Evaluating connectivity and ecological linkages between Perth's protected areas to support biodiversity

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Declaration

I declare this thesis is my own account of my research and contains as its main content, work which has not been previously submitted for a degree at any tertiary education institution.

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Abstract

While protected areas in urban environments provide island refuges for species survival within a hostile urban matrix, linkages between them are necessary to sustain biodiversity. This is especially important for cities such as Perth situated in Western Australia's global 'biodiversity hotspot', where there is high species richness with many now endangered. This research estimated the degree of connectivity for 'formal' and 'semi-formal' protected area networks of the Perth and Peel region of WA. Four metrics providing alternative patch and landscape level perspectives were used to estimate and validate the degree of connectivity. Least-cost path modelling was then used to identify effective placement of ecological linkages for species of different dispersal capabilities, testing a range of ecological distance thresholds (EDT) between 50-1500m. Connectivity between protected areas within the region was low. For example, connectivity for species with an EDT of 1500m, such as the threatened *Calyptorhynchus latirostris*, was at ~0.0005 (range 0-1) for formally protected areas, increasing to 0.0016 when 'semi-formal' areas were included, and much lower for lower EDTs. The importance of 'semi-formal' areas (especially Bush Forever sites) in connectivity was further highlighted with the number of isolated protected areas dropping from 50% to 25% at 50m EDT and the number of protected areas within the largest linked network increasing from ~25% to ~80% at 1000m EDT, when they were included. This lack of connectivity highlights the need of biodiversity conservation planning decisions to be based on ecological information that enhances species movement. The least-cost path modelling identified routes of potential ecological linkages between protected areas through the urban matrix. Analysis of these detailed maps highlighted a suite of strategies to enhance connectivity, including where to break barriers to movement, enhance green spaces, and provide protection for native vegetation. This provides a resource to enable land managers and planners to make appropriate biodiversity conservation actions.

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List of abbreviations and acronyms

BC	Betweenness Centrality
DBCA	Department of Biodiversity, Conservations and Attractions
dIIC	delta Integral Index of Connectivity
DPLH	Department of Planning, Lands and Heritage
EDT	Ecological Distance Threshold
IIC	Integral Index of Connectivity
IUCN	International Union for Conservation of Nature
LCP	Least-cost path
MPR	Metropolitan Planning Region
SC	Size of Components

Glossary of terms

BC	A metric which measures how central a patch (protected area) is within in the landscape based on the number of shortest paths passing through the patch
Component	A set of patches (protected areas) that are linked to each other at a set distance
Connectivity	The degree to which the landscape enables or hinders species movements
dIIC	A metric which measures the loss in connectivity within the landscape when an individual patch (protected area) is removed
EDT	A set distance at which a species is able to disperse within
IIC	A connectivity metric which estimates connectivity both within and between patches (protected areas)
LCP	A linkage between two protected areas which is least hostile for species to disperse based on the landscape features
Patch	A general term referring to vegetated habitat

1. Introduction

Cities are typically built in areas of high biodiversity because the factors which influence soil productivity and water resources which attract humans also support many other species (Grimm et al. 2008; Miller and Hobbs 2002; Ives et al.2016). More than half of the Earth's living species occur in 'biodiversity hotspots', covering a mere 2.3% of the surface of the planet. These areas have been internationally recognised not only for their high quantities of endemic species but also for the rate at which these species are becoming extinct (Mittermeier et al. 2011). Globally, there are 36 acknowledged 'biodiversity hotspots,' all of which contain urban landscapes, with 146 cities situated within or adjacent to these hotspots (such as Chicago, New York City, Mexico City, Brussels, Frankfurt, Cape Town, and Perth (Cincotta et al. 2000; Mittermeier et al. 2011)).

The city that forms the focus of this study is Perth, the state capital of Western Australia, which falls within the Perth and Peel region. Not only is Perth situated within the Western Australian 'global biodiversity hotspot', it occurs in the portion of the hotspot containing the greatest species densities (Gioia and Hopper 2017). Due to anthropogenic practices this urban area now has 372 flora species and 159 fauna species at priority status for conservation (Department of Biodiversity, Conservation and Attractions 2018a; Department of Biodiversity, Conservation and Attractions 2019a).

The need for conserving habitat within an urban environment is particularly pronounced when the range of a species is completely encapsulated within an urban matrix. Soanes and Lentini (2019) identified 39 threatened species in Australia whose whole distribution is now entirely restricted to urban areas, seven of which occur within Perth and Peel region. Without adequate conservation planning within urban areas, the threat of extinction is high (Soanes and Lentini 2019). Research in urban areas for biodiversity conservation is still an emerging area; hitherto urban environments were considered ‘worthless’ for biodiversity (Soanes and Lentini 2019; Miller and Hobbs 2002). This mindset has led to a focus on conservation within natural or rural areas (Soanes and Lentini 2019; McKinney 2008). Environmental legislation and policies within Australia like in other jurisdictions also prioritise biodiversity conservation within intact natural areas over human modified or disturbed environments (Natural Resource Management Ministerial Council 2010). However, given the rapid rate of urbanisation globally, it is essential to consider conservation in these settings as the extent of natural and rural areas is insufficient to meet the goal of protecting biodiversity.

Perhaps it is not surprising that urbanisation, which clears native species habitat, is a significant threat to biodiversity in global hotspots. Urban development can restrict species to remnant patches of undeveloped land. With increasing urbanisation, the size of these remnants decreases, the distance between them increases, and the urban matrix between them can become increasingly hostile for species seeking to move between remnants (Fahrig 2003; Shochat et al. 2006). Habitat linkages are then necessary to sustain biodiversity in urban environments, as without them organisms cannot move across the landscape, inhibiting dispersal, recolonization, breeding and foraging (Cushman and Lewis 2010; Stephans et al. 2007; Clobert 2012; Dingle 2014), which may ultimately lead to species extinctions. Incorporating applicable connectivity measures in adaptive urban planning are essential for enhancing connectivity and biodiversity. A common strategy to conserve biodiversity is the creation of protected areas, but is this strategy sufficient, particularly when these vegetated remnants become isolated in a hostile urban matrix? We need to consider the permeability of the urban landscape and the degree of connectivity between habitats if we are to conserve biodiversity into the future.

Urban green spaces provide important refuges for biodiversity between protected areas; they encompass a range of habitat types such as native remnant vegetation, wetlands, gardens, verges, parks, and urban waste lands (Threlfall et al. 2017). Native vegetation within these green spaces plays an important role in providing resources for local fauna (Threlfall et al. 2017). The reintroduction, restoration, and maintenance of native vegetation within these urban green spaces aids local species survival. A connected network that allows species movement between areas can be established to improve native species resilience within urban green spaces (Threlfall et al. 2017; LaPoint et al. 2015). However, feral species can also take advantage of these networks (Harris et al. 2010), thereby management need appropriate feral species controls in place with connectivity for improved biodiversity conservation.

To sustain these beneficial natural areas we need to protect them to ensure their capacity to support future generations. If the urban landscape incorporates biodiverse green spaces then strong connectivity between native habitats is possible. This also benefits people within the city who will have greater and more equitable access to nature and the associated benefits. Green spaces have economic and social benefits, provide ecosystem services such as storing carbon, improving air and water quality, reducing urban heat island effects (and with it energy costs), increasing property values, improving human mental and physical health, and providing a sense of place (Davies et al. 2013; Sanders 1986; Susca et al. 2011; Kadish and Netusil 2012; Sandifer et al. 2015). Natural areas also have multiple benefits for children's development that include reducing stress, improving self-discipline, reducing attention deficit disorder, improving eyesight, strengthening immune systems, and promoting empathy, whilst also providing a social platform that encourages an overall healthier lifestyle (Taylor et al. 2001; Rose et al. 2008; Bento and Dias 2017; Chawla 2015).

If we are to conserve biodiversity, planners and managers need to integrate, maintain, and manage natural areas in order to improve ecosystem resilience, prevent extinctions, embed nature in urban environments, and connect people to nature as outlined under the Aichi Biodiversity Targets (Department of Agriculture, Water and the Environment 2020). One way of meeting these targets is to endow natural urban areas with formal protection and to create ecological linkages between urban areas in order to improve their resilience. However, meeting both social demands and environmental needs is a complex task that requires planners to turn to the scientific community for tools and methods to facilitate this (La Point et al. 2015). Without adequately informed urban planning, unfettered urbanisation will continue to remove natural habitat whilst leaving smaller, disconnected patches incapable of supporting biodiversity (Kong et al. 2010).

Aims

This study evaluates the connectivity and effective placement of ecological linkages between urban protected areas in order to aid urban planners in the Perth and Peel region to halt or reverse the rapid biodiversity loss consequent to current urbanisation practices. This thesis will review past frameworks which focussed on integrating linkages within the Perth and Peel region and investigate the following:

1. The current degree of connectivity between protected areas (wetlands and bushlands) in the Perth and Peel region; and
2. The most effective placement of ecological linkages to create a connectivity network within the Perth and Peel region. The effective placement of ecological linkages will be considered from both urban planning and ecological perspectives by
    a. Using least-cost modelling between protected areas to develop a network of ecological linkages informed by landscape ecology; and
    b. Comparing the findings of previous studies on ecological linkages in the Perth and Peel region and the least-cost path modelling.

Finally, this thesis will draw on the results from the above to make recommendations on where to integrate effective and efficient linkages to aid planning and management in biodiversity conservation.

2. Perth and Peel: The study area and past frameworks

2.1 Study area

South-west Australia is one of 36 ‘biodiversity hotspots’ around the world and is internationally recognised not only for the incredible richness of its species but also for the rate at which they are going extinct (Myers 2000). This hotspot is home to 5,571 species of plants, 57 species of mammals, 285 species of birds, 177 species of reptiles, and 33 species of amphibians, with many of these species being endemic to the area (Mittermeier et al. 2004). The Perth and Peel region covers over 8,000 km^2 of this ecoregion and encompasses Australia’s fourth largest city, Perth. The Perth and Peel region is not only situated within a ‘biodiversity hotspot’, but its species-richness makes it one of the most biologically diverse urban areas in the world (Gioia and

Hopper 2017). The Kings Park Bushland, for example, which occupies 2.7 km^2 in the centre of Perth, hosts a large number of species including: 324 plant species, 385 fungal species, five mollusc species, 563 insect species, 92 bird species, six mammal species, and 27 reptile species (Friends of Kings Park 2019).

The region's vast diversity and high degree of endemism have been generated over millions of years in a landscape without volcanic or glacial disturbances (McArthur and Bettenay 1960); this stability has allowed species to adapt to the abiotic stresses of the region, which include an active fire regime, a Mediterranean climate, and nutrient poor soils (Powell et al. 1990).

The Perth and Peel region can be geologically divided into two main groups: the Swan Coastal Plain and the Darling Scarp, both of which comprise multiple micro-habitats. Located to the west, the Swan Coastal Plain is inclusive of soft sedimentary successional rock and is made up of three dune systems which are the consequence of oceanic deposits. The dunes form a flat plain comprising of vegetation types such as heathlands, *Banksia* woodlands, and wetlands. To the east lies the Darling Scarp, which is 1.2 billion years old and features hills of metamorphic and igneous rock covered with eucalyptus woodlands (Figure 1) (Gozzard 2007).

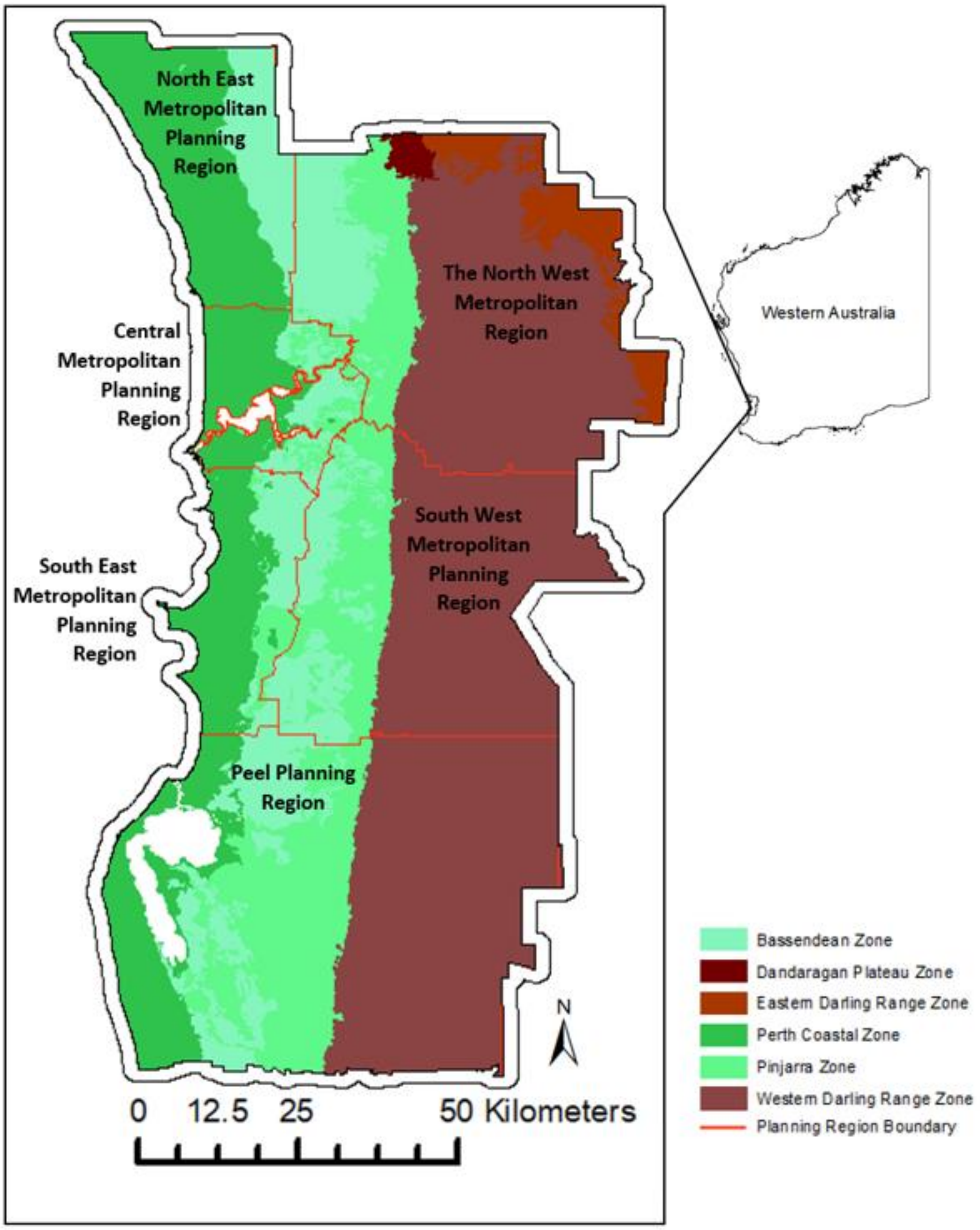

Figure 1. The Perth and Peel region within Western Australia (study area), illustrating the planning regions used by the Department of Planning Lands and Heritage (2018) and the different geographic regions present. The Swan Coastal Plain is highlighted in greens and the Darling Scarp in browns.

