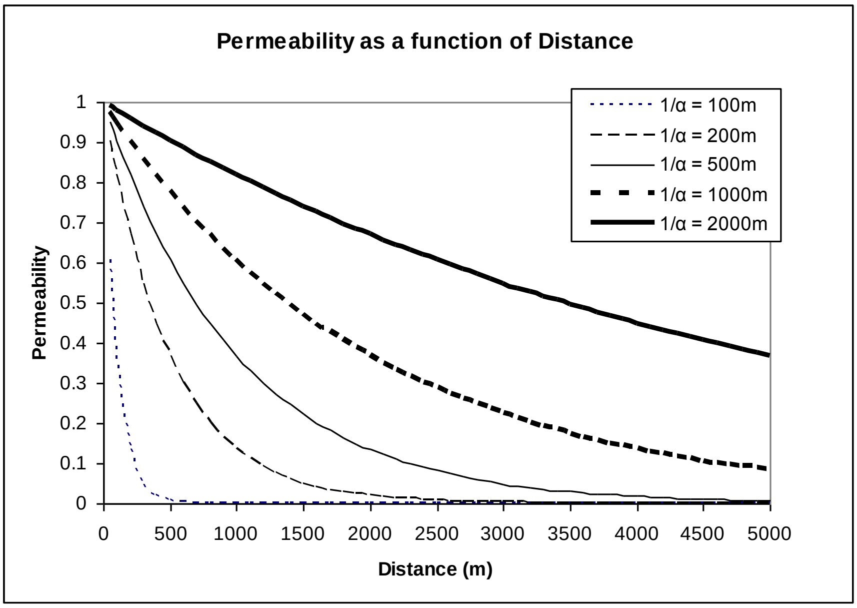


Figure 38 Graph showing the affect of changing the '1/α' parameter on permeability at different distances from a focal cell (raster grid-cell)

6.1 Calculation of NHA – A worked example

This ‘cost-benefit approach’ (CBA) efficiently integrates the *costs* of movement by organisms across a landscape with the *benefits* of access to habitat. For a more detailed description and discussion of this method see Drielsma, Ferrier & Manion (2007). The worked example below is based on the example given in this paper.

Although this worked example of the calculation of the neighbourhood effect for a focal cell is based on a neighbourhood of 5 x 5 cells, this ‘window’ size can be altered by the user. The six steps involved in calculating the total contribution of the 24 neighbourhood cells for the focal cell (shaded in grey) are outlined below.

6.1.1 Step 1: Allocate average movement ability (1/α) and habitat condition value to each landuse class

In this example the spatial pattern of movement ability and habitat condition are modelled using landuse as a simple surrogate for both. Table 6 shows how the average movement ability and habitat condition are assigned to the landuse codes. The average movement ability and habitat condition values are then allocated to each grid cell based on the landuse code mapped at that grid cell (Figure 39 and Figure 40). Future changes in landuse will modify this baseline grid using the lookup values in Table 6 below.

Table 6 Lookup table linking landuse codes to 'A' or 1/α and habitat condition values

Landuse Code	Possible landuse classes	Average movement ability '1/α or A' (meters)	Habitat Condition
1	Cleared Land	45	1
2	Degraded Native Vegetation	60	20
3	Native Vegetation - Grazed	145	60
4	Native Vegetation - Forestry	280	80
5	Native Vegetation - State Conservation Area	450	90
6	Native Vegetation - National Park	950	95

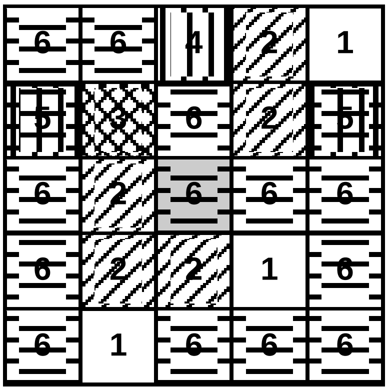


Figure 39 Hypothetical landuse mapping showing landuse codes

6	6	4	2	1
5	3	6	2	5
6	2	6	6	6
6	2	2	1	6
6	1	6	6	6

Figure 40 Grid cells displaying landuse codes from landuse mapping

Using Lookup values from Table 6

950	*950*	*280*	*60*	*45*
450	*145*	*950*	*60*	*450*
950	*60*	*950*	*950*	*950*
950	*60*	*60*	*45*	*950*
950	*45*	*950*	*950*	*950*

Figure 41 Grid cells displaying 'A' or '1/α' average movement ability values (m)

95	*95*	*80*	*20*	*1*
90	*60*	*95*	*20*	*90*
95	*20*	*95*	*95*	*95*
95	*20*	*20*	*1*	*95*
95	*1*	*95*	*95*	*95*

