Linking nature in the city
A framework for improving ecological connectivity across the City of Melbourne
Cover map by Holly Kirk.
Cover photo by Luis Mata ‘Blue-banded bee *Amegilla chlorocyanea* on austral storksbill *Pelargonium australe*’ (Westgate Park, City of Melbourne, October 2017).

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Linking nature in the city: A framework for improving ecological connectivity across the City of Melbourne

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About the Clean Air and Urban Landscapes Hub

The Clean Air and Urban Landscapes Hub (CAUL) is a consortium of four universities: the University of Melbourne, RMIT University, the University of Western Australia and the University of Wollongong. The CAUL Hub is funded under the National Environmental Science Program of the Australian Government's Department of the Environment. The task of the CAUL Hub is to undertake research to support environmental quality in our urban areas, especially in the areas of air quality, urban greening, liveability and biodiversity, and with a focus on applying research to develop practical solutions.

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Executive summary

A key consideration for maintaining biodiversity in urban spaces is the capacity for species to move across the landscape. One of the ways this can be evaluated is by measuring how ‘connected’ different patches of habitat are across the urban matrix. Habitat connectivity is important for animal populations as it allows key biological and evolutionary processes to take place by permitting the movement of individuals. There are two main types of habitat connectivity: structural, measuring just the available habitat; and functional, which accounts for the ability of different species to move across the landscape.

In this report we illustrate the use of a framework for measuring structural and functional connectivity in the City of Melbourne. Using this method, we find that habitat in the municipality appears relatively well connected for woodland birds, tree-hollow using birds and bats, insect pollinators and aquatic insects, but poorly connected for amphibians and reptiles.

We demonstrate how our approach can be used as a planning tool to assess the impact of different development projects. The method is applied to two hypothetical scenarios. The first scenario shows how removing habitat for a road development can have varying effects on functional connectivity, depending on the habitat requirements for each animal group. The second scenario demonstrates how functional connectivity could be improved by adding street trees and mid-storey vegetation to act as stepping stones between parks and waterways. Adding canopy cover to a selection of roads within the City of Melbourne could dramatically improve connectivity for several key animal groups, especially those species which rely on trees for foraging, resting and reproduction such as bats and birds. These corridors of vegetation have the potential to connect the Royal Botanic Gardens with Royal Park via waterways.

The approach outlined in this work is appropriate for the City of Melbourne because it combines structural and functional aspects of connectivity, is tailored to habitats managed by the municipality, and is broad enough to
capture a wide range of species. The framework has been developed based on an understanding of the recent scientific literature and connectivity metrics, extensive consultation with the City of Melbourne to ensure that it addresses key goals, and data availability.

The aim of the framework is to support the City of Melbourne’s efforts to increase ecological connectivity across the municipality. In particular, the framework and evaluation approach can be used by the City of Melbourne to (1) measure how ecological connectivity changes over time; (2) compare the municipality’s ecological connectivity with that of other benchmarked cities internationally, (3) plan biodiversity actions aimed at improving ecological connectivity, and (4) assess the impact that development projects are expected to have on ecological connectivity. A suite of Geographical Information System files containing final maps accompanies this report in order to allow the analyses detailed here to be reproduced easily.
1 Introduction

1.1 Scope and aims

Habitat connectivity, biodiversity and the City of Melbourne

The City of Melbourne is rich in animal biodiversity, with over 1,800 species of insects, fish, frogs, reptiles, birds and mammal recorded in the last 20 years (City of Melbourne 2017; Mata et al. 2016; Mata et al. 2017). The City of Melbourne is committed to protecting and increasing this biodiversity, through a suite of conservation actions and initiatives aimed to improve the habitat suitability and connectivity of the urban environment for a range of taxa. Improving habitat connectivity is particularly important given that urban environments may inhibit the flow of individuals and genes across the landscape and between habitat patches, which can ultimately lead to species’ local extinction.

Accordingly, the Nature in the City strategy (City of Melbourne 2017) includes the priority to “Develop a more ecologically connected urban landscape”, including the following targets:

“By 2027, the City of Melbourne will be a more ecologically-connected city than in 2017, with measurable increases in connectivity; and

By 2027, the City of Melbourne would have achieved a net increase in biodiversity, habitats and ecosystem health.”

There are three actions under these targets which are directly linked to planning for connectivity:

Action 3 – “Undertake plantings to increase understorey habitat on City of Melbourne managed land by 20 per cent”;

Action 7 – “Improve ecological connectivity across the municipality in a systematic, comprehensive and co-ordinated manner, taking into account biodiversity corridors and actions identified in the Urban Forest and Open Space Strategies”; and
Action 8 – “Develop a framework within which all projects in the City of Melbourne can consider impacts to ecological connectivity, with a view to enhancement wherever possible”.

Aims of the project

This project reviews ways to measure structural and functional connectivity in urban environments and describes a framework for evaluating and planning connectivity-focused management actions in the City of Melbourne. We also provide details of how this framework can be applied to urban landscape management. The specific aims of the project are:

1. To develop a rigorous assessment approach for mapping landscape connectivity in the City of Melbourne; and

2. To demonstrate how these landscape connectivity indices and maps can be used to (a) identify areas that could make the greatest contribution to improving connectivity across the municipality, and (b) provide a tool for City of Melbourne to assess and quantify the impact of proposed large infrastructure or precinct developments on the municipality’s landscape connectivity.

1.2 Ecological connectivity in urban environments

What is habitat connectivity and why is it important for biodiversity?

To guarantee their survival and long-term population viability, species need to be able to move through a landscape and access resources (e.g. food, shelter or suitable mates). The ability of species to move through a landscape, combined with the ability of landscape attributes such as vegetation patches and corridors to facilitate or impede species movement is referred to as ecological connectivity (Taylor et al. 1993). Urban environments are often highly fragmented landscapes, in which most habitat suitable for animal species, such as patches of remnant, semi-natural and managed vegetation are surrounded by a matrix of residential, commercial and transportation land-uses that prioritise human activities. A high level of ecological connectivity within an urban landscape will enable animals to move between patchy resources, and also allow post-breeding dispersal, maintaining gene flow and population viability. In contrast, a low level of ecological connectivity prevents the movement of individuals and genes, potentially leading to reduced genetic diversity and inbreeding depression, and ultimately local extinction.
Structural and functional connectivity

There are two ways to conceptualise ecological connectivity: structurally and functionally. The "physical arrangement of habitats within a landscape" is referred to as structural connectivity (Watson et al. 2017). This concept includes large landscape features such as parks and green corridors, and also disconnected features such as vegetation along roadways, isolated trees, and patches of flowering shrubs and fallen logs, all of which may form ‘stepping stones’ (Doerr et al. 2010; Doerr et al. 2014).

Functional connectivity can be viewed as a more refined, species-specific estimate of connectivity within a landscape, combining structural landscape features with an animal’s ability to move, or cross gaps in habitat (Tischendorf & Fahrig 2000; Baguette et al. 2013). Each species within a community has different habitat requirements and dispersal capacities. Importantly, functional connectivity depends on the landscape structural connectivity, but also on landscape and site-based characteristics and elements that influence the actual dispersal of individuals (e.g. spatial and temporal availability and distribution of resources and risks), as well as ecological traits related to movement (e.g. dispersal, recruitment, life-history and behavioural traits). Despite the increasing interest and efforts in understanding and assessing functional connectivity within the field of urban ecology (LaPoint et al. 2015), many studies are still limited by traditionally focusing on structural connectivity.

Protection and restoration of features that provide structural connectivity is increasingly common (Watson et al. 2017); however, the extent to which these features effectively allow the movement of particular species through the landscape is often unclear, as functional connectivity is context and species specific (Doerr et al. 2010; Tischendorf & Fahrig 2000; Watson et al. 2017). Structural connectivity can potentially be maintained and increased in urban landscapes through the protection of patches of remnant, semi-natural and managed vegetation, and by the design and planning of other green space types, including linear green corridors and street trees. However, to achieve functional connectivity, the characteristics of these green spaces must match the needs of both daily animal movements and other dispersal events that lead to stable populations and gene flow (Taylor et al. 1993). This distinction is important, as patches can appear to be structurally connected without being functionally connected. For example, two parks may be structurally connected through a series of street trees, but if the animal species being considered does not use trees then the parks may not be considered functionally
connected for that species. Another illustration of the difference between structural and functional connectivity is to consider two species with different movement capabilities. A species that can move easily over a kilometre will be able to cross larger gaps between habitat patches compared to a more sedentary organism. For this reason it is important to consider both concepts of connectivity, especially if aiming to improve the overall connectedness of landscape for a specific organism or group.

**Measuring functional connectivity**

Functional connectivity depends on structural connectivity, but additionally accounts for the habitat requirements and movement capabilities of a specific organism or group of organisms. Measuring functional connectivity requires each part of the landscape to be characterised based on its potential to provide habitat and impede or promote movement for the targeted taxa. Additional information may be needed, including determining how a species moves through the landscape. Whether a landscape is functionally connected can be assessed using genetic or movement tracking techniques (Tischendorf & Fahrig 2000; Calabrese & Fagan 2004). Tracking data are particularly useful when they can inform and help generalise how a species uses different landscape features and elements, because these data can then be used to map functional connectivity at broader landscape or regional scales. However, collecting information on species movement behaviour or gene flow requires extensive field research, and consequently, empirical data is often scarce (Pe’er et al. 2011; La Point et al. 2015). In the absence of empirical data, available ecological knowledge can be used to estimate how a species moves through the landscape.

Gathering detailed information regarding species’ habitat and space use within the City of Melbourne is beyond the scope of this work, but could form important extensions in the future. This report concentrates on modelling connectivity from existing landscape data within the municipality. There are three main modelling approaches for measuring functional connectivity: (1) least-cost path analysis (Adriaensen et al. 2003), (2) graph theory (Urban & Keitt 2001), and (3) circuit theory (McRae et al. 2008). Least-cost path analysis is one of the most popular methods and has been used across a range of different landscape types (Sawyer et al. 2011). This is raster or grid-based approach that assigns a ‘dispersal cost’ or ‘landscape resistance’ to different land-uses, based on dispersal energetic costs, individual’s willingness to move, and/or exposure to risk associated with moving through those land-uses (Pe’er et al. 2011; Zeller et al. 2012;
Lechner & Lefroy (2014). Graph and circuit theory build on the least-cost path method, but with different computational approaches. Importantly, these methods require complex and computationally expensive steps. We purposefully avoided this by adapting a pre-existing structural connectivity index, the City Biodiversity Indicator #2, which was initially developed by Chan et al. (2014). The approach outline in this report will allow our findings to be easily compared with those reported for other cities across the World, and to be robustly reproduced where needed.
2 Method for assessing ecological connectivity across the City of Melbourne

2.1 How we developed our method

There are a range of approaches to measuring connectivity (Calabrese & Fagan 2004). These include identifying features that are thought to act as barriers, measuring the size, shape and distribution of habitat patches, and calculating indices that represent how connected a landscape is. The City Biodiversity Index (CBI) or ‘Singapore Index’ is an internationally recognised tool for measuring biodiversity in cities (Chan et al. 2014), which has been endorsed by the Convention on Biological Diversity. There are 23 indicators under the CBI, and Indicator #2 (CBI #2) specifically captures issues of connectivity (“Connectivity Measures or Ecological Networks to Counter Fragmentation”). We used CBI Indicator #2 as a starting point for developing our method, therefore allowing our findings for the City of Melbourne to be comparable with those reported for other cities.