Since European settlement, the population of Perth has grown to over 2 million people and is expected to reach to 3.5 million by 2050 (Department of Planning, Lands, and Heritage 2018). The footprint of the city has increased accordingly and now spans 150 kilometres along the Western Australian coast (Kennewell and Shaw 2008) (Figure 2). This rapid urban growth is linked to habitat destruction and species endangerment. Green spaces within the region have been set aside and given protection as per the Environmental Protection Act 1986 in order to preserve them for future generations (Stenhouse 2004; Davis et al. 2013; Western Australian Government 1986). However, many areas that have been endowed with protection are smaller than 0.5 km^2 (Stenhouse 2005). Such small areas may not have sufficient resources to support local species populations within this biodiversity-rich region (Fahrig 2003; Martensen et al. 2008). Ramalho et al. (2014) found these small, isolated remnant areas indirect effects of urbanisation negatively impacted species richness and abundance over time, and Ramalho et al. (2018) found that small and medium remnant areas are prone to a "functional extinction debt". Adaptive planning which facilitates species movement between these protected areas is therefore necessary to maintain a healthy and diverse urban environment (Davis et al. 2013; Stenhouse 2004; Ramalho et al 2018). The incorporation of ecological linkages that connect these biodiverse areas within planning has been a growing but not necessarily common practice within the region (Figure 3).

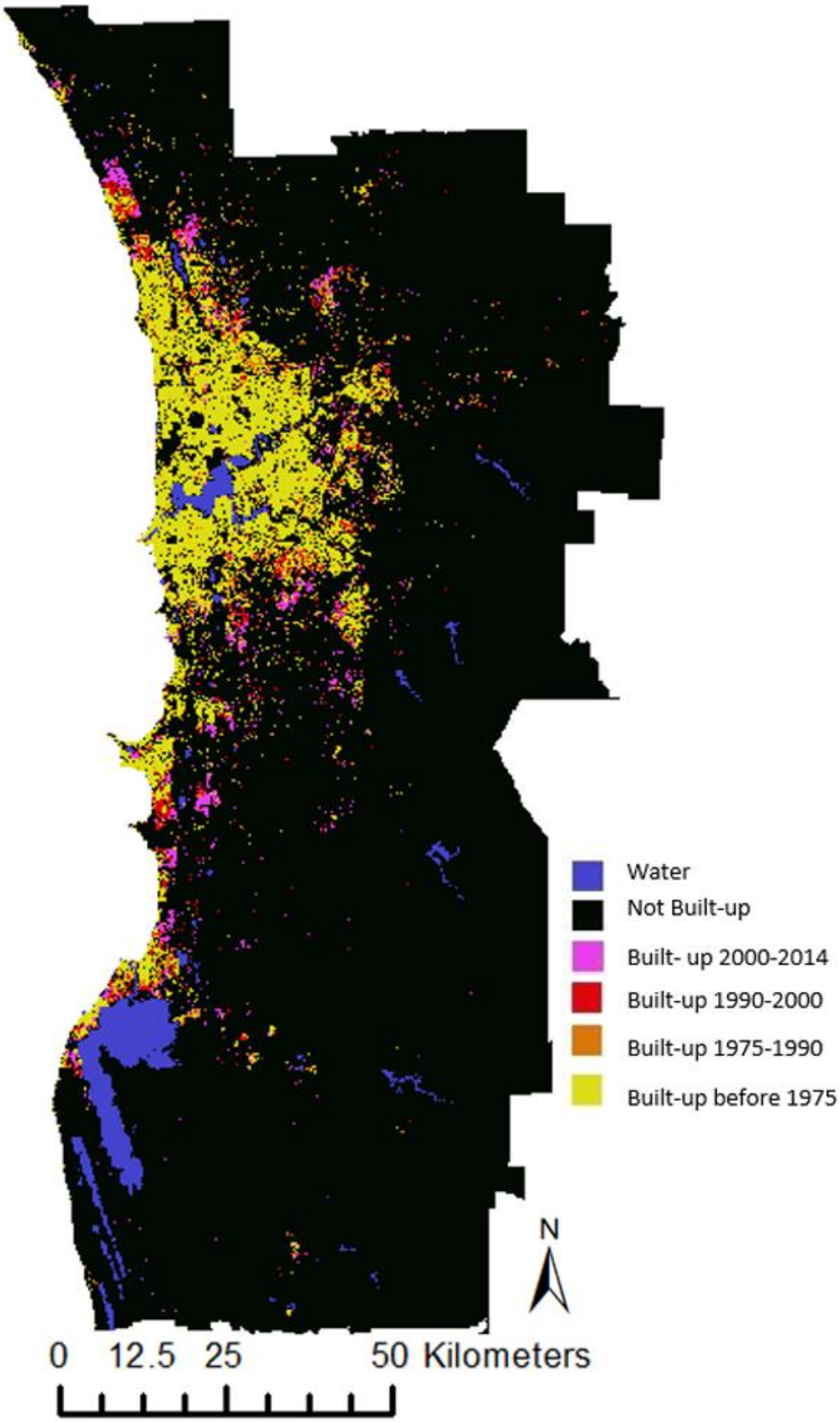

Figure 2. The areas within the Perth and Peel region which have been built upon for urban infrastructure, and the time frames of their development. The yellow highlighted areas represent areas which were developed before 1975, while the pink, red, and orange highlighted areas represent areas which were developed after 1975. The blue highlighted areas represent water bodies. The black highlighted areas represent land which has not been developed (Florczyk et al. 2019).

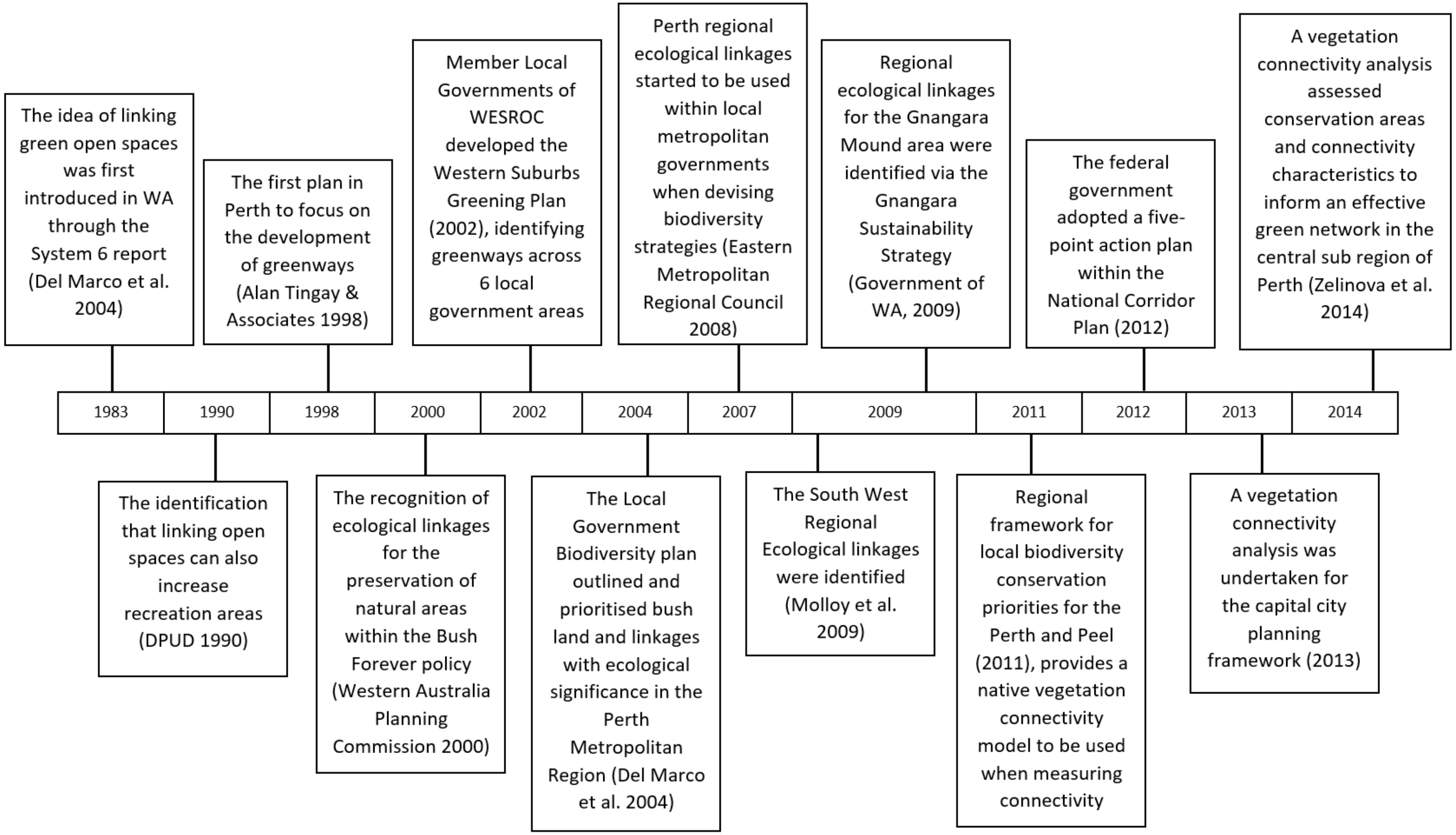

Figure 3. Timeline of the frameworks and plans that have structured ecological linkage planning within Perth and Peel region (no further studies on connectivity across the Perth and Peel were published since 2014).

2.2 The frameworks and concepts of creating ecological linkages within the Perth and Peel region

It is evident that much work has already been produced to create ecological linkages within different areas of the Perth and Peel region. Since 1983, the design and structure of these linkages have evolved to increase their viability for supporting biodiversity (Figure 3). Early frameworks introduced the concept of 'green belts,' which are open areas that link green spaces and limit development (Del Marco et al. 2004). These concepts are good for potentially preserving green areas throughout the urban landscape, however when used primarily for recreation, as they are within the Metroplan (DPUD 1990), these greenbelts may be ecologically simplistic and have limited conservation benefits. Nevertheless, these early frameworks did plant the idea of green infrastructure throughout the city. The first plan to concentrate on developing greenways in Perth was established in 1998, defining these as *"networks of land containing linear elements that are planned, designed and managed for multiple purposes including ecological, cultural, recreational, aesthetic, or other purposes compatible with the concept of sustainable land use"* (Alan Tingay and Associates 1998).

The greenway plan was the first framework that focussed on making potential linkages a concept acceptable to stakeholders. The plan identified sixteen regional parks, seven national parks, and other remnant vegetation within the Perth region which would benefit from ecological linkages (Alan Tingay and Associates 1998). The plan also strove to engage government bodies in recognising the importance of ecological linkages (Alan Tingay and Associates 1998), and in 2000 a whole of government policy called Bush Forever was developed (Western Australia Planning Commission 2000).

The Bush Forever initiative recognised the need for protecting significant vegetation across the Perth region and identified 287 sites representing all the different ecological communities across Perth to help protect local biodiversity. Some of these sites, such as the Canning River, Brixton Street Wetlands, and vegetation at the Perth Airport, were already acknowledged within the Perth Greenway plan (Western Australia Planning Commission 2000). To ensure the viability of greenways for supporting ecological communities for future generations, the Bush Forever policy also recognised the importance of the introduction of greenways into land use planning and supported the recognition of local greenways between natural areas (Western Australia Planning Commission 2000). However, many of the Bush Forever sites are privately owned and are therefore susceptible to clearing. Uptake of this land by the state government in order to provide protection for Bush Forever sites was supposed to be completed by 2010, however sites still remain privately-owned some ten years hence.

Members of the Western Suburbs Regional Organisation of Councils were the first local governments to adopt a systematic and structured plan to integrate linkages over multiple local governments (Ecoscape and Western Suburbs Regional Organisation of Councils 2002). The 2002 Greening Plan classified three vegetation groups: high (bushland), medium (parkland/ golf courses), and low (ovals). This plan also identified greenways to connect these vegetated areas. Greenways were designed to pass through areas that presented green verges, parks, and schools, while recognising that these areas had to be wide enough to minimise edge effects (Ecoscape and Western Suburbs Regional Organisation of Councils 2002). This notwithstanding, several more years passed before guidelines were formed that would aid all local governments in developing their own strategies for biodiversity conservation (Del Marco et al. 2004).

The Local Government Biodiversity Planning Guidelines for the Perth Metropolitan region were formed in 2004 and marked a big step toward the standardisation of biodiversity management (Del Marco et al. 2004). The plan aimed to help local governments maintain a sense of place whilst also meeting regional level biodiversity targets. The framework of the plan outlined the importance of connections between natural areas and presented the first map of regional ecological linkages across the entire Perth region (Del Marco et al. 2004).

As part of the 2004 guidelines, the Perth Metropolitan Regional Linkages were designed to protect natural areas of regional significance by identifying and maintaining those habitats which form stepping stones between these natural areas. In order to make them as effective as possible, these linkages were designed to cover a wide range of flora communities and fauna habitats (Del Marco et al. 2004).

The mapped linkages were broadly drawn to signify the direction of the intended link and were buffered to a width of 500 m (Del Marco et al. 2004) (Figure 4). The linkages on the Swan Coastal Plain were based on linkages recognised by Bush Forever (volume 2) and reinterpreted to a scale of 1:20,000 with the use of aerial photography from 2000 and the Perth Bushland data (Del Marco et al. 2004). The Jarrah forest linkages were identified by reviewing information on the regionally significant areas, proposed linkages, and proposed surrounding linkages before being peer reviewed and produced at a scale 1:20,000 (Del Marco et al. 2004). These maps provide local governments knowledge of where potential linkages are within their jurisdiction. However, the idea that linkages within an urban area should be 500 m wide is often unrealistic, as in many cases urban infrastructure dominates and implementing large green strips is not viable.

The urban matrix between linkages was also not strictly accounted for in the design of the Perth Metropolitan Regional Linkages, hindering their ecological relevance, as barriers (such as transport infrastructure) between vegetation can prohibit species movement (Forman and Alexander 1998; Trombulak and Frissell 2000; Shepard et al. 2008). Integrating more permeable elements in the urban matrix’s design between vegetation may be more achievable than a 500 m greenway, while still aiding species movement between habitats. An effective and efficient way to improve connectivity between habitats would be by identifying routes that recognise the landscapes features which are least hostile to local native species, and in turn further enhancing these.