Figure 42 Grid Cells displaying habitat condition values (0–100)

6.1.2 *Step 2: Calculate Permeability or 'cost surface'*

Permeability between points *i* and *j* (w_{ij}) is calculated using a non-linear distance decay function shown in Equation 2:

$$w_{ij} = e^{-\alpha d_{ij}} \qquad \textbf{Equation 2}$$

Where 'd' is the distance travelled and 'α' is a parameter that modifies the permeability value according to how far the target organism can travel. The value of α ranges from zero to one and determines the rate at which permeability drops off over distance. In the scientific literature on modelling of animal movement the term '1/α' is often used to describe this parameter as it equates to a distance measure that has more ecological meaning. The 1/α parameter can be described as the theoretical limit or average distance that an organism can travel. How this parameter affects permeability over distance is illustrated in Figure 43. For ease of reference the 1/α parameter has been replaced by the variable 'A' in Equation 3 below.

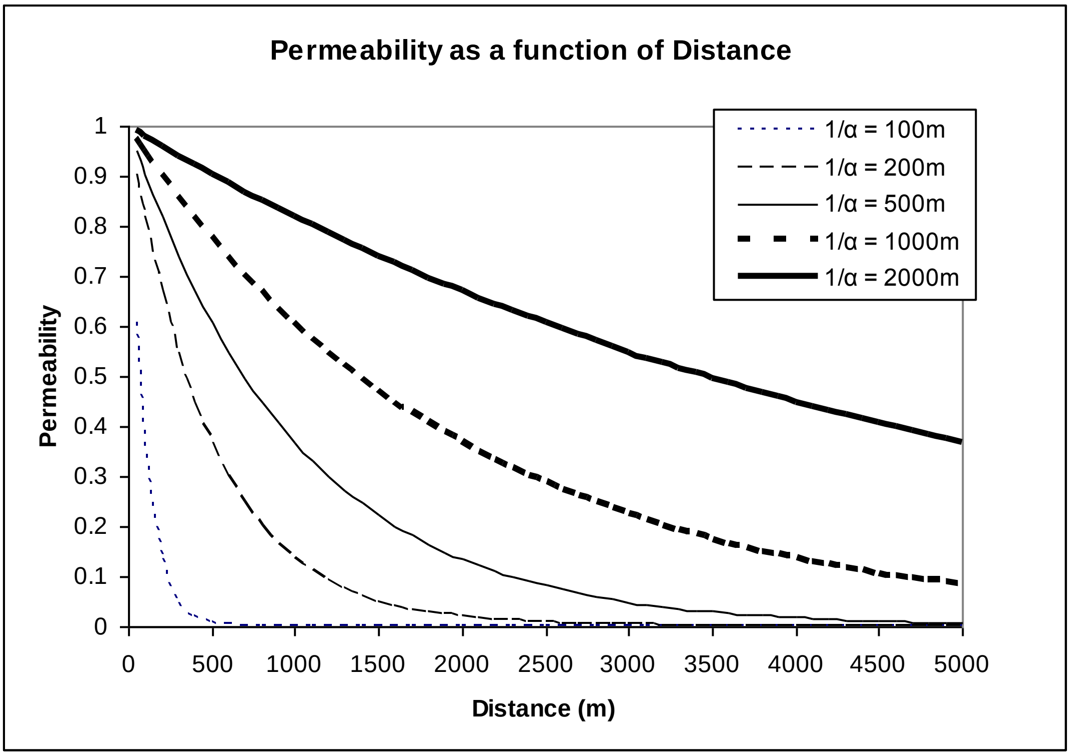


Figure 43 Graph showing the affect of changing the '1/α' parameter on permeability at different distances from the focal cell

Equation 3 is used to calculate the permeability of an individual cell:

$$w_{ij} = e^{-r\left(\frac{1}{\mathrm{A}}\right)} \qquad \textbf{Equation 3}$$

Where '*r*' is the resolution or cell width (100 m in this example) and 'A' is the theoretical limit or distance (in metres) that the organism can travel. The 'A' (or '1/α') parameter will be dependent on the habitat quality of the land cover as it relates to the target organism(s). Figure 44 illustrates the permeability values calculated using Equation 3.

0.9	0.9	0.7	0.2	0.1
0.8	0.5	0.9	0.2	0.8
0.9	0.2	0.9	0.9	0.9
0.9	0.2	0.2	0.1	0.9
0.9	0.1	0.9	0.9	0.9

Figure 44 Grid cells displaying permeability values

6.1.3 Step 3: Find 'least cost path' from focal cell to each neighbour cell

The least cost path algorithm (LCPA) approach models how an animal might travel between the focal cell and each of its neighbour cells given that some cells are more 'permeable' or easier to travel through than others. There are multiple paths an animal can take between the focal cell and a target cell and the cost of travelling this distance can be calculated for each alternative path using cell permeability values. The path with the least cost is the path of least resistance (most permeable) and is not always the shortest distance.