The CBI #2 method establishes an index to calculate the structural connectivity of a city (Chan et al. 2014). The original index was based on effective mesh size, which is “the probability that two randomly chosen locations in the landscape are connected and not separated by barriers” (Jaeger 2000). Deslauriers et al. (2017) recently improved the method for calculating CBI #2 by allowing within patch connectivity to be better quantified and making the index itself easier to interpret. Based on a measure of effective mesh size (Jaeger 2000), the improved CBI #2 considers two patches to be connected if they (1) are ≤ 100 m apart and (2) contain no barriers to movement (such as roads > 10 m wide). The improved method accounts for large continuous areas of habitat, so that decreasing fragmentation intuitively leads to an increasing connectivity value.

Casalegno et al. (2017) developed a method to measure connectivity in urban environments that can be considered a hybrid approach between structural and functional connectivity. The authors used LiDAR data to account for the vertical stratification of vegetation (i.e. grass, shrubs and trees), and compared the results of measuring habitat connectivity using 2D versus 3D habitat models. They
computed several indices including: small patch density, largest patch and the ‘connectivity index’ developed by Jaeger (2000). Although Casalegno et al. (2017) did not target particular taxa or their movement patterns, they refined the structural approach by incrementally increasing the threshold at which patches of habitat are considered to be connected (from a 1 m to a 40 m gap), thus accounting for different dispersal abilities.

The method detailed in the next section is an extension of the improved CBI #2 connectivity index, where we use a similar approach to Casalegno et al. (2017) to allow the measurement of functional connectivity for specific taxa. We do this by varying the type of habitat included in each model (from the data visualised in Figure 2.1) and varying the distances at which habitat patches are considered to be connected in order to allow for specific movement capabilities. Unlike Casalegno et al. (2017), we are using the improved CBI #2, which will allow comparisons of connectivity regardless of the total area being measured and easier comparisons across municipalities. We chose this approach because all data preparation and the calculation of the index can be undertaken using standard GIS and spreadsheet software. This method does not require specialist knowledge of statistical or programming software.

2.2 Outline of our method

Based on the current scientific literature and specific needs and context of the City of Melbourne, we combined both structural and functional approaches to evaluate ecological connectivity. The structural method reproduces the improved City Biodiversity Index #2 (Deslauriers et al. 2017), which uses very broad definitions of habitat, barrier and interpatch distance. This means that, aside from being used as a standard benchmark comparison with other municipalities, this structural connectivity measure is harder to interpret in real terms from the perspective of animal species living in the City of Melbourne. By including the functional connectivity approach and choosing more realistic definitions for the model parameters, the connectivity index we employ throughout this work can be tailored to a single species or species group. This gives a better estimate of how habitable the landscape is for specific animals (see the definition of functional connectivity in Chapter 1). Our framework combines the assessment of structural connectivity for three classes of vegetation, and functional connectivity for seven key animal groups.

Detailed methods for the calculation of both structural and functional connectivity can be found in the appendices, including details of the
raw GIS data used to produce the ‘habitat’ and ‘barrier’ land-use layers (Appendix I and II). All connectivity indices were calculated using the formula proposed by Deslauriers et al. (2017), the improved CBI #2, which disregards the overall area of the landscape under consideration, thus allowing for the direct comparison of different habitat areas. The connectivity index increases as the habitat patches within the landscape become more connected (Deslauriers et al. 2017). The formula can be simplified to the following:

$$ CI = \frac{\sum (Area)^2 \cdot n}{\sum Area} $$

Where $CI$ is the connectivity index and $n$ is the number of connected areas.

The landscape area modelled here includes all classes of land-use that could be regarded as ‘habitat’ for different groups of animals. In most cases, the GIS data combines both information on City of Melbourne managed land and LiDAR data collected in 2014, which also covers land within the municipality but not managed by the City of Melbourne. In both the structural and functional connectivity measures detailed below, features classed as barriers, such as tall buildings and wide roads, act to remove habitat from the landscape. This means that any vegetation growing on or near these features will not be counted as viable habitat within the model. This decision was made in order to simplify the set of parameters chosen for this initial model and can easily be altered in future applications; for example, re-classifying roads that have a good proportion of tree canopy cover to no longer be considered as barriers.

Benefits of using this method for the City of Melbourne

The approach provides a measure of change over time, enabling evaluation of the impacts of different management actions;

The framework allows comparison of different scenarios or management actions before implementation; and

Output from the analyses aids understanding of the connectivity value of different habitats and for different types of taxa.

2.3 Structural connectivity for different classes of vegetation

We followed the method outlined by Casalegno et al. (2017), using the updated CBI #2 equation, as described in Deslauriers et al. (2017), to compute connectivity metrics for three key classes of vegetation that are relevant to the City of Melbourne management activities (Figure 2.1).
We calculated the structural connectivity for all vegetation within the municipality and separately for three different vegetation heights: understorey plants (including turf), midstorey shrubs and the tree canopy (Figure 2.1). We used the same definitions as those set out by Deslauriers et al. (2017) for the Improved City Biodiversity Index.
Indicator #2 (CBI #2) to determine the distance between habitat patches and potential barriers. In the following three structural connectivity definitions, all roads and railways wider than 10 m were considered barriers. These features were also buffered by 7.5 m to account for edge effects (Deslauriers et al. 2017). Habitat patches were considered connected if they were less than 100m apart. In order to allow for animal movement outside the City of Melbourne municipal border, any impervious surfaces beyond the boundaries were also buffered by 10m and considered as barriers to potential movement.

**Structural connectivity parameters**

Understorey plants, defined as vegetation with a LiDAR-derived height below 50 cm and all areas mapped as turf by the City of Melbourne.

Mid-storey, including planted beds mapped by the City of Melbourne, and LiDAR-derived vegetation height between 50 cm and 300 cm.

Tree canopy, as mapped by the 2016 canopy cover data layer from the City of Melbourne Open Data Portal (data.melbourne.vic.gov.au) combined with LiDAR derived vegetation height greater than 300 cm.

### 2.4 Functional connectivity for seven key animal groups

We calculated functional connectivity for seven animal groups (Figure 2.2), with varying habitat requirements and movement abilities (Table 2.1). Functional connectivity for each group was calculated using the same formula as the improved CBI #2, but habitat combinations (e.g. water and vegetation) and barrier definitions varied for each group. Each species group has a different movement capability that dictates their interpatch distance, that is, how far apart patches of habitat can be before they are no longer considered as connected. This movement capability was used as the buffer distance in the GIS software. For example, if a species disperses 1000 m (i.e. can cross a 1000 m gap between patches of habitat), the habitat for this species was buffered by 500 m. This essentially allows the measurement of space around each patch of habitat. Where patches are less than 1000 m apart, the buffered areas touch (see more detail in Figure 2.2). The land-use areas classed as barriers for each group were then used as a mask to remove underlying habitat and the remaining habitat patches were classified according to the connected area in which they resided (Figure 2.2).

Predicting functional connectivity is data intensive, as it requires detailed information about the target species’
Figure 2.2 Representatives of the seven animal groups chosen for measuring functional connectivity: the blue-banded bee *Amegilla chlorocyanea* seen here visiting the flowers of the indigenous austral storks bill *Pelargonium australe* in Westgate Park, City of Melbourne (A, photo by Luis Mata); the blue skimmer *Orthetrum caledonicum* flying through Westgate Park, City of Melbourne (B, photo by Luis Mata); the spotted marsh frog *Limnodynastes tasmaniensis* (C, photo by Kirsten Parris); the eastern blue-tongued lizard *Tiliqua scincoides* (D, photo by Kazredracer - Flickr, Creative Commons); the superb fairywren *Malurus cyaneus* (E, photo by Patrick K - Flickr, Creative Commons); the red-rumped parrot *Psephotus haematonotus* (F, photo courtesy of Rodger Scott); and the Gould’s wattle bat *Chalinolobus gouldii* (G, photo courtesy of Ryan Francis).
Table 2.1 The seven animal groups used to define different functional connectivity estimates within the City of Melbourne.

<table>
<thead>
<tr>
<th>Group</th>
<th>Ideal habitat requirements</th>
<th>Barriers</th>
<th>Median dispersal distance (m)*</th>
<th>Example taxa</th>
<th>References</th>
<th>Land use Layers included in model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insect pollinators</td>
<td>Midstorey vegetation and trees, turf close to shrubs/trees</td>
<td>Roads &gt; 10 m width</td>
<td>350</td>
<td>Blue-banded bee <em>Amegilla chlorocyanea</em></td>
<td>Stevens et al. 2012; Haddad 1999</td>
<td>LiDAR mid-storey, shrub beds, canopy. Turf or LiDAR grass &lt; 25 m from cover.</td>
</tr>
<tr>
<td>Aquatic insects</td>
<td>Ponds, rivers and creeks, vegetation close to water</td>
<td>Roads &gt; 10 m width</td>
<td>1500</td>
<td>Blue skimmer <em>Orthetrum caledonicum</em></td>
<td>Theischinger &amp; Hawking 2006;</td>
<td>All water features and rivers. LiDAR mid-storey, shrub beds, LiDAR grass or canopy within 500 m of water.</td>
</tr>
<tr>
<td>Amphibians</td>
<td>Ponds and creeks, understorey vegetation close to water</td>
<td>Roads &gt; 5 m width, all buildings</td>
<td>1000</td>
<td>Spotted marsh frog <em>Limnodynastes tasmaniensis</em></td>
<td>Heard et al. 2012; Hale et al. 2013</td>
<td>Water features, Moonee Ponds Creek and turf/grass/shrubs within 10 m of water.</td>
</tr>
<tr>
<td>Reptiles</td>
<td>Mid-storey cover, understorey vegetation, all turf</td>
<td>Roads &gt; 5 m width, all buildings</td>
<td>1000</td>
<td>Eastern blue-tongued lizard <em>Tiliqua scincoides</em></td>
<td>Koenig et al. 2001; Souter et al. 2007</td>
<td>LiDAR mid-storey, shrub beds, LiDAR grass and turf.</td>
</tr>
<tr>
<td>Woodland birds</td>
<td>Mid-storey cover, trees, turf very close to vegetation</td>
<td>Roads &gt; 15 m width, Buildings &gt; 10 m.</td>
<td>1500</td>
<td>Superb fairywren <em>Malurus cyaneus</em></td>
<td>White et al. 2005; Watson et al. 2008</td>
<td>LiDAR mid-storey, shrub beds, canopy. Turf or LiDAR grass &lt;10m from cover.</td>
</tr>
<tr>
<td>Tree-hollow using birds</td>
<td>Tree-hollows, trees and turf close to hollows</td>
<td>Roads &gt; 15m width, Buildings &gt;10m.</td>
<td>500</td>
<td>Red-rumped parrot <em>Psephotus haematonotus</em></td>
<td>Lowry &amp; Lill 2007; Lees &amp; Peres 2009</td>
<td>Tree hollows and canopy within 1000m of hollows. Turf less than 500m from hollows.</td>
</tr>
<tr>
<td>Tree-hollow using bats</td>
<td>Tree-hollows, trees close to hollows</td>
<td>Roads &gt; 15m width, Buildings &gt;10 m.</td>
<td>1000</td>
<td>Gould's wattleed bat <em>Chalinolobus gouldii</em></td>
<td>Lumsden et al. 2001; Threlfall et al. 2013; Wilson 2013</td>
<td>Tree hollows and canopy within 250m of hollows.</td>
</tr>
</tbody>
</table>