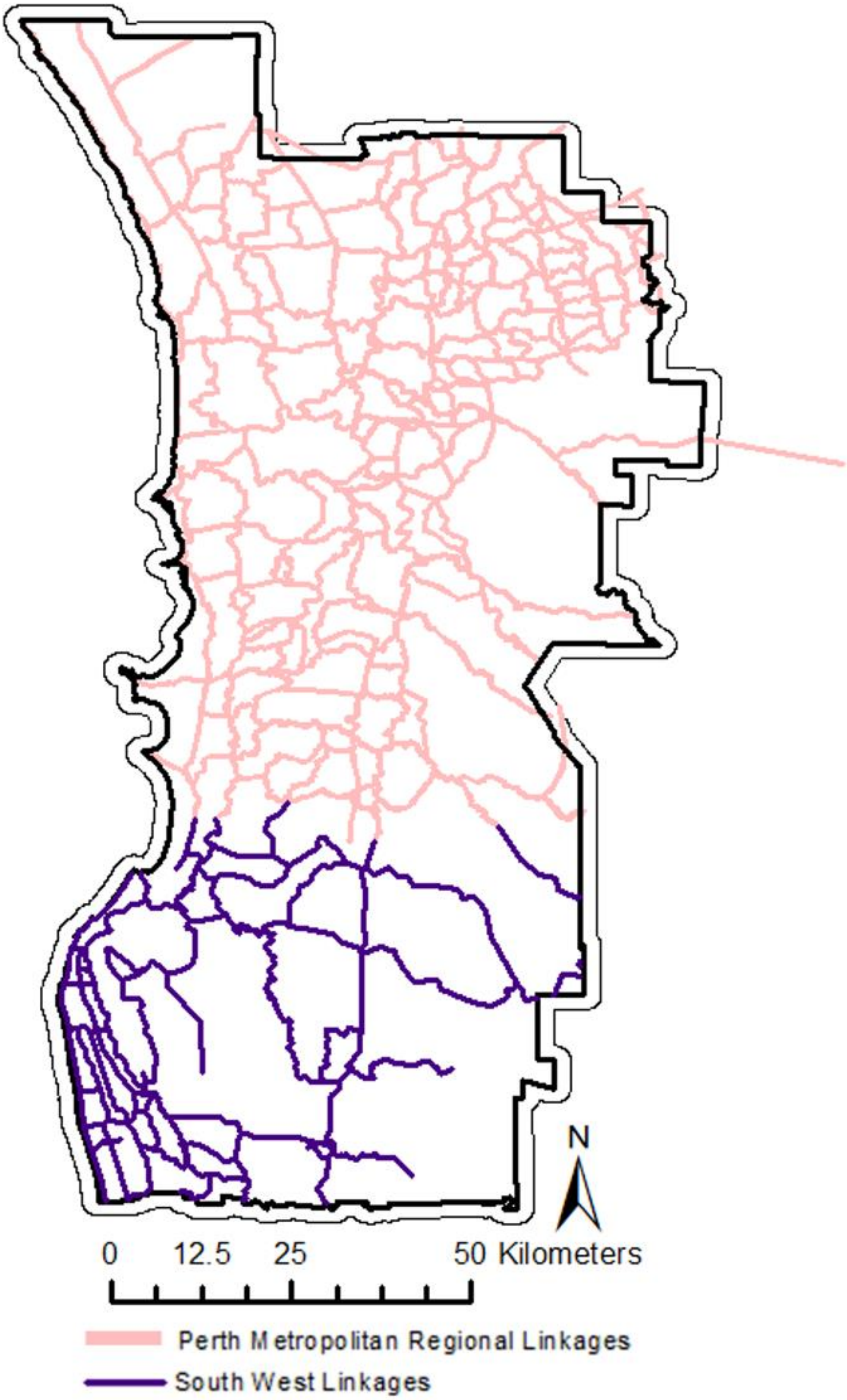

Figure 4.The Perth Metropolitan Regional Linkages in pink as identified by Del Marco et al. (2004), which have helped guide local governments on their biodiversity strategies, with the South West Regional Linkages in purple identified by Molloy et al. (2009).

Since 2007, local governments have devised biodiversity strategies in accordance with the Local Government Biodiversity Guidelines (Eastern Metropolitan Regional Council 2008; Ironbark and Eco Logical Australia 2009). These strategies are designed to help protect and maintain local natural areas that support biodiversity. The Perth Metropolitan Regional Linkages identified in 2004 are incorporated in the strategies to guide local governments on the development of ecological networks (Eastern Metropolitan Regional Council 2008; Ironbark and Eco Logical Australia 2009).

The use of regional linkages as identified in the plan supports biodiversity, with some users building on these regional linkages by recognising local linkages within the individual government area (City of Wanneroo 2018; City of Swan 2015; City of Canning 2018). Most local governments within the Perth and Peel region do have biodiversity strategies, whether comprised individually or in collaboration with other governments (Eastern Metropolitan Regional Council 2008). However, the implementation and maintenance of these linkages has not been publicly documented; a factor which makes it difficult to recognise their success.

In 2009, the South West Regional Ecological (SWRE) linkages were identified by incorporating the guidelines produced by the Perth Biodiversity Project in 2004 (Molloy et al. 2009). These linkages covered the south west region from the Peel Inlet to the south coast (Figure 4) and were recognised for their valuable contribution to maintaining patch viability due to their proximity to other native vegetation; aiding biodiversity planning at the local and regional levels (Molloy et al. 2009). The linkages were developed to minimise the effects of fragmentation and climate change within a biological rich region in which only 22% of the original native vegetation remains (Molloy et al. 2009). But again, these linkages do not strictly consider the urban infrastructure between the vegetated areas which could be hostile for species to move between.

The Gnangara Mound Linkages were also proposed in 2009 when the Western Australian State Government announced that three pine plantations on the mound would be cleared by 2029 and replaced with native woodlands and parklands, with linkages across the mound connecting native vegetation (Brown et al. 2009). These linkages provide a greater network of native vegetation since the area is mainly pine with scattered native vegetation. The design of these linkages was built upon previous studies that identified potential local and regional linkages within the area, such as the Perth Metropolitan Regional Linkages and the City of Wanneroo's local linkages, before undergoing community consultation (Brown et al. 2009) (Figure 5). The planned linkages for the Gnangara mound included more linkages than previously identified in other studies towards the North, thus the north west region of the Perth and Peel region has more potential linkages. Yet, there is limited information on the prioritisation of linkages for management or how hostile these linkages are for species.

Figure 5. Linkages identified over the Gnangara Mound in the north west of Perth including the Perth Metropolitan Regional Linkages, the local government linkages, and the linkages through the pine plantations (Brown et al. 2009).

To help local governments prioritise which linkages to establish, the regional Framework for Local Biodiversity Conservation Priorities was developed in 2011 (Perth Biodiversity Project 2011). This framework provides a starting point for prioritising local habitats based on a set of criteria that evaluates their ecological significance (Level 1 prioritisation) and their potential for retaining native vegetation due to existing land use requirements and prior planning choices (Level 2 and 3 prioritisation (Perth Biodiversity Project 2011)). The framework also presents a method for calculating the viability of connectivity for each remnant vegetation patch.

The metrics for calculating the viability of connectivity include local density (viability) and regional density (vegetation connectivity quality) (Perth Biodiversity Project 2011). Local density assesses connectivity that is around a particular habitat patch rather than the whole network, by determining the variation of habitat area versus non-habitat area within a set buffered distance (Perth Biodiversity Project 2011). Regional density builds on local density but varies in that it assesses connectivity for an entire network by calculating all the habitats that are within the buffer of one another at a set distance (Perth Biodiversity Project 2011). These metrics therefore provide an indication of how fragmented a landscape is since they focus on the abundance of habitat versus non habitat. However, for these metrics to be ecologically sound, the estimated buffer needs to be informed by species movement capabilities. The metrics are also limiting as they assume that species can travel to all habitats within a set distance as they do not take in to account the hostility of the landscape configuration between patches. Nevertheless, this framework provides a starting point for governments to gage the viability of their linkages.

Further support for linkages to improve connectivity came from the Australian federal government when they introduced the National Wildlife Corridors Plan: A Framework for Landscape-scale Conservation in 2012 (Department of Sustainability, Environment Water, Populations and Communities 2012). The framework seeks to generate a long-term plan to restore, maintain, and manage Australia's ecological linkages. The federal government aims to deliver these goals through a 5-point plan (Table 1).

Table 1. The Federal government's 5-point plan for improving connectivity through the National Wildlife Corridors Plan: A Framework for Landscape-scale Conservation (Department of Sustainability, Environment Water, Populations and Communities 2012).

1	*Developing and supporting corridor initiatives*
2	*Establishing enduring institutional arrangements*
3	*Promoting strategic investment in corridors*
4	*Working with key stakeholders and supporting regional natural resource management (NRM) planning*
5	*Monitoring, evaluating and reporting*

The Framework recognises the need for connectivity in highly urbanised landscapes to support ecological community viability of flora and fauna in built-up landscapes, while emphasising that success will depend on co-operation to ensure effective management, planning, and reporting (Department of Sustainability, Environment Water, Populations and Communities 2012). Although this plan strengthens support to produce viable linkages within urban environments, it provides little guidance on how governments can assess and improve the linkages they have.

In 2013, the Capital City Planning Framework was constructed with the vision that '*Central Perth will be a world class liveable central city; green, vibrant, compact, and accessible with a unique sense of place'* (Zelinova and Oh 2013). For the framework to achieve this vision multiple objectives were identified, such as improving the sense of place, enhancing the liveability of the city, improving connections with indigenous heritage, decreasing carbon emissions, and minimising the impact of the city on climate change (Zelinova and Oh 2013). Maintaining and restoring native remnant vegetation while connecting them with ecological linkages will help achieve all the identified objectives.

A study to support this framework was conducted which explored the opportunities for linking natural areas in order to form a connected ecological network (Zelinova and Oh 2013). The study was based on The Regional Framework for Local Biodiversity Conservation Priorities for the Perth and Peel and prioritises regionally significant vegetation by using the local and regional density metrics, albeit with an adaption. This adaption, connectivity reach, is a metric which uses the same methods as the regional connectivity metric; however, instead of calculating connectivity as all the available habitat patch area within a set radius distance, connectivity reach calculates the total habitat patch area that can be reached by traversing a gap no greater than a set distance. This new metric more accurately indicates fragmentation than the local and regional density metrics since it takes into account the actual gap distance between two habitat patches that a species needs to cross and thereby provides a better indication of the habitat network available for a species. This new metric, however, remains ecologically simplistic as it again fails to factor in the hostility of the urban matrix between the habitats. These metrics could be further improved if an indication were provided with regard to how important each patch is for maintaining a connectivity across the landscape. An example of such an indication is the delta Integral Index of Connectivity (IIC), which calculates the loss of connectivity within the landscape when a patch is removed (Pascual-Hortal and Saura 2006 (further described in section 3.1.3)).

The vegetation connectivity analysis delivered in 2014 aimed to provide ecological information for the establishment of an effective network which connects conservation and other natural areas in the Central Metropolitan Planning Region (MPR) (Figure 1) by assessing the present conservation area's connectivity characteristics (Zelinova and Oh 2014). The study was implemented in three main steps. Firstly, the authors identified natural areas of high ecological value by using the three classification levels of prioritisation set out by the Regional Framework for Local Biodiversity Conservation Priorities for the Perth and Peel region. Then, a connectivity analysis of the identified priority habitat patches was applied by using the local (fragmentation) and regional connectivity metrics, which was outlined in The Regional Framework for Local Biodiversity Conservation Priorities for the Perth and Peel region, and by using the logarithm of 'connectivity reach' developed in the Capital City planning framework (Zelinova and Oh 2014). The study then went on to assess the impacts on connectivity due to spatial changes in the landscape by assessing three different scenarios: all known native vegetation (scenario 1), removal of vegetation not in a protected area (scenario 2), and the patches from scenario 2 and the selected open green spaces (scenario 3) (Zelinova and Oh 2014). This study found: less than 10% of the native vegetation remains in the Central Metropolitan Planning Region; the Swan Estuary, Swan River, Canning River, and Conservation Category Wetlands play an important role in providing habitat for local species; 49% of the remaining native vegetation is contained within Bush Forever sites, and finally that all other vegetation remaining within this region represents threatened vegetation complexes.

Much work has been done to create ecological linkages within the different areas of the Perth and Peel region and since 1983 the design and structure of these linkages has continued to develop, thereby increasing their viability for supporting biodiversity (Figure 3). The increased awareness of the importance of ecological linkages for maintaining Perth's biodiversity has led to a growth in frameworks and assessments. Much of this work, however, was done more than 10 years ago and has not yet become common practice. Since the proposed Perth Metropolitan Regional Linkages in 2004 and the South West Linkages in 2009, Perth has further urbanised, and given such changes, these linkages have doubtlessly decreased in efficacy. To ensure that the planners and managers of the Perth and Peel region area are able to make the most informed decisions in support of biodiversity, it is critical that they have up-to-date information which guides the decision-making process. It is therefore paramount that the current connectivity between protected conservation areas is evaluated and estimated and that current effective linkage placement is investigated in order to assist planners and managers support local biodiversity. It is also important that the resources created to aid connectivity decision making can be readily available, cost effective, and easily updated to retain their efficacy for management.

3. Methods

3.1 Investigate the current degree of connectivity between protected areas

3.1.1 Connectivity assessments

Connectivity was assessed between areas of protected remnant vegetation and wetlands within the Perth and Peel region because these sites provide an assurance of their preservation into the future and are considered to be long term refuges of biodiversity. However, since protected areas are subject to different levels of protection for conservation a series of analyses were performed. The first set of analyses was on protected areas termed as 'formal' in this study, due to the clarity in the high level of protection they receive for conservation given by government bodies. These consisted of IUCN Category 1-4 lands; Ramsar Sites; land managed by the Botanical Gardens and Parks Authority; and land managed by the Department of Biodiversity, Conservation and Attraction (DBCA) as a National Park, Nature Reserve, Conservation Park, Conservation Category Wetland, or under the CALM Act Section 5 (1) (g) Reserves.

In other protected areas within the Perth and Peel region, the level of protection for conservation is less clear. In this study, such areas have been termed 'semi-formal' protected areas. These include Regional Parks, Bush Forever sites, and Class 'A' reserves. Regional Parks are large areas recognised for conservation and recreation with multiple stakeholders. A multi-agency approach gives Regional Parks a high level of protection, but the portion of the parks considered as recreation versus conservation is unclear (Dooley and Pilgrim 2009). Bush Forever sites are patches of natural bushland that have been identified as locally significant and in need of protection. The 287 sites covering 51,200 hectares are under a variety of ownership and therefore some sites have more protection than others (Department of Planning Lands and Heritage 2019a; Western Australia Planning Commission 2000). Class 'A' reserves have a higher level of protection compared to Regional Parks and Bush Forever sites, since any changes to a site has to be approved by the WA Minister for Environment and the parliament; these sites are, however, not only for ecological conservation but are also recognised as sites that have high community value and include places such as community centres and recreational areas (Department of Planning Lands and Heritage 2020). Each category of 'semi-formal' protected areas was combined individually with the 'formal' protected areas for analysis, and in a final analysis of 'formal' and all types of 'semi-formal' protected areas together. Analysing each type of 'semi-formal' protected areas separately served to determine their importance in connecting the 'formal' protected areas.

The degree of connectivity between the protected areas is a function of the distance a species can disperse and the placement of the protected areas in the urban landscape. To determine the different distances that species can move (which is termed the ecological distance threshold) a literature review was undertaken for threatened species or species which are important for maintaining ecological communities within the Perth and Peel region. Information about the ecological distance thresholds (EDT) was limited for local species so information was supplemented with studies of similar species within regional WA, nationally, and internationally (Table 2).