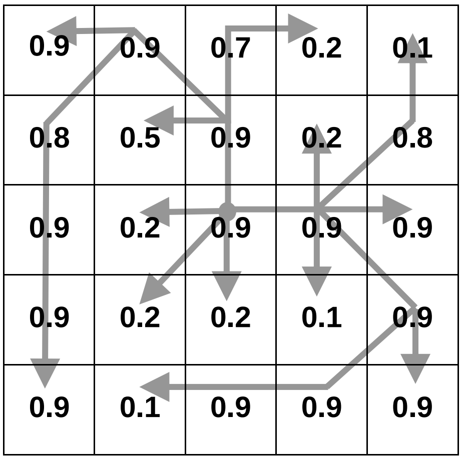
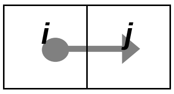


Figure 45 Grid cells showing permeability values and the least cost paths (links) from the focal cell to each neighbourhood cell

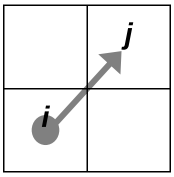
The permeability of a link between sites *i* and *j* (w_{ij}) that comprises habitat units indexed by *n* can then be derived alternatively as the product of the component permeability values:

$$w_{ij} = \prod_{n} w_n$$ **Equation 4**



The link permeability between two directly adjacent cells (edge to edge) is calculated as the distance between the centroids of the two cells and can be described using Equation 5:

$$w_{ij} = \prod_n w_n^{\left(1/2\right)}$$ **Equation 5**

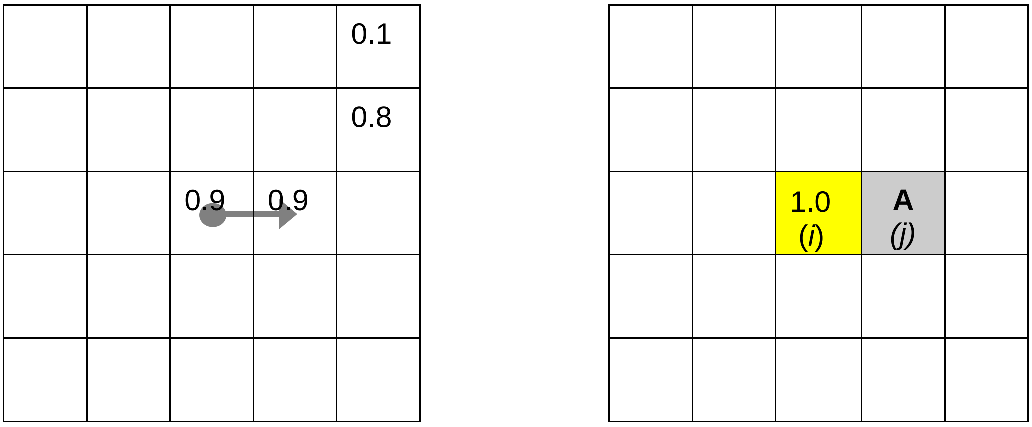


While the link permeability between two diagonally adjacent cells (corner to corner) is calculated as the diagonal distance between the centroids of the two cells and can be described using Equation 6:

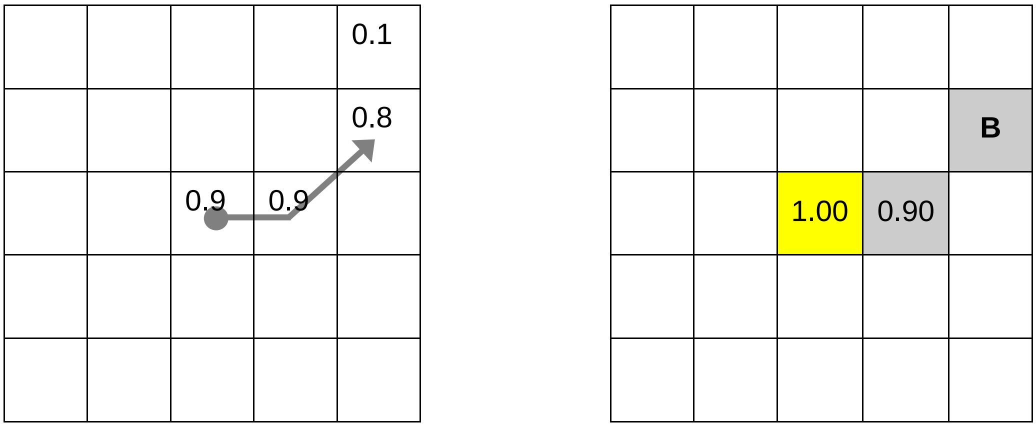
$$w_{ij} = \prod_n w_n^{\left(\sqrt{2}/2\right)}$$ **Equation 6**