*Gap crossing ability, smallest mean home range/minimum mean movement distance*
movement abilities, habitat preferences and potential barriers to dispersal. This information is often not known or unavailable. To ensure that our approach can represent the ecological connectivity of a broad range of animal species within the municipality, we decided to use a species group approach, by which we considered seven key groups or ‘movement guilds’ of animals that share broad dispersal abilities and habitat requirements. The groups were:

**Insect pollinators** – species where the adult stages depend on flowering vegetation as a food resource (e.g. blue-banded bees; Figure 2.1A);

**Aquatic insects** – species dependent on waterbodies for larval life stages but that are also able to move overland as flying adults (e.g. blue skimmer dragonflies; Figure 2.1B);

**Amphibians** – species that depend on waterbodies for reproduction and are limited in overland dispersal (e.g. spotted marsh frogs; Figure 2.1C);

**Reptiles** – species that depend on adequate ground cover for refuge, including leaf litter, rocks and coarse woody debris (e.g. eastern blue-tongued lizards; Figure 2.1D);

**Woodland birds** – species that depend on dense or complex mid-storey vegetation for nesting and resources (e.g. superb fairy wrens; Figure 2.1E);

**Tree-hollow using birds** – species that depend on tree hollows for reproduction and fly above and below the tree canopy during the day (e.g. red-rumped parrots; Figure 2.1F); and

**Tree-hollow using bats** – species that depend on tree hollows for refuge and reproduction, and move within or closely associated to the tree canopy during the night (e.g. Gould’s wattled bats; Figure 2.1G).

The definitions for each of these groups were based on discussions during a workshop with City of Melbourne staff and local experts (11th August 2017; see acknowledgements). For each animal group, we then used the primary literature to identify an approximate movement distance or median dispersal distance (Table 2.1), as well as both barriers and habitat requirements within the landscape. This movement distance is used to define the maximum distance an animal will travel across a gap in habitat, or the interpatch distance. Further details on the characteristics of each group and the species within them are provided...
in Table 2.1. These groups cover the range of habitat requirements and movement abilities of many types of animals within the City of Melbourne, including multiple taxa (e.g. insects, amphibians, reptiles, birds and mammals), and multiple levels of habitat structure (e.g. water, ground cover, mid-storey and tree canopy). This allows the connectivity framework to guide specific management actions, such as increasing flowering shrub cover and preserving of hollow bearing trees, while remaining applicable to multiple species. Importantly, all groups are susceptible to urban landscape change, but are able to persist in urban environments under the right conditions, meaning that they are likely to respond well to management actions that aim to improve connectivity. Each group also contains species that are charismatic, and more likely to garner public support for conservation actions.

2.5 What are patches? Interpreting maps and results

To interpret the following results it is important to understand how this model defines connected areas and habitat patches. The CBI #2 gives a measure of area (given here in hectares, Ha) as the proportion of connected habitat in relation to the total area of habitat available. The method (described in more detail in Appendix I) assigns each patch of habitat to a “connected area”, which can contain one or more habitat patches that are within the threshold interpatch distance of each other (e.g. 100 m). Figure 2.3 helps to illustrate the steps for calculating tree canopy connectivity. In this example, patches of tree canopy habitat are considered connected if occurring within 100 m of each other (Figure 2.3A and 2.3B). A 50 m “radius” is drawn around each patch (Figure 2.3B) and where these overlap patches are considered to be connected. Barriers to movement, such as roads wider than 10 m, are then overlaid fragmenting the connected areas (Figure 2.3C). The connected areas are re-classified (Figure 2.3C) and the habitat patches within each connected area are given a patch identifier (Figure 2.3D). Therefore, habitat patches that are more than 100 m apart, or separated/dissected by a road, are not considered to be connected.

A useful way to conceptualise this method for measuring connectivity is to consider that the entire landscape has been classed as three different things: habitat (generally vegetation or water), barriers to movement (e.g. roads, railways and buildings) and non-habitat (everything else, often referred to as the urban matrix). The main assumption we make is that animals are able to move from one patch of habitat to the next through the non-habitat, as long as those patches are close enough together and not separated by a barrier.
In the following two results sections, the connectivity index is presented alongside the total area of the corresponding habitat type. The connectivity index we present here can be interpreted as the proportion of habitat area that is connected.

**Figure 2.2** Demonstrating how the CBI #2 methodology works on tree canopy data: the original canopy habitat patches mapped in green (A); then the canopy habitat is buffered by 50 m (joining patches <100 m apart, B); barriers (roads wider than 10 m) are overlaid and the remaining connected areas identified (different colours, C); finally the remaining canopy habitat patches are classified by their corresponding connected area (D). Groups of connected patches are the same colour.
3 Current ecological connectivity in the City of Melbourne

To illustrate the degree or level of connectivity of different habitat types, throughout this chapter we show images of the entire City of Melbourne (Figures 3.1 and 3.4), as well as closer sections showing the area covering the southern end of Royal Park and some other key places around the municipality (Figures 3.2, 3.3, 3.5 and 3.6). Habitat patches are coloured according to the connected area that they have been identified as residing within, with the actual colour randomly assigned.

The results are also presented with information about the GIS layers used to define “habitat” for each index. This is presented with the interpatch distance and the landscape features that were classified as barriers to movement (presented after the ‘ – ’ sign to show these were subtracted from the habitat layers).

3.1 Structural connectivity in the City of Melbourne

All vegetation (Table 3.1, Figures 3.1-3.2)

Layers used: (LiDAR derived understorey/LiDAR derived mid-storey/tree canopy extent/turf land use areas/shrub beds, 100 m interpatch distance) – 10 m roads.

Area: 589.3 Ha

Connectivity Index (CBI #2): 106.7 Ha

Specific caveats: This index is currently the best one to use for comparisons with other municipalities, particularly where the focus has not been on specific vegetation type or species requirements.

Understorey plants (Table 3.1, Figures 3.1-3.2)

Layers used: (LiDAR classified understorey < 50 cm in height/turf land use area, 100 m interpatch distance) – 10 m roads.

Area: 350.4 Ha

Connectivity Index (CBI #2): 68.8 Ha

Specific caveats: Herbaceous plants were the most data-deficient vegetation type, with very little LiDAR derived information available. Some of the largest patches of this class are mostly closely mown turf areas, belonging to heavily utilised sports fields.
Table 3.1 Current structural and functional connectivity indices across the City of Melbourne for eleven different groups of habitat types and land uses. Lower numbers for the Connectivity Index mean a lower level of connectivity for this habitat type.

<table>
<thead>
<tr>
<th>Connectivity type</th>
<th>Number of connected areas</th>
<th>Total area (Ha)</th>
<th>Connectivity Index (Ha)</th>
<th>Total number of habitat patches</th>
<th>Mean patch size (m²)</th>
<th>Maximum patch size (m²)</th>
</tr>
</thead>
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<tr>
<td>Structural connectivity</td>
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<td>Insect pollinators</td>
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<td>Woodland birds</td>
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<td>Tree-hollow using birds</td>
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<td>Tree-hollow using bats</td>
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<td>173.6</td>
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<td>73.1</td>
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</table>

Mid-storey (Table 3.1, Figures 3.1-3.2)

Layers used: (LiDAR classified vegetation height > 50 cm < 300 cm/ shrub bed areas, 100 m interpatch distance) – 10 m roads.

Area: 77.4 Ha

Connectivity Index (CBI #2): 10.2 Ha

Specific caveats: All shrub bed areas were included in this measure, but these are under active management by the City of Melbourne and therefore some may not currently contain plants. Additionally, the barrier effect
of roads means that many verges or linear strips are removed from the model. This result highlights the fact that practitioners using this method may need to be more selective when deciding what landscape features should be included as barriers.

Tree canopy (Table 3.1, Figures 3.1-3.3)

Layers used: (Tree canopy extent/ LiDAR classified vegetation > 300 cm in height, 100 m interpatch distance) – 10 m roads.

Figure 3.1 Patches of all connected vegetation across the City of Melbourne for (clockwise from to top left) all vegetation types; understorey vegetation; mid-storey vegetation; and tree canopy. Areas of connected vegetation share the same colour.
Area: 299.9 Ha
Connectivity Index (CBI #2): 41.3 Ha

Specific caveats: The tree canopy will vary seasonally in the city as deciduous trees shed leaves in the winter. Given the City of Melbourne’s extensive collection of tree data it would also be possible to look at the evergreen canopy layer, which might give a better idea of the year-round area for this vegetation class. Like with the mid-storey vegetation class, the barrier effect of 10 m wide roads

Figure 3.2 Patches of all connected vegetation in Royal Park for (clockwise from to top left) all vegetation types; understorey vegetation; mid-storey vegetation; and tree canopy. Areas of connected vegetation share the same colour.
causes any street trees on these roads to be classed as non-viable habitat in this model.

Comparisons with other cities

Table 3.2 shows three other cities where the City Biodiversity Index indicator #2 (CBI #2) has been calculated. The City of Melbourne has a proportionally smaller area of natural habitat (589.3 Ha) than the three other benchmarked cities, and a lower connectivity index (106.7 Ha). This is most likely due to

<table>
<thead>
<tr>
<th>City</th>
<th>Total area (Ha)</th>
<th>CI (Ha)</th>
<th>Reference</th>
</tr>
</thead>
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<td>Lisbon</td>
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<td>Deslaurier et al. 2017</td>
</tr>
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<td>Montreal</td>
<td>4946.5</td>
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<td>Deslaurier et al. 2017</td>
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<td>Helsinki *</td>
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<td>383.9</td>
<td>City of Helsinki 2016</td>
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<tr>
<td>Melbourne</td>
<td>589.3</td>
<td>106.7</td>
<td>This work</td>
</tr>
</tbody>
</table>

*This was probably calculated using the old version of CBI #2*

![Figure 3.3](image)

Figure 3.3 Left: Tree canopy habitat patches in the Royal Botanic Gardens Melbourne and Fawkner Park, coloured by connected area (showing mostly one colour, meaning fully connected habitat patches). Right: Tree canopy habitat patches in the City of Melbourne Central Business District, coloured by connected area (showing many different coloured patches of habitat, indicating this area is very fragmented).
the inclusion of a large number of small habitat patches (<5 m²) in the City of Melbourne model, whereas the other cities, Montreal in particular, decided to only include larger patches in their calculations. There are advantages and disadvantages to including smaller fragments, in particular smaller patches could be excluded if there were good prior reasons to believe they are not used by specific animals. However, small patches may be important “stepping stones” for some species. Another reason for the difference in CBI #2 between the cities could be due to barrier classifications. Many of the roads in the City of Melbourne are wider than 10 m (the level used by all cities to classify barriers) but many of these wide roads in the City of Melbourne are well vegetated and not heavily used, so could be acting as regular urban matrix, or even connectors. As more Cities publish their CBI results it will be easier to see how the City of Melbourne compares internationally.