Doerr et al. (2011) found that Australian native flora and fauna species had an average EDT of 106 m, although distances did vary between species (Table 2). Seven species had an EDT of less than 50 m, such as insect-dispersed seed from Wandoo trees (*Eucalyptus wandoo)* (Table 2). Eight species, such as the Blue-breasted Fairy-wren

(*Malurus pulcherrimus*), had an EDT of around 100 m, but many birds could disperse for around 300-400 m in open spaces (Table 2). The local endangered species Chuditch (*Dasyurus geoffroii*) could disperse around 500 m between habitats in rural environments, however its dispersal ability in urban environments in unknown. Few species could disperse at distances greater than 500 m, such as Carnaby cockatoos (*Calyptorhynchus latirostris)* travelling up to six kilometres. EDTs also depended on the landscape being crossed with different ecological distance thresholds in rural and urban areas. The Quenda, for example, (Southern brown bandicoot: *Isoodon obesulus obesulus*) could disperse up to around 300 m in rural areas but less than 100 m in urban environments (Table 2). From the information presented in the literature, five EDTs were set for protected area connectivity analyses: 50 m, 100 m, 300 m, 500 m, 1,000 m, and 1,500 m.

Table 2. Ecological distance thresholds (dispersal distances) of species of plants, insects, amphibians, reptiles, mammals, and birds (of local species, or as indicated by comparable species in the literature).

Taxa	Organism	Distance threshold	Urban or Rural	Location	Notes	Author
Plants	*Eucalyptus wandoo* (White gum)	0.6-1.08km	Rural	WA	Dependant on insects (long distance event)	Byrne et al. 2008
	Banksia attenuata (Candle stick Banksia)	0.2-2.6km	Rural	WA	Dependant on winds (long distance event)	He et al. 2009
	Banksia hookeriana (Hooker's Banksia)	29.9m	Rural	WA	Dependant on bird pollination (long distance event)	Krauss et al. 2009
	Banksia hookeriana (Hooker's Banksia)	1.6- 2.5km	Rural	WA	For adjacent populations (long distance event)	He et al. 2004
	Eucalyptus	1-2m	Rural	Perth	per-year	Booth 2017
Insects	*Phyllotreta cruciferae* (Flea beetle)	2m	Rural	International		Kareiva 1985
	Phyllotteta striolata (Flea beetle)	2m	Rural	International		Kareiva 1985
	Tetragonula carbonaria (Stingless bee)	2-200m	Rural	AU		Wallace et al. 2008
	Hylaeus punctulatissimus (Assimulans yellow-faced bee)	100-225m	Rural	International		Zurbunchen et al. 2010
	Hoplitis adunca (Viper's Bugloss Mason Bee)	300m	Rural	International		Zurbunchen et al. 2010
Amphibians	*Arenophryne rotunda* (Leptodactylid frog)	<27.6m	Rural	WA		Tyler et al. 1980
	Anuran	mean 2023.54m	Literature review	Multiple areas	range from 6.68- 35000m	Smith and Green 2005
	Salamanders	mean 576.75m	Literature review	Multiple areas	range from 6.09m -12874.75m	Smith and Green 2005
	Hyla arborea (European Tree Frog)	100m-400m	Rural	International	Depending on road traffic	Pellet et al. 2004
Reptiles	Lizards (geckos, Skinks, dragons, monitors, legless lizards)	Sedentary unless habitats are connected	Rural	WA		Smith et al. 1996
	Pseudemydura umbrina (Western Swamp Tortoise)	movement of 600m across 2 days	Nature reserves in Perth	Perth	Sedentary unless connected	Burbidge et al.2010

	Correlophus sarasinorum (Arboreal gecko)	Farmland complete barrier	Rural	AU		Hansen et al. 2020
Mammals	*Isoodon obesulus obesulus* (Southern brown bandicoot)	<350m	Rural	AU	In any corridor	Paull 1995
	Isoodon obesulus obesulus - female	332m	Rural	AU		Robinson et al. 2018
	Isoodon obesulus obesulus - male	704m	Rural	AU		Robinson et al. 2018
	Isoodon obesulus obesulus - female	65.4m	Urban	Perth		Clunies-Ross and Clark 2011
	Isoodon obesulus obesulus - male	78.9m	Urban	Perth		Clunies-Ross and Clark 2011
	Tarsipes rostratus (honey possum)	30m	Rural	WA	Many individuals moved less than 30m over the study period	Garavanta et al. 2000
	Setonix brachyurus (Quokka)	1km	Rural	WA	Many stayed in their home range with one found to move up to 1km	Hayward et al. 2005
	Dasyurus geoffroii (Chuditch) - female	500m	Rural	WA	Many stayed in their home range	Soderquist and Serena 2000
	Dasyurus geoffroii - male	10km	Rural	WA		Soderquist and Serena 2000
Birds	*Scelorchilus rubecula* (Chocao Tapaculos)	80m	Rural	International	Many reluctant to cross gaps over 60m	Castellón and Sieving 2006
	Many small passerine birds	<100	Rural	WA	Rely heavily on corridors	Saunders and De Rebeira 1991
	Ocyphaps lophotes (Crested Pigeon)	400m	Rural	AU		Watson et al. 2001
	Platycercus elegans (Crimson Rosella)	400m	Rural	AU		Watson et al. 2001
	Platycercus eximius (Eastern Rosella)	300m	Rural	AU		Watson et al. 2001
	Smicrornis brevirostris (Weebill)	400m	Rural	AU		Watson et al. 2001
	Rhipidura leucophrys (Willie Wagtail)	400m	Rural	AU		Watson et al. 2001

Acanthiza chrysorrhoa (Yellow-rumped Thornbill)	400m	Rural	AU		Watson et al. 2001
Acanthiza reguloides (Buff-rumped Thornbill)	500m	Rural	AU		Watson et al. 2001
Malurus cyaneus (Superb Fairy-Wren)	400m	Rural	AU		Watson et al. 2001
Rhipidura albiscapa (Grey Fantail)	400m	Rural	AU		Watson et al. 2001
Daphoenositta chrysoptera (Varied Sittella)	2700m	Rural	AU		Watson et al. 2001
Cormobates leucophaea (White-throated Treecreeper)	400m	Rural	AU		Watson et al. 2001
Pardalotus punctatus (Spotted Pardalote)	400m	Rural	AU		Watson et al. 2001
Sericornis frontalis (White-browed Scrubwren)	300m	Rural	AU		Watson et al. 2001
Acanthiza pusilla (Brown Thornbill)	400m	Rural	AU		Watson et al. 2001
Acanthiza lineata (Stiated Thornbill)	400m	Rural	AU		Watson et al. 2001
Acanthiza nana (Yellow Thornbill)	500m	Rural	AU		Watson et al. 2001
Aphelocephala leucopsis (Southern Whiteface)	2300m	Rural	AU		Watson et al. 2001
Manorina melanocephala (Noisy Miner)	400m	Rural	AU		Watson et al. 2001
Petroica boodang (Scarlet Robin)	1500m	Rural	AU		Watson et al. 2001
Microeca fascinans (Jacky Winter)	400m	Rural	AU		Watson et al. 2001
Colluricincla-harmonica (Grey Shrike-Thrush)	400m	Rural	AU		Watson et al. 2001
Myiagra inquieta (Restless Flycatcher)	400m	Rural	AU		Watson et al. 2001

	Pachycephala rufiventris (Rufous Whistler)	300m	Rural	AU		Watson et al. 2001
	Corcorax melanorhamphos (White-winged Chough)	300m	Rural	AU		Watson et al. 2001
	Taeniopygia bichenovii (Double-barred Finch)	2000m	Rural	AU		Watson et al. 2001
	Neochmia temporalis (Red-browed Finch)	3100m	Rural	AU		Watson et al. 2001
	Stagonopleura guttata (Diamond Firetail)	3000m	Rural	AU		Watson et al. 2001
	Melanodryas cucullata (Hooded Robin)	500m	Rural	AU		Watson et al. 2001
	Pyrrholaemus sagittatus (Speckled Warbler)	400m	Rural	AU		Watson et al. 2001
	Woodland birds	120m	Rural	WA	Estimate of gap tolerance	Brooker 2002
	Pomatostomus superciliosus (White-browed babbler)	400m	Rural	WA		Lynch et al.1995
	Pachycephala rufiventris (Rufous whistler)	450m	Rural	WA		Lynch et al.1995
	Colluricincla-harmonica (Grey shrike-thrush)	150m	Rural	WA		Lynch et al.1995
	Lichenostomus leucotis (White-eared honey eater)	>200m	Rural	WA		Lynch et al.1995
	Pomatostomus superciliosus (White-browed babbler)	270m	Rural	WA		Brooker et al. 1999
	Blue-breasted Fairy-Wren	60m	Rural	WA		Brooker et al. 1999
	Colluricincla-harmonica (Grey Shrike-Thrush)	85m	Rural	AU		Robertson and Radford 2009
	Calyptorhynchus latirostris (Carnaby Cockatoo)	6km	Urban	Perth		The Environmental Protection Authority 2019

3.1.2 Data collection and cleaning

To evaluate the degree of connectivity between protected areas at different ecological distance thresholds, the shapes and locations of protected areas were retrieved from contemporary datasets (within the last three years) in publicly accessible online sources or from the Department of Planning, Lands and Heritage (DPLH) (Table 3). A two-kilometre buffer was added to the Perth and Peel region study area to include connections that might also be used to access protected areas just outside the study area. Thus, all datasets used in this study were acquired for the buffered study area. The projected co-ordinate system used for all datasets in the analysis performed was UTM zone 50s; the use of this reference system minimised distortions to the estimates of areas and the distances between them in the local study area.

To ensure that connectivity was only evaluated for natural habitat within each protected area, the protected area layer was intersected with the native vegetation extent data (Department of Primary Industries and Regional Development 2020, which comprises land with more than 20% natural terrestrial vegetation cover), and the geomorphic wetlands data layer (Department of Biodiversity, Conservation and Attractions 2020 – to include wetland as well as terrestrial natural areas). The geomorphic wetland dataset had to be screened and cleaned so that only natural areas of conservation category wetlands were included within the analyses. Open water areas were also removed from the habitat patches since most land animals cannot live in or cross open water (Tremblay and St Clair 2009; Drucsh 2012; Crossman and Li 2015; Department of Planning, Lands and Heritage 2019b). For this reason, any island habitat in the ocean within the two-kilometre study area buffer was also removed. Protected areas of all sizes were kept for analyses, as small areas can be critical for species movement.

Table 3: The data sets used for the different protected areas within the connectivity analysis

Formal protected areas	Definition	Data set	Data Scale	Protected area classification	Source
IUCN Category 1-4 Lands	"A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (IUCN 2008)	Legislated lands and water DBCA[1]	Not recorded	Formal	DBCA 2019b
National Parks	Protected by federal governments for the preservation of wildlife or human enjoyment	Legislated lands and water DBCA	Not recorded	Formal	DBCA 2019b
Nature Reserve	Land to preserve flora, fauna, and physical features	Legislated lands and water DBCA	Not recorded	Formal	DBCA 2019b
Conservation Parks	Land held by the Crown for conservation purposes	Legislated lands and water DBCA	Not recorded	Formal	DBCA 2019b
Under the CALM Act Section 5 (1) (g) reserves	Land vested in the Conservation and Parks commission that is not a National Park, Nature reserve, or Conservation Park	Legislated lands and water DBCA	Not recorded	Formal	DBCA 2019b
Ramsar sites	Wetlands that have international importance and that are protected under the EPBC act	Ramsar sites DBCA	1:25,000	Formal	DBCA 2017a
Conservation Category wetlands	Wetlands that support a high level of attributes and functions and are of highest priority	Geomorphic Wetlands Swan Coastal Plain DBCA	1:25,000	Formal	DBCA 2020
Botanical Parks Authority	For conservation of biodiversity and Botanic gardens	Legislated lands and water DBCA	Not recorded	Formal	DBCA 2019b
Regional Parks	Large areas recognised for conservation and recreation with multiple stakeholders	Regional Parks DBCA	Not recorded	Semi-formal	DBCA 2017b
Bush Forever	Natural bushland that have been identified as locally significant and requires protection	Owner Bush Forever	Not recorded	Semi-formal	DPLH[2] 2020a
Class A reserve 1	Class A reserves used to protect areas of high conservation or high community values	Legislated lands and water DCBA	Not recorded	Semi-formal	DBCA 2019b
Class A reserve 2	Class A reserves used to protect areas of high conservation or high community values	Crown Reserves	Not recorded	Semi-formal	Landgate 2020a

[1] Department of Biodiversity, Conservation and attractions

[2] Department of Planning, Lands and Heritage

3.1.3 Connectivity analyses

To estimate connectivity between protected areas within the study area, measures derived from the graph theory concept of connectivity were used. Graph theory is a mathematical construct that represents the study landscape by using nodes that characterize the protected areas and edges that correspond to connections (links) between the protected areas at different ecological distance thresholds. These connections were considered to be binary in this study, protected areas were therefore considered connected if they were within the ecological distance threshold chosen and the strength of connections was not considered to vary (Urban and Keitt 2001). Four measures were calculated from the graphs to estimate connectivity: Size of Components (SC), Integral Index of Connectivity (IIC), delta Integral Index of Connectivity (dIIC), and Betweenness Centrality (BC), in order to gain a holistic analysis of the differing characteristics of connectivity, as each metric presents different information (Baranyi et al. 2011; Rayfield et al. 2016).

The SC and IIC both assess overall connectivity for the landscape as a whole. The SC calculates the number of protected areas within each component (a set of protected areas connected to each other at a set EDT). Based on the sizes of all the components within a scenario, two standardised SC values were calculated to summarise the distribution of component sizes: The percent of protected areas that are contained within the single largest component (i.e. the size of the largest connected network of protected areas in the scenario), and the percent of protected areas that are in components with size=1 (i.e. that are completely isolated).

The IIC estimates connectivity both within and between protected areas in the study area. It is calculated from the network of connections between protected areas at set

EDTs, as well as the areas of the protected areas. The IIC therefore recognises that portions of the same protected area are connected to each other and that landscapes with larger protected areas are inherently more connected (Pascual-Hortal and Saura 2006). This measure therefore illustrates whether protected areas are abundant as well as highly connected when compared to measures of pure connectivity such as SC and BC, which are based only on the spatial arrangement of patches and existence of links between them (Freeman 1977). The IIC value ranges between zero and one, where one equates to the whole landscape being occupied by a single large patch of habitat (or in this study protected area habitat) and is therefore completely connected, to zero, where there is no connection between habitat patches (Pascual-Hortal and Saura 2006). The measure is given by the formula:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \cdot a_j}{1 + nl_{ij}}}{A_L^2}$$

(Pascual-Hortal and Saura 2006)

where n = Total number of protected areas,

a_i and a_j = The area of protected areas i and j,

nl_{ij} = The number of links in the shortest routes between protected areas i and j; and

A_L = The area of the total study area.

IIC provides an estimate of connectivity for the total landscape. Measures like dIIC and BC that provide an estimate of connectivity at the patch (each protected area) level complement the high-level perspective of overall estimates of connectivity for the whole landscape by identifying the importance of individual areas to connectivity. The dIIC calculates the loss in connectivity of the landscape – calculated with the IIC – when an individual protected area is removed (Pascual-Hortal and Saura 2006). The measure is expressed as a percentage of the original IIC estimate of overall connectivity; protected areas that are more important for maintaining connectivity therefore have a higher dIIC percentage value. The measure is given by the formula:

$$dIIC\ k = 100 \cdot \frac{I - I'}{I}$$

(Pascual-Hortal and Saura 2006).

where I = The IIC value when all existing patches are present; and

I' = The IIC value after removing patch k.