6.1.4 *Step 4: Calculate 'link permeability' values*

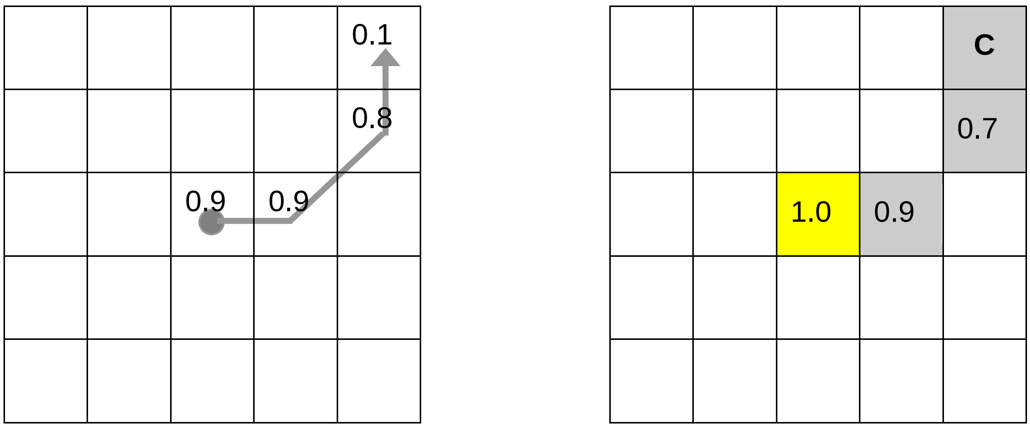
The following example demonstrates the calculation of the permeability of the link between the focal cell and a neighbourhood cell (along the previously identified least cost path).



Link permeability of cell A: $w_{ij} = \sqrt{0.9} * \sqrt{0.9} = 0.9$



Link permeability of cell B: $w_{ij} = \sqrt{0.9} * \sqrt{0.9} * 0.9^{\frac{\sqrt{2}}{2}} * 0.8^{\frac{\sqrt{2}}{2}} = 0.71$



Link permeability of cell C: $w_{ij} = \sqrt{0.9} * \sqrt{0.9} * 0.9^{\frac{\sqrt{2}}{2}} * 0.8^{\frac{\sqrt{2}}{2}} * \sqrt{0.8} * \sqrt{0.1} = 0.20$

6.1.5 Step 5: Multiply 'link permeability' value by habitat value

To estimate the probability of an animal utilising the habitat in each of the neighbourhood cells the habitat value (H) of that cell is multiplied by the link permeability (w_{ij}) which represents the likelihood of the animal making it to the cell. In this example these values are shown in Figure 46 below.

0.70	0.78	0.71	0.27	0.20
0.61	0.60	0.90	0.38	0.38
0.52	0.42	1.00	0.90	0.81
0.47	0.30	0.42	0.27	0.78
0.42	0.18	0.60	0.67	0.70

95	95	80	20	1
90	60	95	20	90
95	20	95	95	95
95	20	20	1	95
95	1	95	95	95

66.3	73.7	57.1	5.3	0.2
55.3	36.2	85.5	7.6	64.2
49.5	8.5	95.0	85.5	77.0
44.6	5.9	8.5	0.3	73.7
40.1	0.2	57.1	63.5	66.3

Figure 46 Grid cell values representing the habitat values of neighbourhood cells modified by the probability of utilisation

6.1.6 Step 6: Combine linked habitat scores

Determination of the total habitat available to the focal cell or 'Neighbourhood Habitat Area' (NHA), also termed the total neighbourhood effect, is calculated as the sum of all linked habitat scores. The neighbourhood effect of site *i*, denoted Γ_i, can then be calculated using the following equation:

$$\Gamma_i = \sum_j \mathrm{H}_i w_{ij} \qquad \textbf{Equation 7}$$

where H_j is the habitat value of site *j* and where all spatial units in the region are indexed by *j*.

In this example Γ_i = 66.3 + 73.7 + 57.1 + 5.3 + 0.2 + 55.3 + 36.2 + 85.5 + 7.6 + 64.2 + 49.5 + 8.5 + 95.0 + 85.5 + 77.0 + 44.6 + 5.9 + 8.5 + 0.3 + 73.7 + 40.1 + 0.2 + 57.1 + 63.5 + 66.3 = <u>1127.1</u>

So the NHA value for the focal cell is 1127.1