3.2 Functional connectivity in the City of Melbourne

Based on current data, the City of Melbourne appears to be relatively well connected for insect pollinators, aquatic insects, woodland birds and tree- hollow using bats and birds (Table 3.1). Habitat that could potentially be used by reptiles and amphibians is less well connected. This is mainly due to the models for these species including stricter barriers to movement; for example, narrower roads and buildings leading to greater levels of fragmentation. To the best of our knowledge, functional connectivity has not been measured for such a varied group of animals in any other municipalities, so we could not draw comparisons with other cities.

Insect pollinators (Table 3.1, Figures 3.4-3.6)

Layers used: (Tree canopy/mid-storey/ (understorey vegetation < 25 m from tree/shrub), 350 m interpatch distance) – 10 m roads.

Available habitat area: 539.4 Ha

Connectivity Index (CBI #2): 105.6 Ha

Interpretations: Royal Park is one large connected patch for this group, as is the residential area within the west of the municipality (Kensington, North Melbourne and West Melbourne); these connected areas however are separated from each other due to the barrier that roads present. It appears that very small patches of habitat are important for providing connectivity across residential areas for this group (Figure 3.6); for example, the western edge of Royal Park could provide a movement corridor, linking the patches within the park (as can be seen in Figure 3.5).

Specific caveats: many mutualistic insect pollinators have closely evolved relationships with specific flowering
Figure 3.4 Habitat patches for insect pollinators, aquatic insects, amphibians, reptiles, woodland birds, tree-hollow using birds and tree-hollow using bats across the City of Melbourne, coloured by the connected area.
Figure 3.5 Habitat patches for insect pollinators, aquatic insects, amphibians, reptiles, woodland birds, tree-hollow using birds and tree-hollow using bats in Royal Park, coloured by the connected area.
plants. This means that the functional connectivity for many of the individual species or taxa in this group may be more restricted to places where specific host plants occur. Flowering times also vary throughout the year, so this functional connectivity measure will also vary temporally.

**Aquatic insects (Table 3.1, Figures 3.4-3.5)**

Layers used: (All permanent waterbodies/ (tree canopy/mid-storey vegetation < 500 m from water), 1500m interpatch

*Figure 3.6* Pollinator habitat patches across the Melbourne suburb, Kensington, coloured by connected area.
distance) – 10 m roads.

Available habitat area: 534.0 Ha

Connectivity Index (CBI #2): 414.9 Ha

Interpretations: As illustrated by Figure 3.5, the main waterways within the City of Melbourne serve as connectors of large areas of the suitable aquatic insect habitat. More isolated patches occur in parks with water features, such as Carlton Gardens and Fitzroy Gardens. Aquatic insects have the highest connectivity index of all the functional groups, this is because although the total habitat area is not as high as others, the patches often form large connected areas. Indeed, this group has the lowest number of connected areas (67) meaning a low level of habitat fragmentation.

Specific caveats: Aquatic insects, such as dragonflies and damselflies, are known to fly long distances, although this behaviour has not been well-tested in urban environments. Relatively little is known about how these animals behave when waterways run underneath large road bridges. Here we assumed that the road bridges acted as deterrents to movement, but it is possible that this definition of a barrier was too strict for this group.

Amphibians (Table 3.1, Figures 3.4-3.5)

Layers used: (Ponds/creeks/understorey/mid-storey vegetation <10 m from water), 1000 m interpatch distance) – (5 m roads/all buildings).

Available habitat area: 80.7 Ha

Connectivity Index (CBI #2): 8.6 Ha

Interpretations: Habitat potentially suitable for amphibians occupied the smallest total area of the City of Melbourne when compared to the other animal groups, and they are also the least connected. This is partly due to the restricted habitat requirements but also because, in this model, buildings and roads act as barriers to movement. The Moonee Ponds Creek has the potential to act as a key connector, but currently lacks substantial riparian habitat and is fragmented by major road crossings (Figure 3.5).

Specific caveats: Many environmental variables affect the ability of amphibians to move across urban landscapes, including the availability of sun/shade and the degree of human disturbance. However, we were limited by the data available to only consider physical barriers such as road width or presence of a building.

Reptiles (Table 3.1, Figures 3.4-3.5)

Layers used: (Mid-storey/understorey vegetation, 1000 m interpatch distance) – (5m roads/all buildings)

Available habitat area: 370.3 Ha

Connectivity Index (CBI #2): 53.7 Ha

Interpretations: Reptiles are the second least-connected species group after amphibians. This is mainly due again
to the fragmentation of habitat by roads and buildings. The majority of reptile habitat patches are found in parks in the City of Melbourne. Because of the roads, train and tramlines running through Royal Park, this area is fragmented into more than five different connected areas, despite the entire park being classed as suitable habitat for reptiles (Figure 3.6).

Specific caveats: It is possible that some transport link areas may not act as strong barriers for this group, in particular if some stretches of train and tram lines, such as in Royal Park, could more easily crossed than busier roads. In addition, information on one important habitat feature for reptiles is missing – no spatial information was available for potential refugia, such as stones and rocks used for shelter.

**Woodland birds (Table 3.1, Figures 3.4-3.5)**

Layers used: (Mid-storey/tree canopy/understorey vegetation < 10 m from tree/mid-storey), 1500 m interpatch distance) – 15 m roads/buildings > 10 m height.

Available habitat area: 481.5 Ha

Connectivity Index (CBI #2): 481.5 Ha

Interpretations: Due to the greater movement capability and reduced road barriers, the municipality is well connected for this group compared to the other targeted taxa. Pockets of isolated habitat do exist south of the Yarra River around Westgate Park and the Docklands area (Figure 3.5).

Specific caveats: A major assumption here is the movement capability of this group. We took dispersal distance data from the literature; however, all these data were measured in rural areas, landscapes which are quite different to urban environments, particularly in terms of human activity.

**Tree-hollow using birds (Table 3.1, Figures 3.4-3.5)**

Layers used: (Tree canopy < 1000 m from tree-hollows/understorey vegetation < 500 m from tree-hollows, 500 m interpatch distance) – 15 m roads/buildings > 10 m height.

Available habitat area: 631.4 Ha

Connectivity Index (CBI #2): 298.6 Ha

Interpretations: The patches north of the Yarra form one largely connected area (Figure 3.5), with habitat in the southern parts of the municipality being more fragmented. Suitable habitat for this group in Royal Park is influenced by the Upfield train line (Figure 3.5).

Specific caveats: The information on tree-hollows used in this model is not yet complete, it is very likely that recalculating the connectivity index for this group and the bats (after current survey work) will result in an increase in CBI #2.
Tree-hollow using bats (Table 3.1, Figures 3.4-3.5)

Layers used: (Tree canopy < 250 m from tree-hollows, 1000 m interpatch distance) – 15 m roads/buildings > 10 m height.

Available habitat area: 331.4 Ha

Connectivity Index (CBI #2): 173.6 Ha

Interpretations: Because of their dispersal capabilities, tree-hollow using bats could potentially access most of the municipality. St. Kilda road forms a major barrier south of the Yarra River (Figure 3.4)

Specific caveats: As with the tree-hollow using birds, this group relies on the tree-hollow location data which is currently incomplete. Given the potential impact of roads and open spaces on this group, an important limitation of this model was the lack of information regarding artificial light at night, the presence/absence of which might influence the effect of a road barrier. For example, the Upfield train line in Royal Park (Figure 3.5) may not actually be barrier to this group if it is mostly unlit at night.

Hybrid map

All the land uses within the City of Melbourne that were classed as habitat for each of the seven animal groups have been combined into one map and coloured by group (Figure 3.7).

Whilst an overall connectivity index was not calculated for all seven types of habitat, the map helps to illustrate the overall habitat coverage within the municipality and potential corridors for some groups. This is particularly clear along the Yarra River and Moonee Ponds Creek for aquatic insects and amphibians (Figure 3.7).

3.3 Caveats and limitations of our assessment

Our assessment of habitat connectivity has some limitations and caveats. These can be considered in three groups: (1) limitations of the connectivity index as a stand-alone measure, (2) data quality and resolution, and (3) assumptions made about the environmental data used to calculate the connectivity index. Further exploration of the GIS layers included with this report will help to illustrate some of these limitations. We outline some of the important issues below.

The connectivity metric

First, it is important to recognise that a connectivity index or metric is not meaningful on its own – the meaning comes through comparisons. For example, it can be used to compare habitat connectivity across municipalities, evaluate the likely impact of two competing development plans, or assess incremental changes over time. Second, how a connectivity
Figure 3.7 Hybrid maps of all seven types of animal habitat. Each animal group is shown in a different colour (tree-hollow using bats in dark blue, woodland birds in brown, insect pollinators in green, reptiles in purple, tree-hollow using parrots in light blue, amphibians in yellow, and aquatic insects in magenta). The top map shows the whole City of Melbourne, while the bottom map shows a zoomed in section on the southern end of Royal Park. Note that the GIS layers are placed on top of each other, so some habitat types will overlap.
index is interpreted relies on understanding the spatial information used to generate the index, as different methods will use data in different ways. For example, the CBI #2 method calculates connectivity independently of the actual area of the habitat, so a landscape could be very connected (high index) but be made up of many small habitat patches. Third, a connectivity index does not indicate presence or absence of a species/group, but assesses the connectivity of potentially suitable habitat for such species or group of species. Finally, a connectivity index does not inform which areas have particularly good or bad quality habitat without habitat quality data being used in the calculation.

Data resolution and accuracy

There are several assumptions that need to be made in the calculation of a connectivity index. These relate to either the spatial data or the information used to determine the functional connectivity parameters for a particular animal group. During this analysis we assumed that all GIS layers were accurate representations of land-use categories currently existing in the City of Melbourne, and that these data were up to date. We also assumed that where land-use was described as “shrub bed” each shrub bed did indeed contain suitable habitat. A similar assumption was made regarding the “turf” land-use layer; however, some areas classed as turf will not be viable habitat for some species, for example, very closely mown sports fields. Finally, the City of Melbourne does not exist as an isolated landscape; it is surrounded by other local government areas. This connectivity assessment only includes data from within the City of Melbourne and does not consider the implications of land-use classes in the broader metropolitan area. We were also missing information about land usage within private residential gardens and some larger properties such as Melbourne Zoo, where vegetation availability may lead to additional habitat patches that were not included in this study.