Because the dIIC measure relies on the IIC for calculating an estimate of connectivity for individual protected areas, it incorporates the size of the protected areas as well as the paths between them. To gain a more traditional estimate of connectivity which only considers the existence of links between the protected areas, Betweenness Centrality (BC) was used. The BC measures the centrality of a protected area within the graph representation of the study area based on the number of shortest paths passing through it (Freeman 1977). A protected area with a high BC is situated within a central position that enables it to form connections to other protected areas. This measure is useful for identifying protected areas that also act as stepping stones in connecting other protected areas and is given by the formula:

$$\mathrm{BC} = \sum_{i<}^{n} \sum_{j}^{n} \mathrm{bij}\ \ (\mathrm{pk})$$

(Freeman 1977)

P_K = A patch used to connect Patch i (i) and Patch j (j);

n = The number of patches within the landscape or graph;

Bij (P_K) = The probability that P_k lies between patch I and j.

Euclidean distance was used to determine whether protected areas were connected at an ecological distance threshold by the shortest distance between them. This parameter does not account for the landscape matrix between patches but only for the actual distance between them; it therefore provides an indication of whether habitats are linked at a distance a species such that can disperse. The Conefor Sensinode 2.6 software package was employed to calculate the connectivity measures chosen above (Saura and Torné 2009).

3.2 Investigate the most effective placement of linkages to create a connectivity network within the Perth and Peel region using least-cost path modelling

Least-cost path modelling (LCP) incorporates the effects of the landscape between protected areas on likely movement routes and is a common technique for identifying appropriate linkages (Teng et al. 2011). This technique is centred around the difficulty of movement through landscape features at each location; it formulates a path from one protected area to another that minimises the stress inflicted on an organism (Adriaensen et al. 2003). LCP modelling requires two GIS data layers: a source layer and a cost layer. The source layer specifies the protected areas that the LCPs must travel between. The cost layer specifies the difficulty of moving through each mapping unit based on the landscape features it contains (Adriaensen et al. 2003).

3.2.1 Source layer construction

‘Formal’ and ‘all’ (i.e. ‘formal’ + ‘semi-formal’ - see section 3.1.1. above) protected areas were used as the source layers for separate LCP models. Having a model with only the ‘formal’ protected areas and one with all the protected areas allows for the evaluation of how the LCPs change depending on the number and locations of protected areas available. The LCP modelling network of linkages is constrained by the locations of the existing protected areas – as a result, gaps in the identified linkages may occur if there are no protected areas in a portion of the study area in the provided source layer. To overcome and to ensure a robust linkage network, a second analysis was performed that augmented the ‘formal’ with the ‘semi-formal’ protected areas.

The protected areas for both analyses were simplified to remove holes and small gaps in or between them at a maximum distance of 50m (the lowest EDT assessed in aim one) using the PatchMorph method outlined by Girvetz and Greco (2007) (Figure 6). The removal of small gaps and holes was considered appropriate because at these small distances protected areas are still ecologically connected, unless the gap is caused by a major barrier dividing protected areas such as freeways. To ensure that freeways (major barrier) were not inappropriately removed by this gap smoothing approach, they were applied as a mask to the smoothed patches. Protected areas under ten hectares were also removed from the modelling because they were determined to be insufficient for maintaining species populations over generations (Ramalho et al. 2014).

Figure 6. The steps taken to remove small holes and gaps between protected areas following the methods developed by Girvetz and Greco (2007). The green lines represent the outlines of the original protected areas, black patches in the left image represent the original protected areas, the white patches in the middle image represent the protected areas with a 25m buffer; the black patches on the right image represent the final, smoothed protected areas following removal of gaps narrower than 50m.

3.2.2 Cost layer construction

The cost layer is an image file that states how much the landscape features enable or inhibit species movement at each pixel in the image (Adriaensen et al. 2003). The cost layer was developed at a 10 m resolution. This fine resolution was used to effectivity capture the fine-scaled heterogeneity of urban areas (Davies et al. 2013). Such a fine scale is necessary to see, for example, whether a house has a garden or not.

The cost values for each landscape element were formulated on how species perceive the environment (Schadt et al. 2002; Ferreras 2001). Lower values represent favoured landscape elements for species movement with increasing values representing elements that impose increased stress and risk to an organism (Adriaensen et al. 2003). Cost values of landscape elements were specified within a range from 1-100, as recommended by Beier et al. (2011), while hard barriers (such as major roads) were given values above 100 (Beier et al. 2011). Cost values can directly influence the length of the resulting path, since the LCP analysis is an optimisation that finds the specific route between two protected areas that minimises the total cost over the entire path. The cost values chosen and their spatial distribution influences the placement of the path as well as its total length. This is because the tolerance of the path to crossing a barrier, or its tendency to detour around the barrier, will depend on how strong the barrier is (i.e. how high its cost value is), the shape of the barrier (e.g. wide barriers would have a high cumulative cost if crossed; small barriers would be easy to go around), and the context of the rest of the landscape the path has to go through (i.e. whether low-cost detours are available in the surroundings).

Landscape elements were divided into three categories: land cover, land use and barriers (Table4) to incorporate their independent effects to movement costs. The land cover category represents the physical features at the ground surface level and includes elements such as vegetation, open bare ground, and open water, with values ranging from one for native remnant vegetation to 100 for water (Table 4). The land use category represents the land's intended purpose and includes features such as protected areas, parks, utility land, primary production land, transport, residential use, industrial use and more. The cost values ranged from one for protected areas to 70 for areas that were intensively used by humans such as industrial and residential areas (Table 4). Utility land was included with a relatively low-cost value of 20 because areas designated for infrastructure such as power lines often have low human traffic and run as long strips throughout a landscape that could potentially link protected areas.

Table 4. A table of the landscape features and their associated cost values for the cost layer given to each element for this study. Land cover and land use layers were averaged together to allow the cost value of each unit to represent a combination of what is present on the ground, and its management. The data layers and processing to prepare the landscape features for the cost layer are described in Table 5.

Layer	Landscape feature	Description	Cost
Land cover			
	Native remnant vegetation	Natural habitat patches for native species	1
	Perennial vegetation	Vegetation species can take advantage of all year round	20
	Annual vegetation	Vegetation which is present seasonally and species can only take advantage for movement seasonally	50
	Urban bare	Bare ground which leave species open to the elements	90
	Open water	Open water a species would have to swim or fly over to cross	100
Land use			
	Protected areas	Native vegetation and wetlands that has a level of protection	1
	Parks and forestry	Land zoned for recreation and forestry	10
	Utilities	Open drainage and transmission powerlines	20
	Rural	Primary Production land	50
	Street block	Residential, industrial, commercial, hospital/medical, education areas	70
	Other	Some transport and other utilities areas	70
Barriers			
	Airport native remnant vegetation	Native remnant vegetation at the airport which is highly affected by noise pollution and fences	20
	Culverts	Tunnels that carry drainage and water	50
	Local roads	Roads managed by local governments designed for local traffic	70
	State roads	Roads managed by state governments designed for large volumes of traffic across multiple jurisdictions	150
	Rail	The Transperth train network and the rail freight corridor, which are less busy than road traffic but have high fences	150
	Airport	Perth and Jandakot airports	150
	Freeway	Roads designed for high speed traffic which are unhindered by intersections.	200
	Open water	Open water a species would have to swim or fly over to cross	200

The barrier category represents landscape elements that restrict or prevent species movement and includes features such as local or state roads, freeways, airports, and open water. Culverts were also included as a barrier because they are part of the road structure, but they were given a lower value since they have been found to aid small- and medium-sized mammal movement (Clevenger et al. 2002) (Table 4). Barrier values ranged from as low as 50 for culverts to as high as 200 for freeways and open water. The values for roads differed depending on the road type since roads such as freeways are wide, have high traffic volumes, and fast speed limits when compared with local roads that are smaller, with lower traffic volumes and lower speed limits (Table 4). When building the cost layer, individual layers were first prepared for each landscape feature listed (see section 3.2.1.3 below). These individual layers assigned the specified cost value (Table 4) to pixels containing the feature of interest, and a background value to all other pixels. They were synthesized into an intermediate cost layer for each category, with the land cover features being compiled first. The final land cover cost layer was assembled by overlaying all of the individual ones in the order (bottom to top) of open water, bare ground, annual vegetation, perennial vegetation, native remnant vegetation, where the final pixel value was determined to be the top-most non-background value in the stacked layers. The land use features which included protected areas, parks and forestry, utility areas, rural land, built-up land, and other infrastructure were constructed the same way as the land cover image, but in the order of other infrastructure, built-up land, rural land, utility areas, parks and forestry, with protected areas on top. The land cover cost image and the land use cost image were overlayed and averaged to form a single layer. Averaging the cost values allows landscape features with the same land use but different land cover to have different associated cost values, and vice versa. For example, residential areas with no vegetation will have higher cost values than residential areas that have perennial vegetation, and remnant vegetation in protected areas will have lower cost than remnant vegetation in residential areas, given the different management they are likely to experience.

The barrier layer was applied separately, with the barriers overlayed and stacked in order of open water, local roads, state roads, freeways, railways, airports, and culverts on top. Unlike the land cover and land use layers, the barrier layer does not cover the entire study area and only represents where barriers are present; background pixels thus have 0 cost due to barriers in this intermediate cost layer. The barrier image was then laid on top of the averaged land use and land cover image, and the final unit values for the combined cost layer was the top-most non-background value. The values in the final cost layer were therefore those for the barriers and land cover/land use layer in pixels with no barrier.

3.2.3 Data collection and cleaning

To construct the LCP layers, contemporary data sets within the last three years were retrieved from the Department of Planning, Lands, and Heritage and from publicly-accessible online sources (Table 5). All land cover classes except for native vegetation were mapped from two dates of satellite image data: 29 September 2020 (spring) and 1 January 2020 (summer; dates within the seasons were picked based on clarity of images owing to no cloud cover) acquired by the Sentinel-2b satellite sensor (Drusch et al. 2012). Two images from different seasons were used to determine where annual and perennial vegetation existed within the landscape since annual vegetation tends to flourish in spring and die off in summer (Powell et al. 1990); vegetation present in spring but not in summer was classified as annual while the vegetation present in both dates was classified as perennial. The normalised difference vegetation index (NDVI, which estimates vegetation density based on the near infrared and red reflectance bands) was calculated for both dates. NDVI values of 0.3 and over were considered as vegetation and less than 0.3 were bare ground or water. The 0.3 threshold was determined by screening the NDVI images. The data set native vegetation extent was used to determine where native vegetation existed (Department of Primary Industries and Regional Development 2019). The identified open water came from two datasets: the surface hydrology polygon data set (Crossman and Li 2015) and polygons with the water attribute from the urban forest parcels data set (Department of Planning, Lands, and Heritage 2019). These two datasets were combined to create a single polygon layer which containing waterbodies identified in either data set, with their original attributes, and screened to remove any water that is now developed land or fields. The water polygons in these datasets covered fringing vegetation which would be expected to have a low cost for species movement compared to water. The water polygons were therefore updated to exclude fringing vegetation interpreted from the Sentinel-2 image data.

Table 5. Data used to form the cost raster for the least-cost path modelling.

Feature/element	Definition	Data set / sets	Scale	Source
Native remnant vegetation	Patches of native flora which covers more than 20% of an area	Native vegetation extent	1:20,000	DPIRD[1] 2019
Perennial vegetation	Vegetation that exists all year round calculated using NDVI[2]	Sentinel 2b 7/01/2020	10m resolution	Drusch et al. 2012
Annual vegetation	Seasonal vegetation calculated using NDVI	Sentinel 2b 29/09/2019	10m resolution	Drusch et al 2012
Urban ground	Bare ground or urban infrastructure	Sentinel 2b 7/01/2020	10m resolution	Drusch et al. 2012
		Sentinel 2b 29/09/2019	10m resolution	Drusch et al. 2012
Open water	Long-term surface water	Sentinel 2b 7/01/2020	10m resolution	Drusch et al 2012
		Surface Hydrology Polygon	1:250,000	Crossman and Li 2015
		Urban Forest Parcels	Not recorded	DPLH[3] 2019b
Protected areas	From aim 1 table 2			
Parks and forestry	An open vegetated area used for recreation	Urban Forest Parcels	Not recorded	DPLH 2019b
	Large areas covered in trees and undergrowth	Forest Management Plan	1:500,000	DBCA[4] 2018b
Utilities	Land for overhead power lines	Restricted zones	Not recorded	Western Power 2020
	Drain waterways with no pumps or pressure systems connected	Open drainage water channel	Not recorded	WaterCorp 2019
Rural	Primary production land	Urban Forest Parcels	Not recorded	DPLH 2019b
Street block	Residential, commercial, industrial, hospital/medical, education, and some agricultural and transport	Urban Forest Parcels	Not recorded	DPLH 2019b
Other	Rail, airport, and some utility infrastructure	Urban Forest Parcels	Not recorded	DPLH 2019b
Culverts	Drains or pipes that are designed for water to run under roads	Culverts	Not recorded	Main Roads WA 2017
Local roads	Roads owned by local government	Road network	Not recorded	Main Roads WA 2018
		Urban Forest Parcels	Not recorded	DPLH 2019b
State roads	Roads owned by state government	Road network	Not recorded	Main Roads WA 2018
		Urban Forest Parcels	Not recorded	DPLH 2019b
Freeway	Large roads owned by state governments with no intersections	Road network	Not recorded	Main Roads WA 2018
		Urban Forest Parcels	Not recorded	DPLH 2019b
Rail	Train lines	Public transport routes	Not recorded	Public Transport Authority 2020
		Railway corridor	Not recorded	Landgate 2020b
Airport	Airport land	Leased federal airports	Not recorded	DIRDC[5] 2018

[1] Department of Primary Lands and Heritage [2] Normalised difference vegetation index [3] Department of Planning Lands and Heritage [4] Department of Biodiversity, Conservation and Attractions [5] Department of Infrastructure, Regional Development and Cities

The land use data consisted of multiple datasets (Table 5). The protected areas came from the ‘formal’ protected areas that were described in section 3.1. Parks and forestry area came from the Forest management plan (Department of Biodiversity, Conservation and Attractions 2018) and the parks attribute came from the Urban forest parcels (Department of Planning, Lands and Heritage 2019b). Utility data sets came from Restricted zones (Western Power 2020) and Open drainage data (WaterCorp 2019). The street block information that includes residential, industrial, commercial, hospitals/medical, education areas, some transport, and some agricultural areas came from the Urban forest parcels (Department of Planning, Lands, and Heritage 2019), as well as the rural information that incorporated land for primary production and other infrastructure that incorporates some transport and other utilities.

The barrier data also included multiple data sets (Table 5). Roads were derived from the Road network data (Main Roads WA 2018) and the roads information from the Department of Planning, Lands and Heritage (2019b) Urban forest parcel data. The rail data consists of the Public transport service routes (Public Transport Authority 2020) with the Rail freight network data (Landgate 2020b). The Perth and Jandakot airport information were extracted from the Federal leased airport data (Department of Infrastructure, Regional Development and Cities 2018). Culverts were from Culverts Main Roads WA (2017), and the open water layer was the same as the one used within the landcover category.