Small-scale urban green spaces, such as green roofs and road verges, were not included in the model. This is because the barrier effect of roads and/or buildings was modelled as the main contributor to a fragmented landscape; so habitat directly on, or within a few meters, was not considered as viable in this particular model. This conservative approach was taken to ensure that the connectivity assessment was in line with that undertaken by other municipalities. However, as suggested before, this could be approached more sensitively by further refinement of how barriers and habitat are defined, especially for different animal groups. This would allow a more accurate assessment of
the contributions of green roofs and road verges to connectivity. In addition, more complex techniques, such as developing resistance surfaces, may help clarify the value of these features, if their value for a specific species with known dispersal and habitat affiliation data can also be collected.

Assumptions about the environmental data

In addition to the specialist knowledge shared among the co-authors of this report, we also consulted with several other biodiversity experts from the Melbourne area. This, along with the primary literature, helped us to decide on appropriate habitat and dispersal parameters for each of our seven functional groups (see Appendix I for more information). However, most of the information on species dispersal has been gathered outside urban habitats, either in suburban or agricultural landscapes. Currently, there is relatively little information on how animal species move within or across urban environments (La Point et al. 2015). It is therefore possible that the dispersal abilities of each functional group have been over or underestimated in this assessment.

Missed environmental considerations

For the calculation of ecological connectivity for the City of Melbourne we used basic habitat features, such as vegetation in different height classes/categories, the presence of water or tree hollows, as well as barriers, such as roads and buildings. However, there are other environmental features that are likely relevant for functional connectivity. For example, some animals may have habitat requirements, such as proximity to refugia (structures used by amphibians and reptiles for shelter), specific species of flowering plants (for insect pollinators) or native vegetation. Also, while we varied the classification of barriers according to road width, it may be that traffic volume plays a greater role in determining whether a given taxa will cross a road than road width. For nocturnal species, the presence of artificial light at night may create barriers to movement. Additionally, it may be that areas we have assumed were suitable habitat for a species are in fact unsuitable due to high levels of human activity (e.g. within a park). Finally, there is temporal variation (daily, weekly and yearly) in both habitat areas and perceived barriers, which will alter the connectivity of the landscape. By collecting other environmental data across the municipality, the accuracy of the functional connectivity calculations could be improved.

Specificity: Species-specific habitat affinity and dispersal capabilities

We took a species group approach for modelling functional connectivity.
in order to study a variety of different habitat requirements, potential barriers and dispersal capabilities. However, this means that the subtleties of different species within each group will be lost in the assumptions made about how those organisms behave. For example, the European honeybee Apis mellifera will behave differently to Australian native bee species such as the blue-banded bee Amegilla chlorocyanea (Figure 2.1A), requiring different plant species and nesting resources; however, at the moment both species are considered broadly as ‘insect pollinators’.

Another important subtlety is that viable residency habitat, that is, the spaces used by an animal every day for breeding and/or foraging, is different to what may be considered a movement corridor, where species spend less time, using it just for dispersal. For example, because the threshold for road barrier width was set to 10 m, our assessment suggests that members of the insect pollinator group could disperse through residential areas (Figure 3.7) despite there being limited habitat available. If narrower roads were considered barriers for this species, then these small patches of habitat would no longer be classed as being connected. The key information we are missing here is what types of “non-habitat” features these animals can cross and whether they will disperse using these habitat “stepping stones” and what size these stepping stones need to be.

We suggest that an important next step for The City of Melbourne could be to test the accuracy of the mapped connected areas and validate their use by specific animal species/groups. This could be done by collecting data on species occurrences in mapped connected areas, validating the dispersal distances used here, and collecting further information on the barrier effects of roads and other urban stressors. This information can be then used to update the metrics calculated here and refine the input parameters.
4 Using the framework for habitat planning

4.1 Example scenarios for using the connectivity framework

One of the most important uses of this framework is as a planning tool. This could be for deciding on the best place to position new garden beds, measuring the potential impact of a proposed development, or comparing the City of Melbourne to other municipalities, both locally and globally. In this section we will use two different scenarios to demonstrate how our connectivity framework can be used for planning in the City of Melbourne. The scenarios represent two different applications of the framework; one potentially positive, such as adding habitat, and one potentially negative, such as removing habitat, and the corresponding connectivity calculations. In order to allow comparison of the ‘before and after’ connectivity indices we used the same functional connectivity groups, and their corresponding habitat requirements, as analysed in Chapter 3.

These scenarios were chosen, after consultation with the City of Melbourne, as being the most representative of current planning considerations. Other options included: improving riparian habitat along rivers and creeks; identifying small gaps that could be easily connected; improving a habitat patch to make it a corridor for more species; and mitigating the barrier effect of roads for different animal groups.

4.2 Scenario 1: Addition of a major road development – worked example

Scenario outline

What are the implications of a major transport infrastructure development for ecological connectivity in the City of Melbourne? Any development can have a range of impacts on connectivity, both negative (e.g. lost habitat or increased barriers to movement) and positive (e.g. if revegetation takes place). Here, we assessed the extent to which a large road project in North and West Melbourne (Figures 4.1 and 4.2) influences functional connectivity of all species groups. Adding this development to the municipality also reduces the total area of habitat for all
Figure 4.1 Overview of the City of Melbourne municipality with existing habitat patches (green) and proposed new road development (red).

Figure 4.2 Closer view of the main impact area of the new road development (red).
Table 4.1 Structural (all vegetation and tree canopy habitat alone) and functional connectivity indices as calculated the same way as in Chapter 2, showing before and after the addition of a major road development to the Footscray Road and Docklands area.

<table>
<thead>
<tr>
<th>Connectivity type</th>
<th>Number of connected areas</th>
<th>Total area (Ha)</th>
<th>Connectivity Index (Ha)</th>
<th>Total number of habitat patches</th>
<th>Mean patch size (m²)</th>
<th>Maximum patch size (m²)</th>
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<td>173.5</td>
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</tbody>
</table>
groups. However, this scenario simply assesses the footprint of the proposed final road development and does not account for a potential increase in traffic levels or the habitat loss and disturbance caused in the surrounding areas during the building phase of the project.

The following scenario is applied to the habitat layers outlined in Chapter 3, where the habitat for each species group is made up of a combination of different layers and rules, using logical statements such as AND/OR. A worked example of the process for calculating the connectivity index for this scenario can be found in Appendix 1 (Table A1.2).

**Effect on habitat patches of tree canopy (Table 4.1)**

Area: 588.6 Ha

Connectivity Index (CBI #2): 106.8 Ha

Interpretations: The connectivity index decreased very slightly for this habitat type, probably because of a very small reduction in area where patches would be lost from underneath the development (Figures 4.3 and 4.4). This was the only structural connectivity index included here as the pre-existing mid-storey and understorey vegetation in this area was minimal.

**Effect on insect pollinator habitat (Table 4.1)**

Area: 538.8 Ha

Connectivity Index (CBI #2): 98.6 Ha

Interpretations: A total of 7 Ha reduction in CBI #2. The major intersections fragment the habitat around the Moonee Ponds Creek, and around Dynon Road and Footscray Road (Figure 4.3).

**Effect on aquatic insect habitat (Table 4.1)**

Area: 532.1 Ha

Connectivity Index (CBI #2): 409.0 Ha

Interpretations: A total of 6.85 Ha reduction in connectivity, with the majority of this habitat loss occurring along Footscray Road, and also under the major intersection in Figure 4.3, where the Moonee Ponds Creek passes under the proposed structure.

**Effect on amphibian habitat (Table 4.1)**

Area: 80.1 Ha

Connectivity Index (CBI #2): 8.6 Ha

Interpretations: Connectivity Index remained the same despite a slight decrease in overall habitat area (-0.6 Ha). This is due to the removal of some very small patches of habitat, which reduced the number of patches overall, and therefore acted to reduce habitat fragmentation in this model (Figure 4.3).
Figure 4.3 Overview of the City of Melbourne showing the effect of a proposed road project on habitat patches of tree canopy and on habitat patches for insect pollinators, aquatic insects, amphibians, reptiles, woodland birds, tree-hollow using birds and tree-hollow using bats, classified by connected area. The road development is shown in red.
Figure 4.4 View of proposed major road development and the surrounding habitat patches of tree canopy and for insect pollinators, aquatic insects, amphibians, reptiles, woodland birds, tree-hollow using birds and tree-hollow using bats, classified by connected area. The road development is shown in red.
Effect on reptile habitat (Table 4.1)
Area: 370.1 Ha
Connectivity Index (CBI #2): 53.5 Ha
Interpretations: A decrease in CBI #2 (-0.2 Ha). Figure 4.3 illustrates the highly fragmented landscape for this group around the proposed development. Given that reptiles, and also amphibians, may struggle to move across busy roads the likelihood of the patches around this road development being used is very low.

Effect on woodland bird habitat (Table 4.1)
Area: 480.5 Ha
Connectivity Index (CBI #2): 408.8 Ha
Interpretations: A very slight increase in CBI #2 (+0.4 Ha) due to the reduction in the number of habitat patches overall (reducing fragmentation, Figure 4.3).

Effect on tree-hollow using bird habitat (Table 4.1)
Area: 540.7 Ha
Connectivity Index (CBI #2): 104.7 Ha
Interpretations: CBI #2 decreased by 193.9 Ha. Although there are habitat patches remaining underneath the road project (Figures 4.3 and 4.4), it is likely that these will remain very isolated and highly disturbed, and therefore not meaningfully contributing to the connected habitat as a whole. This large decrease in connectivity is probably due to the removal of several trees with hollows when this development is added to the landscape (acting as a barrier). For the moment, the data used here on tree-hollow location is limited, so any removal of tree-hollows for this group has a big impact on connectivity.

Effect on tree-hollow using bat functional connectivity (Table 4.1)
Area: 331.2 Ha
Connectivity Index (CBI #2): 173.5 Ha
Interpretations: A small reduction in CBI #2 (-0.1 Ha). As with tree-hollow using birds, this is because the remaining habitat had slightly fewer habitat patches but ended up with more areas that were connected (within 1500 m interpatch distance). This means that the road development removed some especially fragmented areas of habitat (Figures 4.3 and 4.4).

4.3 Scenario 2: Adding biodiversity corridors to the City of Melbourne

Scenario outline
What could structural and functional connectivity look like in 20 years’ time? As part of the Urban Forest Strategy (City of Melbourne 2012), the City of Melbourne identified some key locations as potential biodiversity corridors. Addition of garden beds and tree plantings over the next 10 years would ideally result in full tree canopy cover across the targeted streets in 20 to 30 years. To model this, we
added blocks of canopy habitat to all the identified streets, simulating full canopy coverage for that street (Figures 4.5 and 4.6). We also added small areas to represent garden bed plantings, which could provide important habitat for some animal groups (e.g. insect pollinators and reptiles). In this model, the action of significantly increasing canopy and mid-storey habitat along roads will remove the barrier effect that these roads had in the original assessment.

In this scenario, habitat connectivity across the City of Melbourne increased for all the investigated animal groups (Table 4.3), which is due to an increase in total habitat area and a reduction in the number of different habitat fragments; that is, more habitat patches were connected to each other. Amphibians were not included in this scenario as we did not “add” any suitable understorey vegetation near to water, meaning the overall habitat remained unchanged for this group.

Effect on insect pollinator habitat (Table 4.2, Figure 4.7)
Area: 706.7 Ha
Connectivity Index (CBI #2): 164.4 Ha
Interpretations: The Connectivity Index increased by 59 Ha. This was due to a decrease in fragmentation of this habitat type, leading to a smaller number of habitat patches overall (the proposed corridors linking lots of smaller patches together, to create fewer larger ones). Figure 4.8 highlights this with a before and after close-up of East Melbourne. The number of patches in this area, shown in different colours, was reduced from 15 (before) to 3 (after adding the corridors).

Effect on aquatic insect habitat (Table 4.2)
Area: 672.4 Ha
Connectivity Index (CBI #2): 509.3 Ha
Interpretations: The number of connected areas fell to just 39 for this group, as the biodiversity corridors modelled here decrease the fragmentation of existing habitat. The Connectivity Index increased by +94 Ha allowing Royal Park to be connected to the Royal Botanic Gardens via the waterways (Figure 4.7).

Effect on reptile habitat (Table 4.2)
Area: 381.6 Ha
Connectivity Index (CBI #2): 79.4 Ha
Interpretations: Despite only a small increase in habitat area (11.3 Ha) compared to the other groups, the biodiversity corridor simulation still resulted in an increase in connectivity (+26 Ha). This improvement is most noticeable around Kensington and Parkville (Figure 4.7), while Royal Park is still fragmented for this group.
Figure 4.5 Overview of the City of Melbourne showing proposed tree canopy cover for nine precincts after the Urban Forest planting strategy. The biodiversity corridors (yellow) should have full tree canopy cover by 2023. Existing vegetation is shown in green.

Figure 4.6 Close up of the East Melbourne precinct biodiversity corridor showing the projected canopy cover (yellow) and additional garden beds (orange), overlaid on current vegetation (green).
Table 4.2  Structural (tree canopy habitat) and functional connectivity indices as calculated following the framework methodology, showing before and after the addition biodiversity corridors across nine City of Melbourne precincts.

<table>
<thead>
<tr>
<th>Connectivity type</th>
<th>Number of connected areas</th>
<th>Total area (Ha)</th>
<th>Connectivity Index (Ha)</th>
<th>Total number of habitat patches</th>
<th>Mean patch size (m²)</th>
<th>Maximum patch size (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Structural connectivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree canopy</td>
<td>254</td>
<td>190</td>
<td>299.9</td>
<td>374.7</td>
<td>41.3</td>
<td>46.3</td>
</tr>
<tr>
<td>Functional connectivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insect pollinators</td>
<td>218</td>
<td>156</td>
<td>539.4</td>
<td>706.7</td>
<td>105.6</td>
<td>164.4</td>
</tr>
<tr>
<td>Aquatic insects</td>
<td>67</td>
<td>39</td>
<td>534.0</td>
<td>672.4</td>
<td>414.9</td>
<td>509.3</td>
</tr>
<tr>
<td>Reptiles</td>
<td>263</td>
<td>192</td>
<td>370.3</td>
<td>381.6</td>
<td>53.7</td>
<td>79.4</td>
</tr>
<tr>
<td>Woodland birds</td>
<td>199</td>
<td>184</td>
<td>481.5</td>
<td>637.6</td>
<td>408.4</td>
<td>512.7</td>
</tr>
<tr>
<td>Tree-hollow using birds</td>
<td>202</td>
<td>186</td>
<td>631.4</td>
<td>786.3</td>
<td>298.6</td>
<td>451.5</td>
</tr>
<tr>
<td>Tree-hollow using bats</td>
<td>159</td>
<td>146</td>
<td>331.4</td>
<td>493.3</td>
<td>173.6</td>
<td>397.8</td>
</tr>
</tbody>
</table>
**Effect on woodland bird functional connectivity (Table 4.2)**

Area: 637.6 Ha  
Connectivity Index (CBI #2): 512.7 Ha

Interpretations: Woodland birds were one of the best-connected groups originally, because their habitat (tree canopy) is widely distributed across the municipality. Adding more canopy resulted in a big increase in connectivity for woodland birds (+104 Ha). Notably, habitat patches in the Port Melbourne area remains separated from the rest of the city (Figure 4.7).

**Effect on tree-hollow using bird functional connectivity (Table 4.2)**

Layers used: Only biodiversity corridors within 500m of known tree hollows were included in this model.  
Area: 786.3 Ha  
Connectivity Index (CBI #2): 451.5 Ha

Interpretations: The Connectivity Index of habitat for tree-hollow using birds increased (+153 Ha) with addition of the proposed corridors with only the Yarra River still forming a significant barrier for this group (Figure 4.7). More information on the movement characteristics of these species would improve the accuracy of this predicted result (e.g. will they cross wide waterbodies?).

**Effect on tree-hollow using bat functional connectivity (Table 4.2)**

Layers used: Only biodiversity corridors within 500m of known tree hollows were included in this model.  
Area: 493.3 Ha  
Connectivity Index (CBI #2): 397.8 Ha

Interpretations: After adding the biodiversity corridors, most habitat patches in the City of Melbourne could be considered as part of the same connected area (Figure 4.7). This has resulted in the biggest increase in connectivity of all the animal groups (+224 Ha).

**Comparing all connectivity indices**

The connectivity indices are mainly useful when used comparatively, particularly over time. Here we demonstrate this by comparing the current connectivity indices for the City of Melbourne (from Chapter 3) with the two hypothetical planning scenarios. Figure 4.9 highlights the large increase in connectivity when additional tree canopy cover is modelled for the biodiversity corridor scenario. It also clarifies where removing already fragmented habitat under the road development scenario has only a small effect for some species groups.
Figure 4.7 Overview of the City of Melbourne showing the effect of the proposed biodiversity corridors on structural connectivity of tree canopy and on functional connectivity of insect pollinators, aquatic insects, amphibians, reptiles, woodland birds, tree-hollow using birds and tree-hollow using bats, classified by connected area.
Figure 4.8 Closer view of the suburb of East Melbourne, showing the number of different habitat patches before (top) adding biodiversity corridors and after (bottom). The reduced number of colours shows that connectivity has increased.
Figure 4.9 Bar graph showing the three connectivity estimates calculated for each of the seven animal groups and tree canopy within the City of Melbourne. The current connectivity estimate for each group is shown in dark grey, along with the hypothetical connectivity indices for the road development (mid grey) and biodiversity corridors (light grey) scenarios.
5 Summary and conclusions

5.1 Conclusions and considerations for future application

How to use the connectivity framework

One of the main aims of this project is to provide a framework by which connectivity can be calculated for the municipality, in an easy and reproducible way. This report contains both a detailed methodology (Appendix I) and worked examples in order to facilitate calculations for a variety of different management planning applications, with the potential for both positive and negative outcomes. Below we outline the advantages of using this framework to investigate existing and potential connectivity within the City of Melbourne, and also how it can be used as a management tool. We hope that this framework, along with further data collection and development can be used to inform future planning within the municipality.

Use of the index - structural vs functional

We would advocate the evaluation of functional connectivity where possible, over structural connectivity, as it is a more specific approach, and therefore more useful to the City of Melbourne. In particular, functional connectivity indices for species that are capable of moving further than 100m (most animals) will differ most from the more general structural approach, as well as those with more specialised habitat requirements, such as reptiles, aquatic insects and amphibians. In the future, if using this method to measure connectivity for individual species, it would be important to make the definitions of habitat and movement capability (e.g. gap crossing ability) as accurate as possible. Tree canopy and mid-story cover are used by almost all animal groups and therefore careful mapping of these vegetation types would be advantageous for improving the accuracy of the functional connectivity measurements. Despite the increased specificity of a functional connectivity approach, the structural index proposed here based on common definitions of habitat, barrier and distance thresholds would be more appropriate for international comparisons (as demonstrated in Chapter 3).
Use of the framework to assess proposals/guide actions

Issues to consider when using this framework include:

Goal identification – in particular what species or habitat type is the focus? This would dictate which spatial data will be used;

Comparing different options for functional connectivity parameters, such as barrier definitions (e.g. how wide or how busy are road barriers?);

Validating the chosen habitat by ground truthing (i.e. what habitat is currently being used by that species in the City of Melbourne?);

Adding in species distribution data for a more accurate baseline evaluation of current connectivity; and

Exploring sensitivity by incrementally varying the species dispersal capabilities.

Identifying opportunities

Visually exploring the files included with this report in a GIS software will allow the identification of potential places for future management actions. Using the method detailed here, habitat is coloured according to the connected area it belongs to. Places where connectivity could be improved can be identified as areas on the maps where the colour changes. This usually occurs where an animal would have to cross a gap in habitat greater than its dispersal capability or where there is a barrier such as a road or building. By re-running the model with incremental changes, the framework can also evaluate adding small pieces of habitat, such as corridors, green laneways, green roofs and pop-up parks, in these strategic areas, and also simulate the growth of habitat features such as tree canopy or herbaceous cover. An important next step will be testing the sensitivity of this proposed method to changes in the chosen parameters used to define what is habitat, what is a barrier and how close patches have to be in order to be connected. This would be particularly beneficial for understanding how the fragmenting effect of roads can be mitigated, both within the confines of the model and for practical management of their impact on ecological connectivity within the City of Melbourne.

To use this framework for evaluating potential developments it is important to generate accurate GIS layers for these projects. This includes outlining the footprint of the project so it can be appropriately added to either the habitat or barrier layers for each connectivity calculation. We also
advocate for analysing the Greater Melbourne Metropolitan Area, or at least the neighbouring municipalities if possible, as animals will be moving across the various adjacent local government areas. If the land-use data are available (e.g. GIS layers of different vegetation type, waterbodies and potential barriers) the same methods outlined here can be easily repeated.

Understanding connectivity for multiple species at a landscape scale is a common goal in biodiversity management. However, with myriad methods available, and little scientific consensus, selecting the ‘right’ metrics and approaches is difficult. Each method has different pros and cons, as well as different data requirements and assumptions. Ultimately, the best approach for a given location is one that can effectively guide management actions. That is, one that takes into account the management context, the actions that are feasible, the scale at which these actions are implemented, and broadly represents the species/taxa of interest.

Aboriginal perspectives on connectivity

Consulting with the City of Melbourne Aboriginal community was unfortunately beyond the scope of this project; however, it should form an important component of any extension to this work. This would require dedicated engagement to explicitly consider Aboriginal perspectives on connectivity planning in the City of Melbourne.