When creating the cost layers, data gaps for land use occurred within the study area. To resolve any missing data, Google maps was used as a base map to identify what type of land use was present in the gaps and to determine an appropriate cost value.

Gap areas within the study area were assigned a cost of 70 since most of these areas were found to be used for residential and industrial use. Areas with missing data that fell within the 2km buffer were awarded a land use cost of 50 since most were being used for primary production.

3.2.4 Least-cost path modelling

To determine the most effective placement of linkages between protected areas, LCPs were identified using the Linkage Pathways tool from the Linkage Mapper 2.0 ArcMap extension (MaRae and Kavanagh 2011). The tool was set to identify the four closest protected areas to each protected area, using the distance data given by Conefor output (Saura and Torné 2009). It then calculated the least-cost paths between the protected areas based on cost values within the cost layer, and produced a final output of a line vector layer of all the computed LCPs that was linked to a database with attributes for each path, including path lengths and total costs.

4. Results

4.1 Investigate the current degree of connectivity between protected areas

All metrics indicated that the landscape of the Perth and Peel region is more connected for species with greater dispersal abilities, as shown in comparison of the results from the suite of ecological distance thresholds (EDTs) from 50 to 1,500 m. Both the overall landscape level metrics (IIC and SC), and the patch-level metrics (importance of individual protected areas - dIIC and BC) showed a similar pattern. Connectivity was poor between protected areas at 50 m EDT, with connectivity remaining little changed in EDTs up to 500 m and only increasing at EDTs greater than 500 m

The IIC metric assesses connectivity within the protected area and between protected areas. This indicated a low connectivity value of approximately 0.003 at the 50 m EDT. For reference, if the entire study area were a ‘formal’ protected area then the IIC value would be 1. An increase in the IIC value was not obvious until 1,000 m EDT, and only increased slightly to 0.0005 at 1,500 m (Figure 7). The SC metric at 50 m EDT found that nearly 50% of ‘formal’ protected areas were in isolation and less than 5% were within the largest component (set of protected areas linked to each other), meaning they were part of the same interconnected network of patches. In contrast, at 1,500 m less than 5% of ‘formal’ protected areas were isolated and around 50% were in the largest component (Figure 8 and Figure 9). The median value of Betweenness Centrality (BC) (which is related to the position of an individual protected area along routes connecting other protected areas) was ~0 at 50 m EDT and did not change until

500 m EDT, increasing to ~ 0.005 at 1,500 m (Figure 10). This is evident on the map, with the majority of the ‘formal’ protected areas having low BC values (Figure 11).

Inclusion of ‘semi-formal’ protected areas, especially Bush Forever sites, increased connectivity for species movement. This pattern is supported by the landscape level metric IIC, where ‘all’ protected areas and the Bush Forever sites have a larger IIC value than the other ‘semi-formal’ and ‘formal’ protected areas (Figure 7). The larger IIC value becomes increasingly apparent at the 1,000 m EDT, where the IIC is notably higher for the two assessments that included Bush Forever sites (Figure 7).

The SC landscape metric also supports this pattern of increased connectivity contributed by Bush Forever sites, with nearly 50% of ‘formal’ protected areas in isolation at 50m EDT, in contrast to ~25% of protected areas in isolation for ‘all’ protected areas and Bush Forever sites (Figure 8). At 1000 m EDT, the SC metric indicated ~ 80% of patches for Bush Forever sites and ‘all’ protected areas were connected in the largest component, but with only ~20% of patches connected within the largest component for the other sets of ‘semi’ and ‘formal’ protected areas (Figure 9).

The increase in connectivity across the landscape when ‘all’ protected areas are considered compared to only ‘formal’ protected areas is also observed in the patch level metrics BC and dIIC. The increase in the aggregated BC value indicated that the connectivity of the median patch increases by ~0.15 (scaled values, see Figure 10) at 1000 m EDT, and for protected areas individually comparisons can be seen in the maps Figure 11 and Figure 12. The increase in connectivity is also indicated by the dIIC metric mapped in Figure 13 and Figure 14. To view all BC maps for each EDT and category see Appendix A. To view all dIIC maps for each EDT and category see Appendix B.

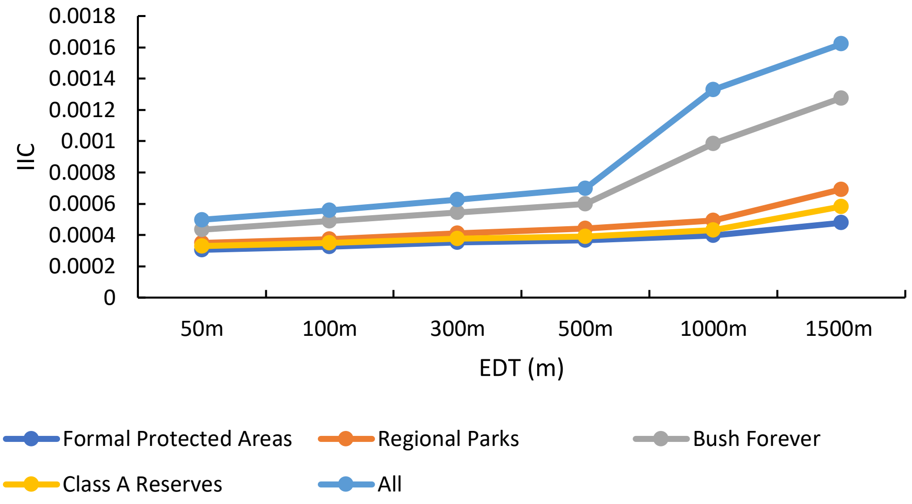

Figure 7.The Integral Index of Connectivity (IIC) values, as estimated for the different ecological threshold distances (EDT) and sets of protected areas. The Regional Parks, Bush Forever and Class A Reserves categories also all include the 'formal' protected areas.

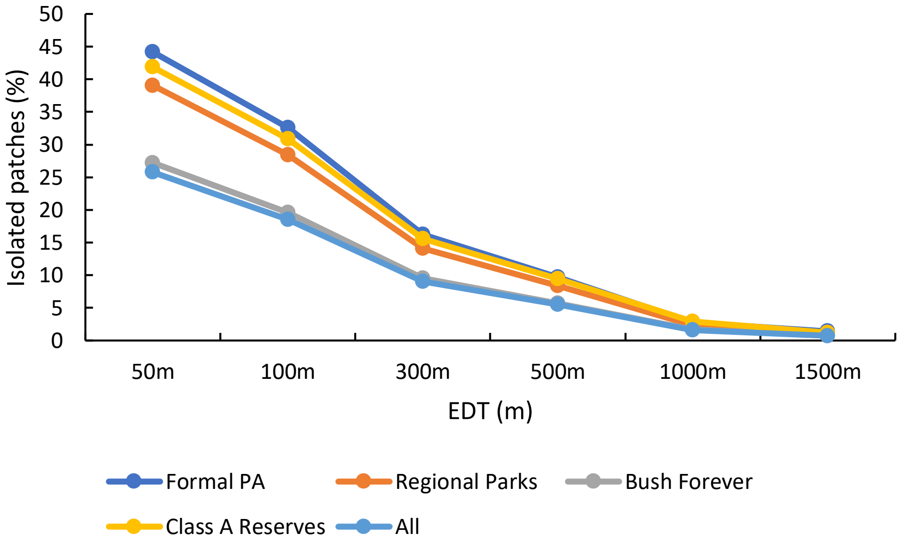

Figure 8. The percentage of protected areas that are isolated (i.e., are in a component with size =1), as estimated for the different ecological threshold distances (EDT)and sets of protected areas. The Regional Parks, Bush Forever and Class A Reserves categories also all include the 'formal' protected areas.

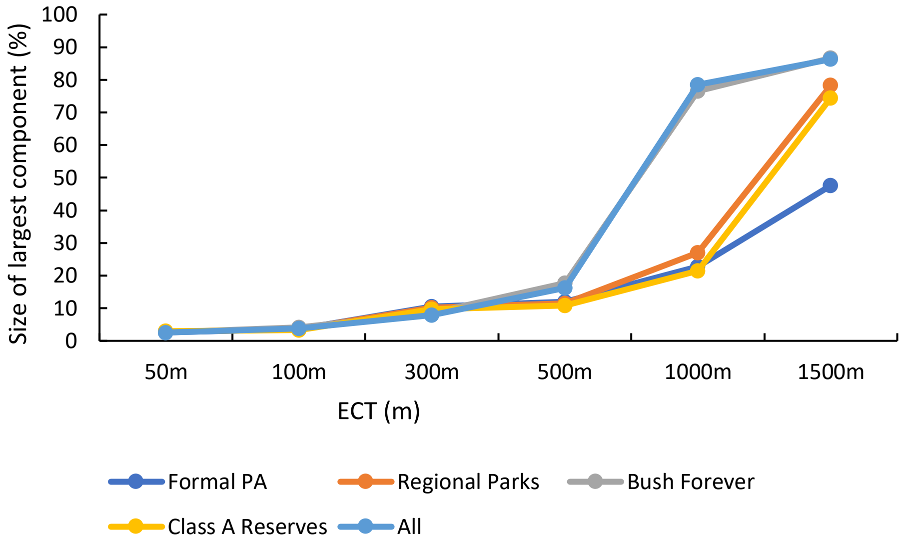

Figure 9. The percentage of patches that are within the largest component (patches that are connected to each other) for the ‘formal’ protected areas and the ‘semi-formal’ protected areas (each includes the ‘formal’ protected areas), at different ecological threshold distances. The Regional Parks, Bush Forever and Class A Reserves categories also all include the ‘formal’ protected areas.

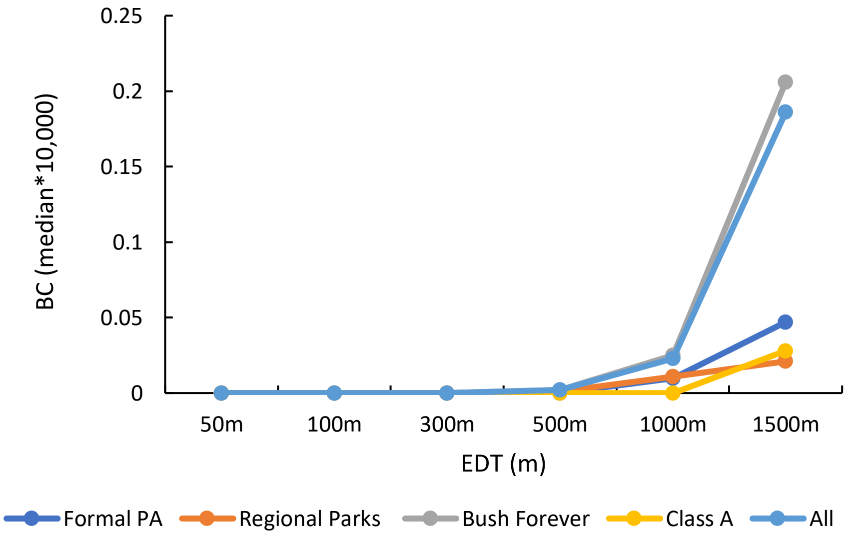

Figure 10. The median values*10,000 of Betweenness Centrality (how central a patch is to the other patches within the landscape) for the ‘formal’ protected areas and the ‘semi-formal’ protected areas (each includes the ‘formal protected areas), at different ecological threshold distances. The Regional Parks, Bush Forever and Class A Reserves categories also all include the ‘formal’ protected areas.

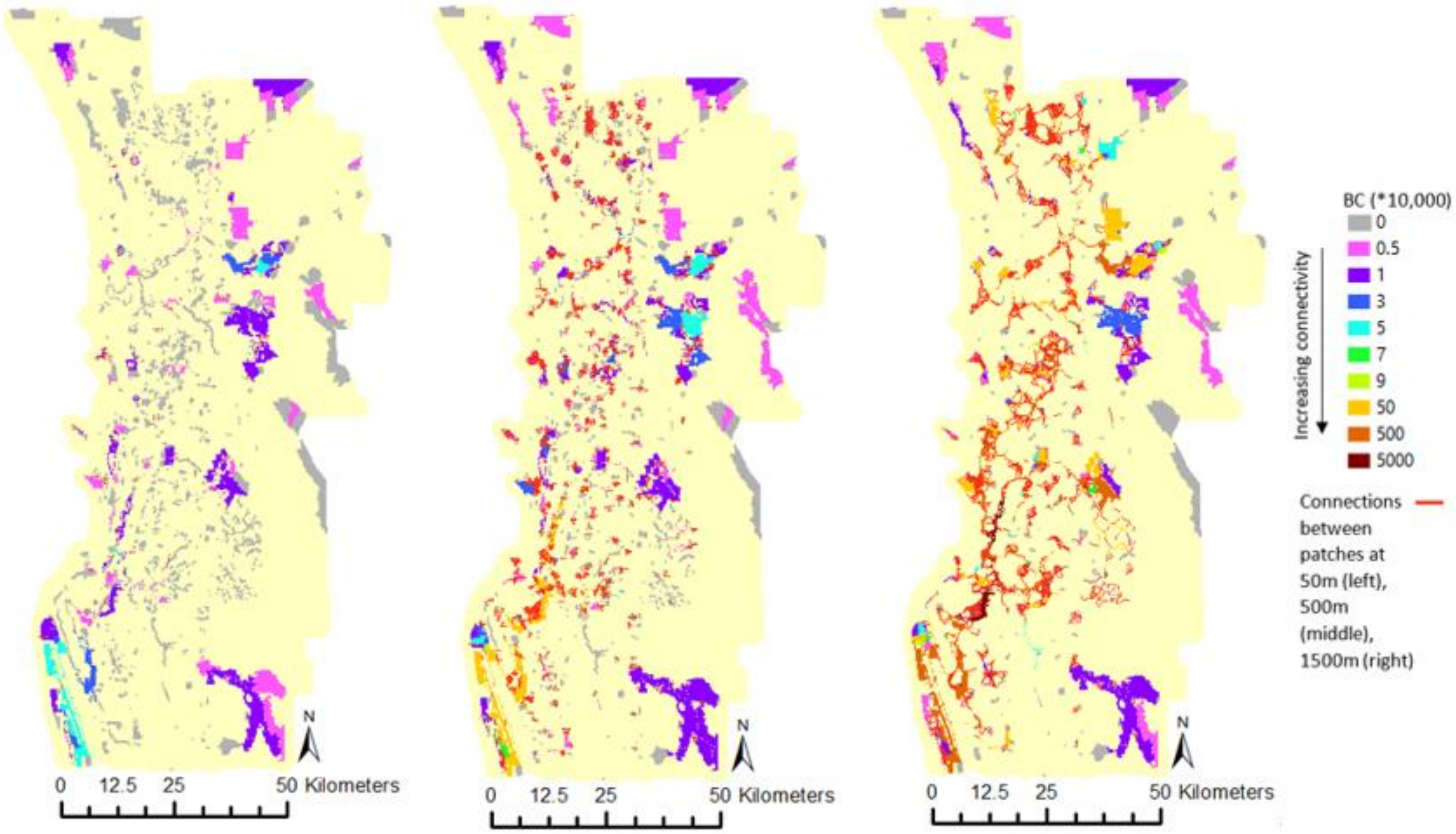

Figure 11. The individual role of 'formal' protected areas in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 50m (left), 500m (centre), and 1,500m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result.