Conclusions

Ecological connectivity has a key role to play in urban landscapes (Correa Ayram et al. 2015; La Point et al. 2015) and is particularly important for maintaining species populations and attracting species back into urban areas. Measuring and modelling connectivity is therefore advantageous for management and planning, and needs to be evaluated with methods that are easily reproducible. We have summarised an approach for measuring ecological connectivity within the City of Melbourne that can be repeated in other municipalities, and can be used to estimate changes over time. Our findings suggest that the City of Melbourne is relatively well connected for several key animal groups, including birds, bats, insect pollinators and aquatic insects, but poorly connected for amphibians and reptiles. By using the maps produced for this report, the Council can identify areas where connectivity can be improved. Useful extensions to this project might include species and habitat surveys for increased spatial accuracy and quantifying the sensitivity of the model to better account for input parameter uncertainty. We believe the approach outlined in this work is appropriate for the City of Melbourne.
because it combines structural and functional aspects of connectivity, is tailored to habitats managed by the municipality, and is broad enough to capture a wide range of species. We note however that there are important limitations in that not all species are encompassed here. The framework has been developed based on an understanding of the recent scientific literature and connectivity metrics, extensive consultation with the City of Melbourne to ensure that it addresses key goals, and the amount of data available. We believe it is the right blend of approaches to support the City of Melbourne’s efforts to increase ecological connectivity across the municipality.


City of Helsinki. (2016) City Biodiversity Index. Department of Environmental Protection, City of Helsinki, Finland.


Deslaurier MR, Asgary A, Nazarnia N, Jaeger JAG. (In press) Implementing the connectivity of natural areas in cities as an indicator in the City Biodiversity Index (CBI). Ecological Indicators.


Appendix I  Detailed methodology

The following methodology is adapted from the City Biodiversity Index Indicator #2 calculation as improved by Deslauriers et al. (2017). Initially, structural connectivity measures were calculated using the same parameters as Deslauriers et al. (2017). Functional connectivity was then determined for the seven key animal groups by varying the habitat requirements or assumed dispersal capabilities for each group - similar to the methods used by Casalegno et al. (2017). A generalised method is provided in Table AI.1, and Table AI.2 contains a fully worked example for calculating functional connectivity for woodland birds, with the additional steps for the road development scenario from Chapter 4 highlighted for clarity. An example of how the connectivity index formula is applied can be seen in Figure AI.1

Structural connectivity

Following methodology outlined by Deslauriers et al. (2017). A rough summary of this as follows:

1. Buffer around areas of ‘natural habitat’ (e.g. 50 m);
2. Remove any ‘barriers’ from this layer (e.g. roads > 10 m wide);
3. With remaining buffered habitat, use GIS software to identify connected areas and the original habitat within them; and
4. Calculate area of connected habitat patches, and then apply the improved City Biodiversity Index indicator #2 (CBI 2) equation to estimate the connectivity index and effective mesh size (i.e. the probability that two points dropped at random into the landscape will be connected).

The improved CBI 2 equation is reproduced from Deslauriers et al. (2017).

\[
CBI\ 2 = \frac{1}{A_{\text{total}}} (A_{G1}^2 + A_{G2}^2 + A_{G3}^2 + \ldots + A_{Gn}^2)
\]

Where \( n \) is the number of connected areas; \( A_{G1}^2, A_{G2}^2, A_{G3}^2, \ldots \) indicate the size of each connected area; and \( A_{\text{total}} \) is the total area of all habitat patches in the landscape. The unit
Table A1.1 General step-by-step methodology for calculating connectivity index from Deslauriers et al. (2017) and Jaeger et al. (2008). Note that after each step a new layer is made, which is then used in subsequent steps.

<table>
<thead>
<tr>
<th>Step/sub-step</th>
<th>Method</th>
</tr>
</thead>
</table>
| 1. Prepare habitat layers | Unify habitat layers | Unify the habitat layers (you may also like to dissolve after each union to limit file size).  
Geoprocessing tools > Union > Input the two layers you wish to combine.  
Buffer habitat layers | Buffer & dissolve habitat layers.  
Geoprocessing > Buffer > Distance value is half the dispersal distance for your species. |
| 2. Prepare barrier layers | Unify barrier layers | Unify the barrier layers (you may also like to dissolve after each union to limit file size).  
Geoprocessing tools > Union > Input the two layers you wish to combine. |
| 3. Create fragmentation geometry | Erase barriers from the habitat layer | Input layer = final buffered habitat layer.  
Clip layer = final buffered barrier layer.  
Geoprocessing > Clip. |
| 4. Identify connected areas | Find remaining connected patches | Input layer = buffered habitat AFTER barrier removal.  
Geoprocessing > Arc Toolbox > Data Management Tools > Features > Multipart to singlepart.  
Identify connected areas | Right click on the layer created in this step, open attribute table and toggle editing on.  
Open ‘field calculator’ and ‘create new field’ using ‘row_number’ function. |
| 5. Identify connected habitat patches | Intersect original habitat layer with identified connected areas | Inputs = layer created in Step 4 & original habitat layer (made up of combined habitat types).  
Geoprocessing > Intersect. |
| 6. Calculate area and export | Calculate area of each patch | Right click on the layer created in Step 5, open attribute table and toggle editing on.  
Open ‘field calculator’ and ‘create new field’ using ‘area’ function.  
Export attribute table to ‘.csv’ | Right click on layer name in layers panel and select ‘save as’, make sure to select csv file type. |
| 7. Connectivity calculation | Calculation of (area)² | Spreadsheet should include a column with patch ID and area.  
Calculate square of patch area for each habitat patch (i.e. for the whole column of data).  
Calculation of connectivity index (CBI 2) | Connectivity index = SUM of squared connected patches/SUM of original habitat area. |

1 If using more than one habitat layer, combine them to form one layer (e.g. grass AND trees). Do this step as many times as needed to combine 3 or more layers.
2 Habitat classed as ‘connected’ if it is less than the dispersal distance apart. Patches closer than this will merge.
3 Combine the different types of barrier together to make single layer (e.g. roads AND buildings).
4 Barriers such as roads may have an effect on the habitat around them. Buffer accordingly.
5 The barriers prevent movement, even in patches that are connected, so erase the connected habitat.
6 Checks which of the buffered habitat areas are still connected and which are now on their own.
7 Gives each area that remained connected a unique number in a new field. Call the new field something sensible like ‘patchID’ or ‘patch_number’.
8 Links each original habitat patch with its related connected area so that connected patches of habitat are grouped together.
9 This step calculates the actual area of each connected habitat patch.
10 Be sure to use the maximum level of precision possible (e.g. 10 dp and ‘select decimal number’ rather than ‘integer’).
11 The final calculation is done with a spreadsheet software.
of measurement used in this study is m\(^2\). For more information about the connectivity calculation and effective mesh size consult Jaeger (2000) and Jaeger et al. (2008). An example of how the connectivity index formula is applied can be seen in Figure A1.1, where hypothetical area values are used to calculate the connectivity index for a landscape containing 4 patches of habitat.

Three separate structural connectivity indices were calculated for different vegetation types: herbaceous plants, mid-storey and tree canopy. The separate habitat areas were defined by combining land use polygons (e.g. shrub bed, turfed areas or tree locations) and vegetation height classes derived from LiDAR data.

Herbaceous plant layers: LiDAR herbaceous plant layers (vegetation height class 0-50 cm)

Mid-storey layers: LiDAR mid-storey layers (height 50-300 cm) and shrub bed land use layer from City of Melbourne.

Tree canopy layers: LiDAR canopy layers and open source canopy layer combined.

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*Functional connectivity*

The determination of functional connectivity was very similar to the methodology followed for structural connectivity, except ‘habitat’ and ‘barriers’ are defined more explicitly according to each animal group. In addition, the dispersal distance differs for each group, ranging from 350 m to 1500 m. These values were taken from the primary literature for the example or related species.

Following the combination of Casalegno et al. (2017) and Deslauriers et al. (2017) methods (as summarised above), a rough rubric for creating connectivity maps and calculating their corresponding indices is to:

1. Decide what habitat the ‘animal’ needs;
2. Buffer this habitat according to dispersal capabilities;
3. Remove habitat that coincides with barriers; and
4. Divide the remaining habitat into patches according to whether these are connected or not.
Table 4.1 Step-by-step methodology for quantifying the potential effect of a major road development on woodland bird functional connectivity.

<table>
<thead>
<tr>
<th>Step/sub-step</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Prepare habitat layers</td>
<td>Combine all woodland bird habitat layers. Geoprocessing &gt; Union. ¹ Combine canopy layers, mid-storey layers. Geoprocessing &gt; Union. Geoprocessing &gt; Buffer &gt; Distance value is 10 m. ² Buffer the combined layers by 10 m. Geoprocessing &gt; Buffer &gt; Distance value is 10 m from cover. Input &quot;turflayer&quot; and buffered cover layer. Geoprocessing &gt; Intersect. Unify &amp; dissolve 10 m turf layer and combined cover/habitat layers. Geoprocessing &gt; Union. ³</td>
</tr>
<tr>
<td>Account for woodland bird dispersal distance</td>
<td>Woodland bird dispersal distance is 1,500 m. Makes 'All woodland bird habitat buffered'. ⁴ Geoprocessing &gt; Buffer &gt; Distance value is half the dispersal distance (750 m).</td>
</tr>
<tr>
<td>Filter existing barrier layers</td>
<td>Filter the road layer to width (&gt; 10 m) and the building layer to height (&gt; 10 m). ⁴</td>
</tr>
<tr>
<td>Create new road development layer</td>
<td>Combine the cover habitats for this animal group. ¹ Finding the area 10 m around the canopy and mid-storey cover. ⁵ Only wide roads and tall buildings are barrier for this group. ⁶ Barriers such as roads may have an edge effect on the habitat around them. ⁷ The barriers prevent movement, even in patches that are connected, so erase the connected habitat. ⁸ This step checks which of the buffered areas are still connected and which are now on their own. ⁹ This step gives each buffered area that remained connected a unique number in a new field. Call the new field something sensible like ‘patchID’ or ‘patch_number’. ¹⁰ Makes ‘Buffered woodland bird habitat, connected area identified’.</td>
</tr>
<tr>
<td>Create fragmentation geometry</td>
<td>Erase barriers from the habitat layer. ¹¹ Makes ‘All woodland bird barriers’. Geoprocessing &gt; Clip. This leaves the buffered habitat, minus all potential barriers.</td>
</tr>
<tr>
<td>2. Prepare barrier layers</td>
<td>Input layer = All woodland bird habitat buffered. ⁶ Clip layer = All woodland bird barriers. Geoprocessing &gt; Clip.</td>
</tr>
<tr>
<td>Find remaining connected areas</td>
<td>Input layer = the buffered habitat with barriers removed (Step 3). ⁷ Geoprocessing &gt; Arc Toolbox &gt; Data Management Tools &gt; Features &gt; Multipart to singlepart.</td>
</tr>
<tr>
<td>Identify connected areas</td>
<td>Right click on the layer created in this step, open attribute table and toggle editing on. ⁸ Open ‘field calculator’ and ‘create new field’ using ‘row_number’ function. Make sure you save the edits to this layer. ⁹</td>
</tr>
<tr>
<td>3. Create fragmentation geometry</td>
<td>Intersect original habitat layer with identified connected areas. ¹⁰ Makes ‘Woodland bird habitat, connected area identified’.</td>
</tr>
<tr>
<td>4. Identify connected areas</td>
<td>Intersect the original woodland bird habitat (Step 1) with the results of Step 4. ¹⁰ Geoprocessing &gt; Intersect.</td>
</tr>
<tr>
<td>Calculate area and export</td>
<td>Right click on the layer created in Step 5. Open attribute table and toggle editing on. ¹¹ Open ‘field calculator’ and ‘create new field’ using ‘area’ function. ¹² Remember to save the layer edits, calling the new column ‘habitat area’ or similar.</td>
</tr>
<tr>
<td>5. Identify connected habitat patches</td>
<td>Calculate area of each patch. Spreadsheet should include a column with patch ID and habitat area. Delete all other columns. ¹³</td>
</tr>
<tr>
<td>6. Calculate area and export</td>
<td>Create a new column, ‘Square patch area’ Apply =POWER(cell number, 2) to the whole column. ¹³</td>
</tr>
<tr>
<td>7. Connectivity calculation</td>
<td>Total sum of squares (SUM ‘Square patch area’ column). Total sum of original habitat area (SUM ‘habitat area’ column). Connectivity = Sum of squares/Sum original area. ¹³</td>
</tr>
</tbody>
</table>

---

1 Combine the cover habitats for this animal group.
2 Finding the area 10 m around the canopy and mid-storey cover.
3 Makes ‘All woodland bird habitat’.
4 Only wide roads and tall buildings are barrier for this group.
5 Barriers such as roads may have an edge effect on the habitat around them.
6 The barriers prevent movement, even in patches that are connected, so erase the connected habitat.
7 This step checks which of the buffered areas are still connected and which are now on their own.
8 This step gives each buffered area that remained connected a unique number in a new field. Call the new field something sensible like ‘patchID’ or ‘patch_number’.
9 Makes ‘Buffered woodland bird habitat, connected area identified’.
10 This step links each actual habitat patch with its related connected area so that connected patches of habitat are grouped together.
11 This step calculates the actual area of each connected habitat patch.
12 Be sure to use the maximum level of precision possible (e.g. 10 dp and ‘select decimal number’ rather than ‘integer’.
13 The final calculation is done in a spreadsheet software.
Figure A1.1 Worked example calculation with diagram. In this example, the landscape contains four patches of habitat (A). Buffering these habitat patches by a fixed distance determines which are considered to be connected (B). In this example, the two red patches are part of the same connected area. The area of each individual patch is then calculated (C). These values are used to calculate the connectivity index (CI) (D). Note that the two patches that make up the red connected area are summed together.

The seven animal groups used in this report were determined during the ‘Species Selection Workshop’, 11th August 2017. The details of the habitat requirements and movement parameters for each functional connectivity group were further refined using the primary literature. Please refer to Chapter 2 for more information on parameter selection. Table 2.1 summarises the essential habitat, barriers and average dispersal distance for each functional connectivity group. Where ‘OR’ is used, the assumption is that the animal will freely move between these habitats, but outside this enters the regular matrix of ‘non-natural area’ and begins crossing a ‘gap’ which relates back to the dispersal capabilities.

<table>
<thead>
<tr>
<th>Patch ID</th>
<th>Patch area</th>
<th>Square of patch area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>(12+5) = 17</td>
<td>289</td>
</tr>
<tr>
<td>Blue</td>
<td>12</td>
<td>144</td>
</tr>
<tr>
<td>Grey</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td><strong>30</strong></td>
<td><strong>434</strong></td>
</tr>
</tbody>
</table>

CI = Sum of squares/Sum original area
CI = 434/30 = **14.5 Ha**
Appendix II  List of GIS layers

Original base map layers
AllWater_fixedValid (Contains all water features including creeks, ponds and rivers)
BuildingFootprint
Property
LidarMidStorey50to600cm
Midstorey
ShrubBed
LidarUnderstorey0to50cm
Turf
TreeCanopy2016_correctCRS (Converted to same CRS as rest of project)
TreesWithHollows

Barrier layers
BuildingTaller10m
ImperviousEdge_10mBuffDiss (Buffered by 10 m and the dissolved to simplify the layer)
RoadRail_widerThan5m
RoadRail_widerThan10m
RoadRail_widerThan15m
EdgeRoadRail5m_7.5mBuffDiss (Buffered by 7.5 m and then dissolved to simplify)
EdgeRoadRail10m_7.5mBuffDiss
EdgeRoadRail15m_7.5mBuffDiss

Structural connectivity
Tree canopy habitat
OriginalTreeCanopy_2mBuff (Habitat layer)
EdgeRoadRail10m_7.5mBuffDiss (Barrier layer)
1. TreeCanopy_50mBuffDiss
2. TreeCanopy_50mBuffDiss_BARRIERRemoved (Barrier layer overlaid, to fragment buffered layer)
3. TreeCanopyAreaID
4. OriginalCanopyPatchID (Original habitat classified by connected area)

*Mid-storey habitat*

AllMidstorey_2mBuffDiss
EdgeRoadRail10m_7.5mBuffDiss
2. AllMidstorey_50mBuff_BARRIERRemove
3. AllMidstorey_50mBuff_BARRIERRemove_AreaID
4. OriginalMidstorey_PatchID

*Understorey habitat*

AllUnderstorey
EdgeRoadRail10m_7.5mBuffDiss
1. AllUnderstorey_50mBuffDiss
2. AllUnderstorey_50mBuff_BARRIERRemove
3. AllUnderstorey_50mBuff_BARRIERRemove_AreaID
4. OriginalUnderstorey_PatchID

*All vegetation types*

AllVegetation
EdgeRoadRail10m_7.5mBuffDiss
1. AllVeg_50mbuffdiss
1. AllVeg_2. AllVeg_50mbuffdiss_barrierRem
3. AllVeg_50mbuffdiss_barrierRem_AreaID
4. OriginalAllVeg_PatchID

*Functional connectivity*

*Amphibians*

AllAmphibHabitat_WaterFeatures_Vegetation10mFromWater
AllAmphibBarriers_5mRoadRail_AllBuildings
1. AmphibHabitat_500mBuffDiss
2_AmphibHabitat_500mBuff_BarriersRem
3_AmphibHabitat_500mBuff_BarriersRem_AreaID
4_OriginalAmphibHabitat_PatchID

Aquatic insects
AllAquaticInsHabitat_Water_Veg500mFromWater
EdgeRoadRail10m_7.5mBuffDiss (Barrier layer)
1_AquaticInsHabitat_750mBuffDiss
2_AquaticInsHabitat_750mBuff_BarriersRemoved
3_AquaticInsHabitat_750mBuff_BarriersRemoved_AreaID
4_OriginallAquaticInsHabitat_PatchID

Insect pollinators
AllPollinatorHabitat_TreesMidUnderstoreyNearTrees
EdgeRoadRail10m_7.5mBuffDiss
1_PollinatorHabitat_175mBuffDiss
2_PollinatorHabitat_175mBuff_BarrierRem
3_PollinatorHabitat_175mBuff_BarrierRem_AreaID
4_OriginalPollinatorHabitat_PatchID

Reptiles
ReptileHabitat_MidstoreyUnderstorey
AllReptileBarriers_5mRoadRail_AllBuildings
1_ReptileHabitat_500mBuffDiss
3_ReptileHabitat_500mBuffDiss_BarrierRem_AreaID
4_OriginalReptileHabitat_PatchID

Tree-hollow using bats
AllTreeHollowBatHabitat_TreeCanopyAndHollows
AllTreeHollowBatBarriers_15mRoadRail_10mBuilding
1_BatHabitat_500mBuffDiss
2_BatHabitat_500mBuff_BarrierRemoved
3_BatHabitat_500mBuff_BarrierRemoved_AreaID
4_OriginalBatHabitat_PatchID
Tree-hollow using birds

AllTreeHollowBirdHabitat_TreesHollowsUnderstoreyNearby
AllTreeHollowBirdBarriers_15mRoadRail_10mBuilding
1_TreeHollowBirdHabitat_250BuffDiss
2_TreeHollowBirdHabitat_250Buff_BarrierRem
3_TreeHollowBirdHabitat_250Buff_BarrierRem_AreaID
4_OriginalTreeHollowBirdHabitat_PatchID

Woodland birds

Understorey_10mFromCover (Understorey vegetation less than 10m from trees)
AllWoodbirdHabitat_TreeMidUnder
AllWoodbirdBarriers_15mRoadRail_10mBuilding
1_WoodbirdHabitat_750BuffDiss
2_WoodbirdHabitat_750Buff_BarrierRem
3_WoodbirdHabitat_750Buff_BarrierRem_AreaID
4_OrginalWoodbirdHabitat_PatchID

Scenario 1 – Road development

RoadDevelopmentFootprint (Shape of the new road development)

Woodland birds

1_WoodbirdHabitat_750Buff_BarrierRem (Buffered layer from functional connectivity above)
2_Woodbird_750Buff_NewBarriersRemoved (Additional road barriers removed)
3_Woodbird_750Buff_NewBarriersRemoved_AreaID (Connected areas reclassified)
4_OriginalWoodbird_ClassifiedByNewConnectedArea (Habitat patched reclassified)

Amphibians

Amphibian_500mBuff_NewRoadRemoved_AreaID
OriginalAmphib_ClassifiedByNewConnectedArea

Aquatic insects

AquaticInsect_750Buff_NewRoadRemoved_AreaID
OriginalDragonfly_ClassifiedByNewConnectedArea
Insect pollinators
Pollinator 175mBuff_NewRoadRemoved_AreaID
OriginalPollinator_ClassifiedByNewConnectedArea

Reptiles
Reptile_500mBuff_NewRoadRemoved_AreaID
OriginalReptile_ClassifiedByNewConnectedArea

Tree canopy
TreeCanopy_50mBuff_NewRoadRemoved_AreaID
OriginalTreeCanopyHabitat_ClassifiedByNewConnectedArea

Tree-hollow using bats
TreeHollowBat_500mBuff_NewRoadRemoved_AreaID
OriginalBat_ClassifiedByNewConnectedArea

Tree-hollow using birds
TreeHollowBird_NewRoadRemoved_AreaID
OriginalTreeHollowBird_ClassifiedByNewConnectedArea

Scenario 2 – Biodiversity corridor
BiodiversityCorridor (Shape outline for all proposed biodiversity corridors in each precinct)

Aquatic insects
Aqu insect_ViableBioCorridors (Biodiversity corridors near water)
NewAquInsectHabitat (Add viable biodiversity corridors to original habitat)
1_NewAquInsect_750mBuff (Buffer by 750 m)
2_NewAquInsect_750mBuff_AddBioCorr_AreaID (Identify the new connected areas)
3_NewAquInsectHabitat_PatchID (Classify habitat patches by connected area)

Insect pollinators
Pollinator_175mBuff__AddBioCorr_AreaID
NewPollinatorHabitat_PatchID

Reptiles
Reptile_500mBuff_AddBioCorr_AreaID
NewReptileHabitat_PatchID
Tree-hollow using bats
TreeHollowBat_500mBuff_AddBioCorr_AreaID
NewTreeHollowBatHabitat_PatchID

Tree-hollow using birds
TreeHollowBird_250mBuff_AddBioCorr_AreaID
NewTreeHollowBirdHabitat_PatchID

Woodland birds
Woodbird_750mBuff_AddBioCorr_AreaID
NewWoodbirdHabitat_PatchID