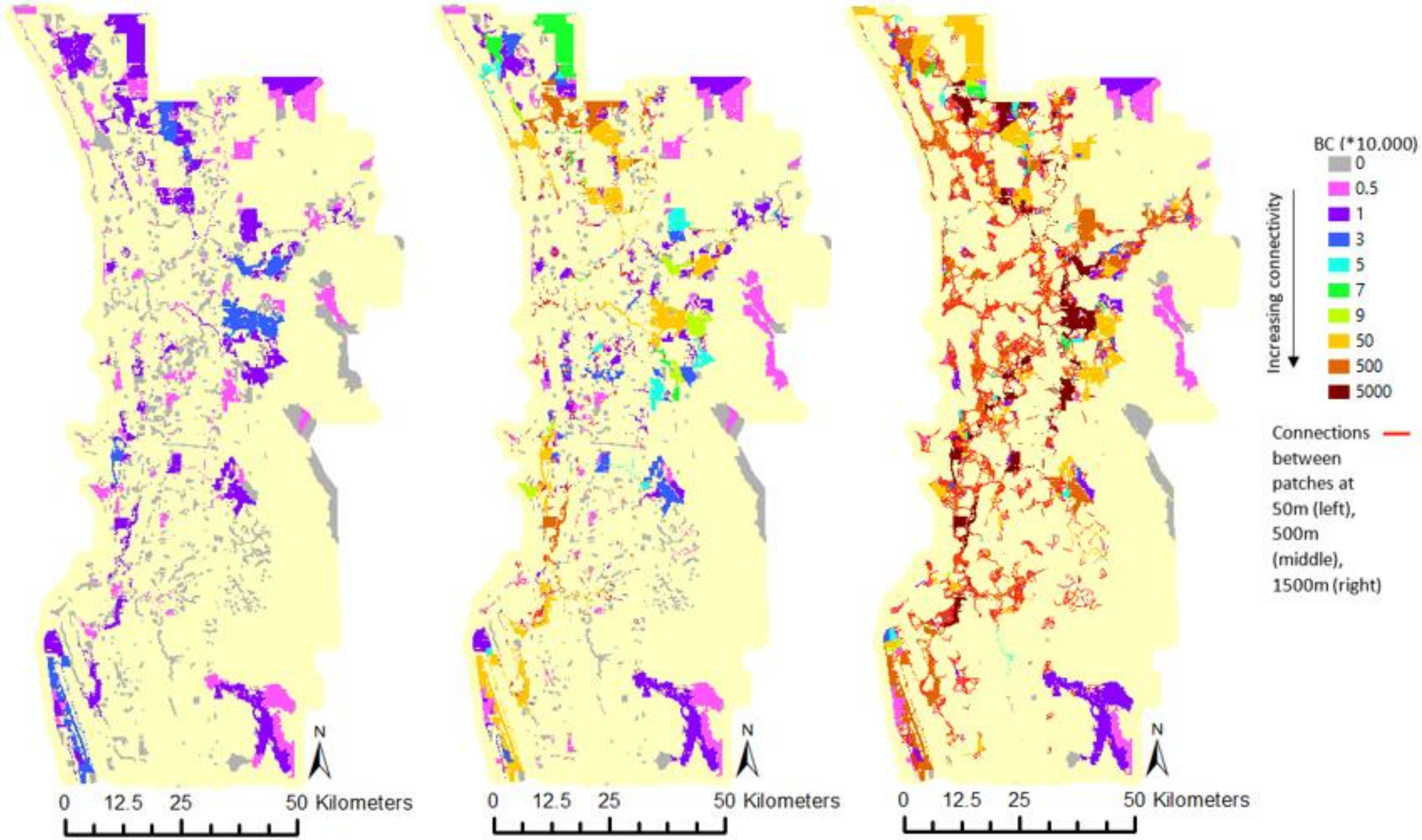

Figure 12. The individual role of 'all' protected areas in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 50m (left), 500m (centre), and 1,500m (right). The grey protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result.

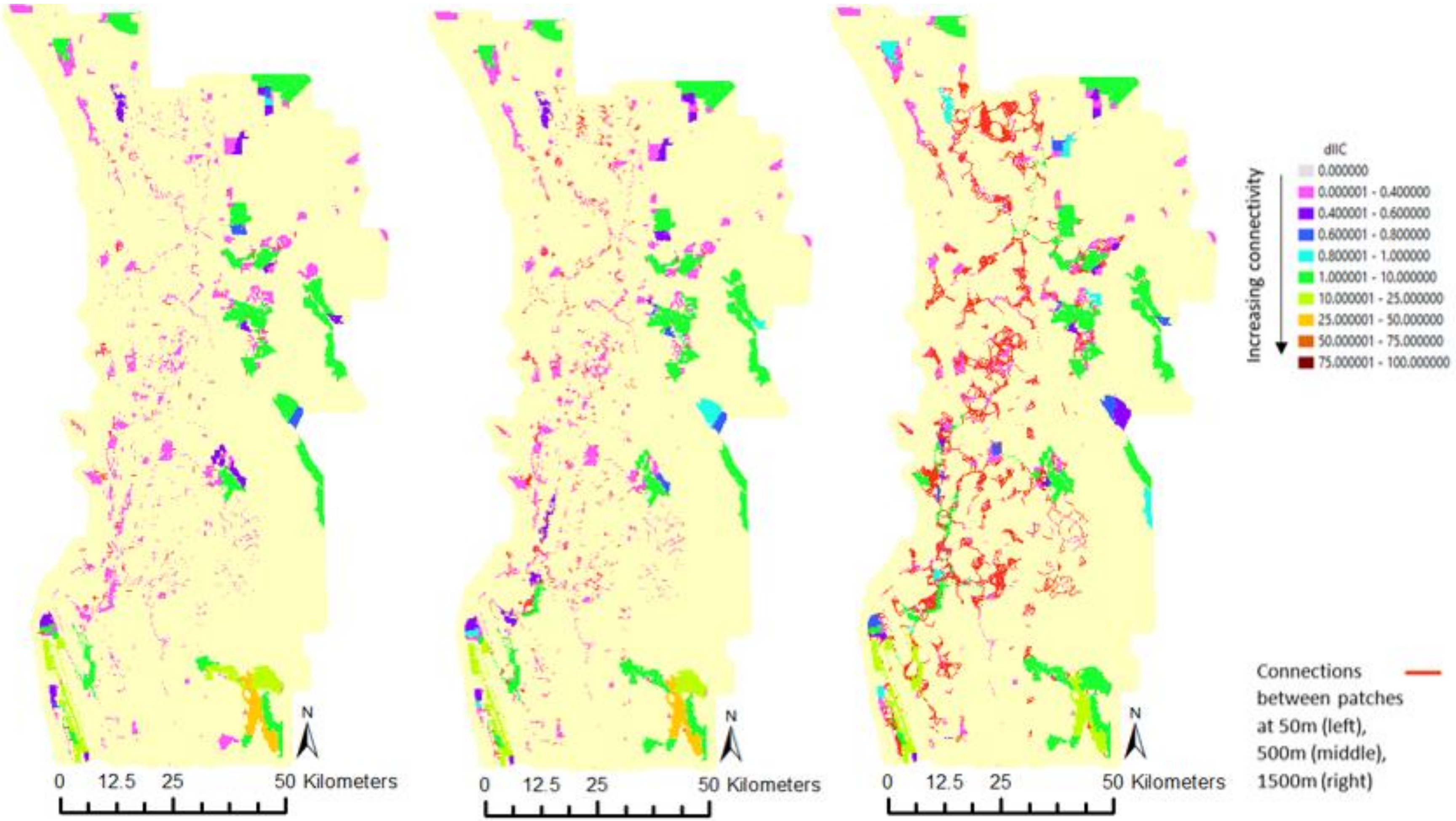

Figure 13. The individual role of the ‘formal’ protected area in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 50m (left), 500m (centre), and 1,500m (right).

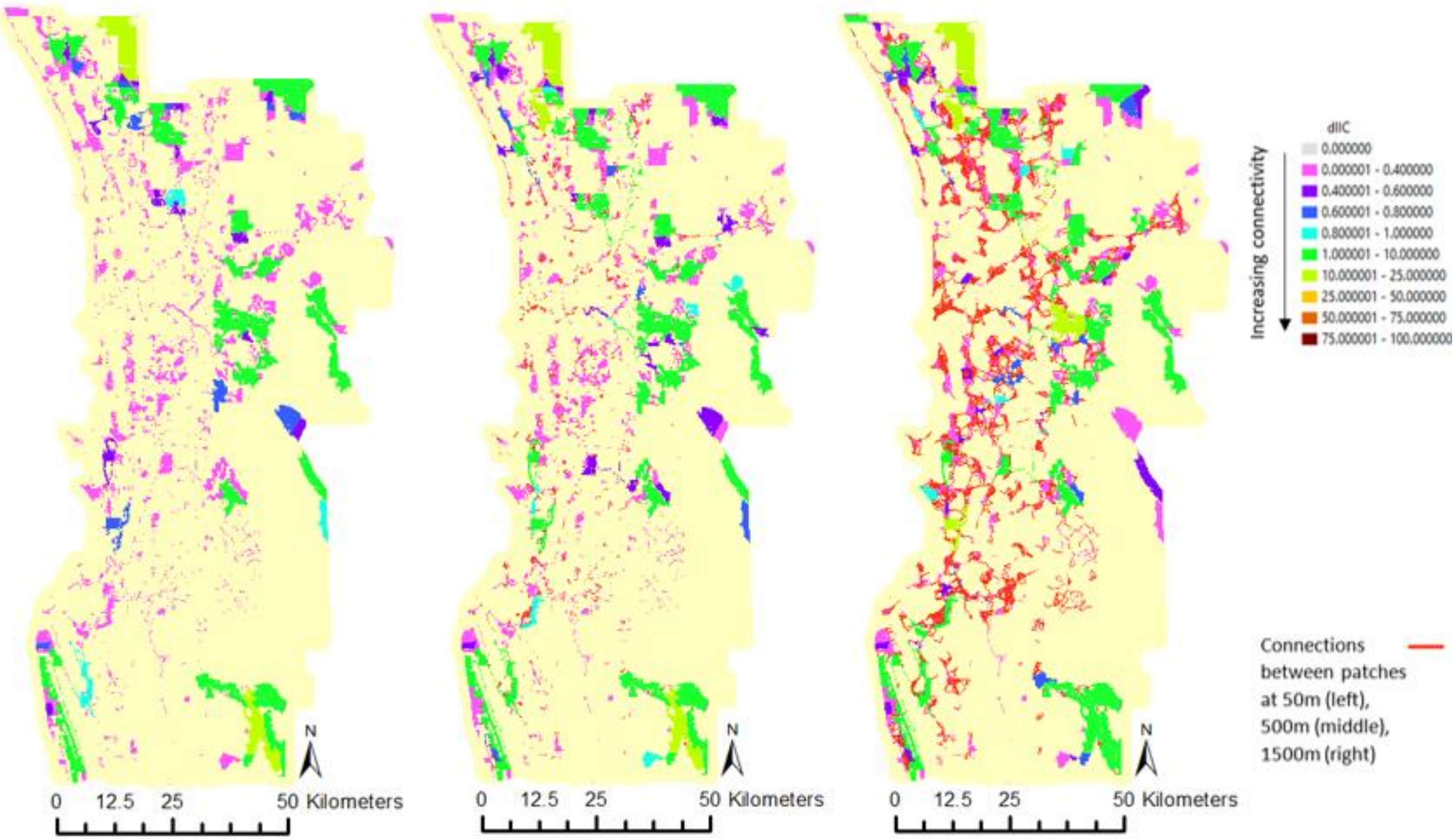

Figure 14. The individual role of the 'all' protected area in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 50m (left), 500m (centre), and 1,500m (right)

4.2 Investigate the most effective placement of linkages

The least-cost path modelling produced a series of linkages between the ‘formal’ and ‘all’ protected areas based on the associated cost (difficulty) of a species moving through each landscape element. Over the entire study area, the ‘all’ protected area analysis found more linkages than the ‘formal’ protected area analysis (Table 6), likely due to the greater number of protected areas as the analysis is constrained to linking each protected area to the four closest neighbouring protected areas.

The Central Metropolitan Planning Region (MPR) had the highest average cost per LCP by over 40,000 compared to the Peel Planning region with second highest average cost per LCPs (Table 6). The Central (MPR) also had the longest average Euclidean distances between the ‘formal’ protected areas, and the LCPs on average cover the longest distance between the ‘formal’ protected areas (Table 6). This suggests the protected areas in the Central MPR are sparse and the urban matrix between is extremely costly for species movement compared to all the other planning regions.

The South West MPR on average had the lowest Euclidean and LCP distances for both the ‘formal’ and ‘all’ protected areas (Table 6). The average cost of the LCPs however is higher than the North East MPR, North West MPR, and the South East MPR (Table 6), suggesting there is a high number of protected areas in close proximity in the region compared to the others, but a quite hostile urban matrix between them.

The North East MPR is the only region where the ‘formal’ protected areas LCPS are on average shorter than the ‘all’ protected areas LCPs (Table 6). This indicates that within the region the ‘semi-formal’ protected areas form clusters where there are many short

LCPs. Compared to the other regions where ‘formal’ protected area LCPs are on average longer than the ‘all’ protected area LCPs (Table 6), indicating a wider distribution of ‘semi-formal’ protected areas across the regions.

Every planning region had more LCPs in the ‘all’ protected area analysis compared to the ‘formal’ protected area analysis, apart from the South East MPR which had 19 more LCPs in the ‘formal’ protected area analysis (Table 6). This indicates that within the South East MPR some of the ‘semi-formal’ protected areas are joined to the ‘formal’ protected areas to form one large protected area and therefore a LCP is not needed to join the protected areas. The Peel region has the most LCPs for both the ‘formal’ and ‘semi-formal’ protected areas (Table 6), indicating that this area has more protected areas to link, which could also be due to it being the largest region. The North West region however has the lowest number of LCPs for both the ‘formal’ and ‘semi-formal’ protected area analysis (Table 6).

The LCP linkages substantially differed in some areas from the Perth MPR linkages (2004) and the South West linkages (2009) previously identified in the Perth and Peel region, but in other areas they mimic them closely (Figure 15).The linkages identified are explored further within their planning regions (Figure 16) to gain a clearer understanding of what landscape elements they pass through and what they avoid (see below).

Table 6. The average distances (meters) of the least-cost paths (LCPs) and Euclidean (straight line) paths, standard deviations, as well as the average cost of the LCPs, for the entire study area and each planning region. The total number of LCPs for each region is shown in the far-right column.

Region	Protected area	Distance m/cost	Mean	SD	Total LCPs
Entire study area	Formal'				
		Euclidean distance m	3084.91	3322.25	
		LCP distance m	5184.82	5914.26	1053
		Cost per LCP	66515.8	71655.01	
	All				
		Euclidean distance m	2590.01	2949.95	
		LCP distance m	4549.37	5960.92	1268
		Cost per LCP	72030.99	71455.37	
North West planning region	Formal'				
		Euclidean distance m	3681.51	3533.61	
		LCP distance m	5684.68	5706.9	129
		Cost per LCP	53817.55	68071.7	
	All				
		Euclidean distance m	1955.24	2525.83	
		LCP distance m	4157.91	6703.36	200
		Cost per LCP	55753.59	55251.67	
North East planning region	Formal'				
		Euclidean distance m	3375.23	3430.72	
		LCP distance m	6053.68	6311.84	263
		Cost per LCP	58922.38	74154.99	
	All				
		Euclidean distance m	3730.62	2525.83	
		LCP distance m	6897.85	6703.36	312
		Cost per LCP	46303.58	55251.67	
Central planning region	Formal'				
		Euclidean distance m	3697.99	3292.16	
		LCP distance m	6586.36	6110.64	147
		Cost per LCP	118834.96	95468.57	

	All				
		Euclidean distance m	2405.75	1735.92	
		LCP distance m	4209.47	4118.92	226
		Cost per LCP	111021.19	85225.46	
South West planning region	Formal'				
		Euclidean distance m	2471.44	2143.24	
		LCP distance m	4324.68	4244.48	206
		Cost per LCP	63528.82	64246.18	
	All				
		Euclidean distance m	2298.92	2202.67	
		LCP distance m	4143.65	4611.72	225
		Cost per LCP	76111.47	66098.66	
South East Planning region	Formal'				
		Euclidean distance m	2780.1	2656.57	
		LCP distance m	4791.82	4879.7	296
		Cost per LCP	60059.94	58898.81	
	All				
		Euclidean distance m	2502.9	2464.71	
		LCP distance m	4300.05	4542.46	276
		Cost per LCP	71898.63	64675.21	
Peel planning region	Formal'				
		Euclidean distance m	3230.25	3724.97	
		LCP distance m	5410.51	6831.5	332
		Cost per LCP	74577.18	75774.24	
	All				
		Euclidean distance m	3301.92	3661.98	
		LCP distance m	5741.55	7361.93	361
		Cost per LCP	78245.7	75742.37	

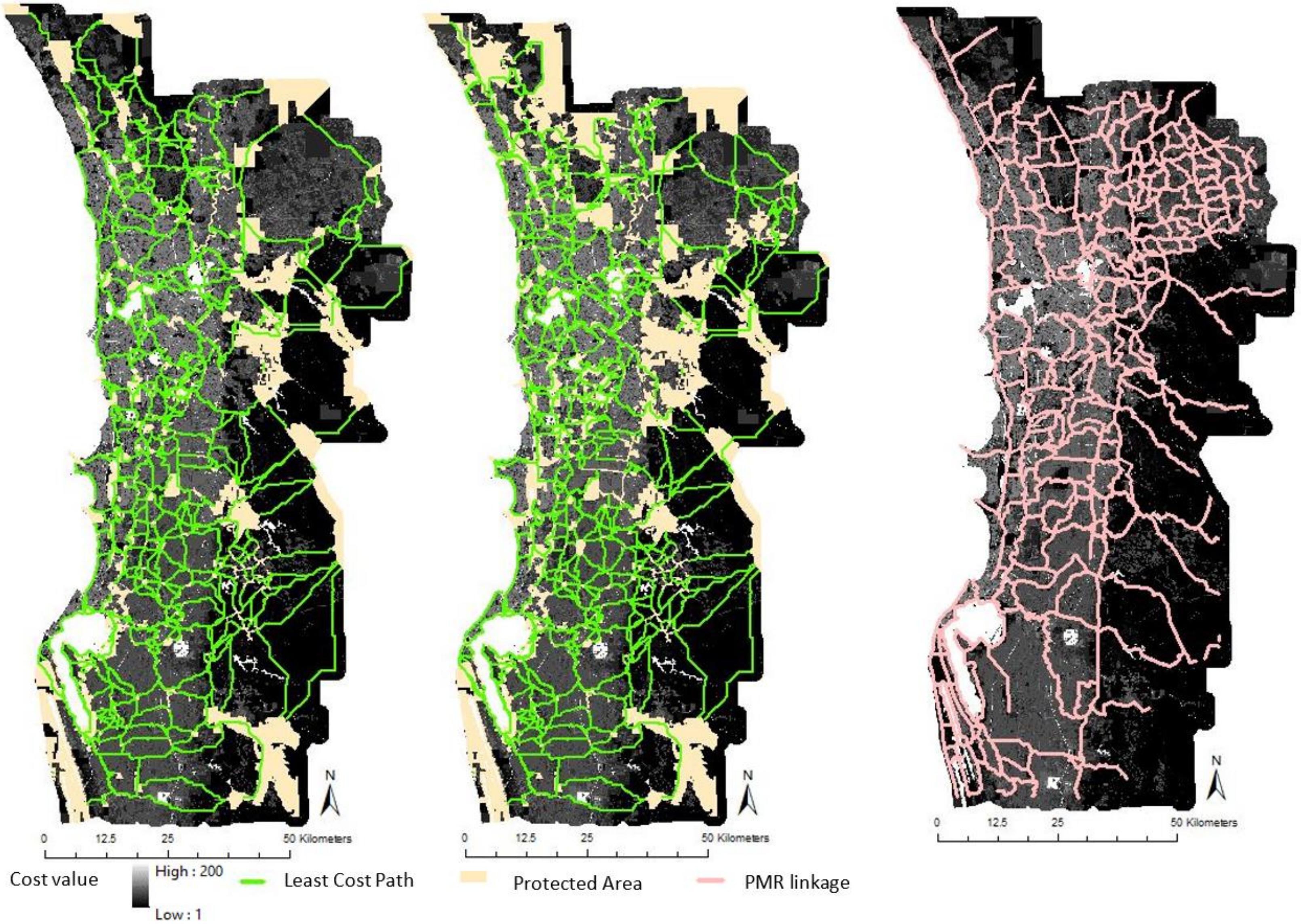

Figure 15. The least-cost path (LCP) results between the ‘formal’ protected areas (left), with 1053 LCP linkages, between the all protected areas (centre), with 1269 LCP linkages, and the Perth Metropolitan Regional Linkages with the South West linkages (right).

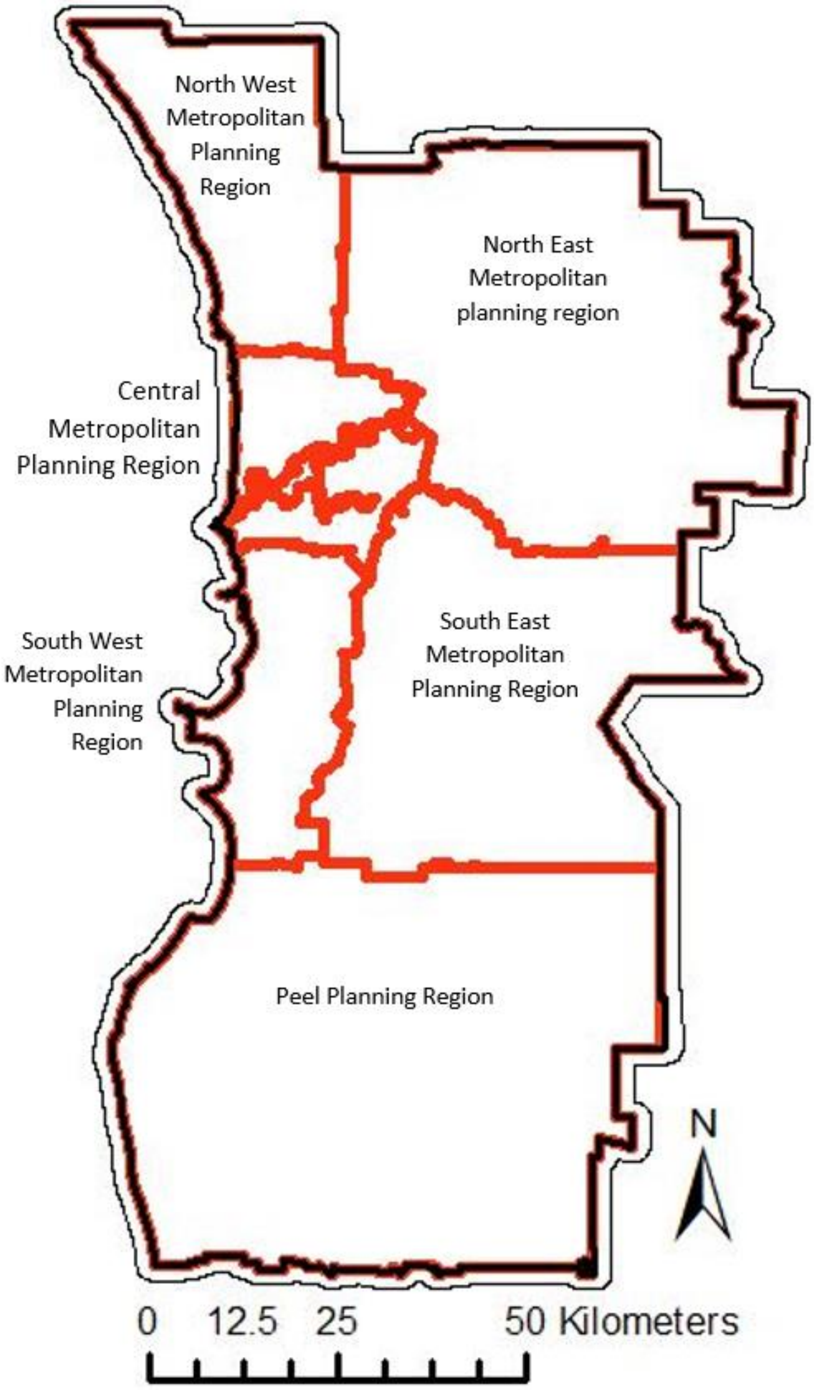

Figure 16. The Perth and Peel Planning regions separated by red lines retrieved from Perth and Peel @ 3.5 million report (Department of Planning Lands and Heritage 2018).

The LCPs in the North West MPR demonstrate the importance of the wetland system Yellagona Regional Park for facilitating connectivity. The wetlands run through the centre of the region parallel to the coast and connect to Neerbup Nature Reserve, thereby creating a strong north–south linkage (Figure 17 and

Figure 18). Yellagona Regional Park also helps to facilitate east-west linkages by enabling the protected areas on either side to use the park as a stepping stone (Figure 17 and

Figure 18). When Bush Forever sites are included within the set of 'source' protected areas for the LCP modelling, further linkages open north of the Mindarie Marina, emphasising that these sites are important in forming strong linkages along the coast (Figure 17 and

Figure 18). Marinas represent major barriers in the least-cost path modelling. At the Two Rocks Marina, LCP modelling selected alternative paths and protected areas to link rather than the two protected areas on either side of the marina (Figure 17 and

Figure 18). In the dense urban areas of the region, pocket parks and bike paths aid linkage between protected areas surrounded by human infrastructure, due to the lower costs associated with these land uses (Figure 17 and

Figure 18). The Perth Metropolitan Regional Linkages closely mimic the LCPs in this region with slightly more LCPs apparent than previous linkages (Del Marco et al. 2004) (

Figure 18).

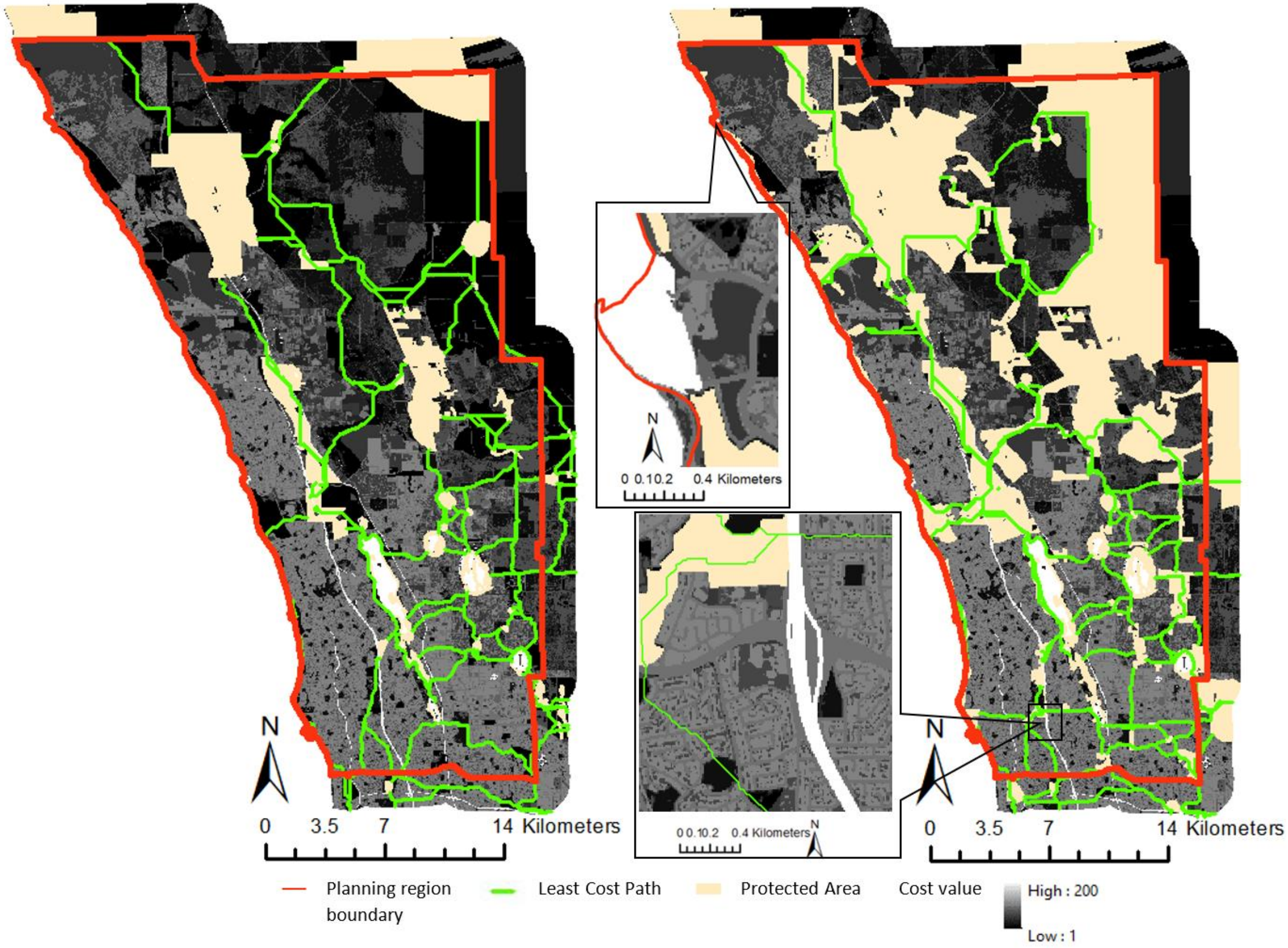

Figure 17. The left image identifies North West Metropolitan Planning Region with a 2 km buffer, the 'formal' protected areas, and their least-cost paths; the right image identifies all protected areas with their least-cost paths. The top inset shows the barrier created by the Two Rocks Marina which is not traversed by a LCP; the bottom insert shows a least-cost path using a cycle path (in the NE of the inset) and small parks in a dense urban area (in the SW).

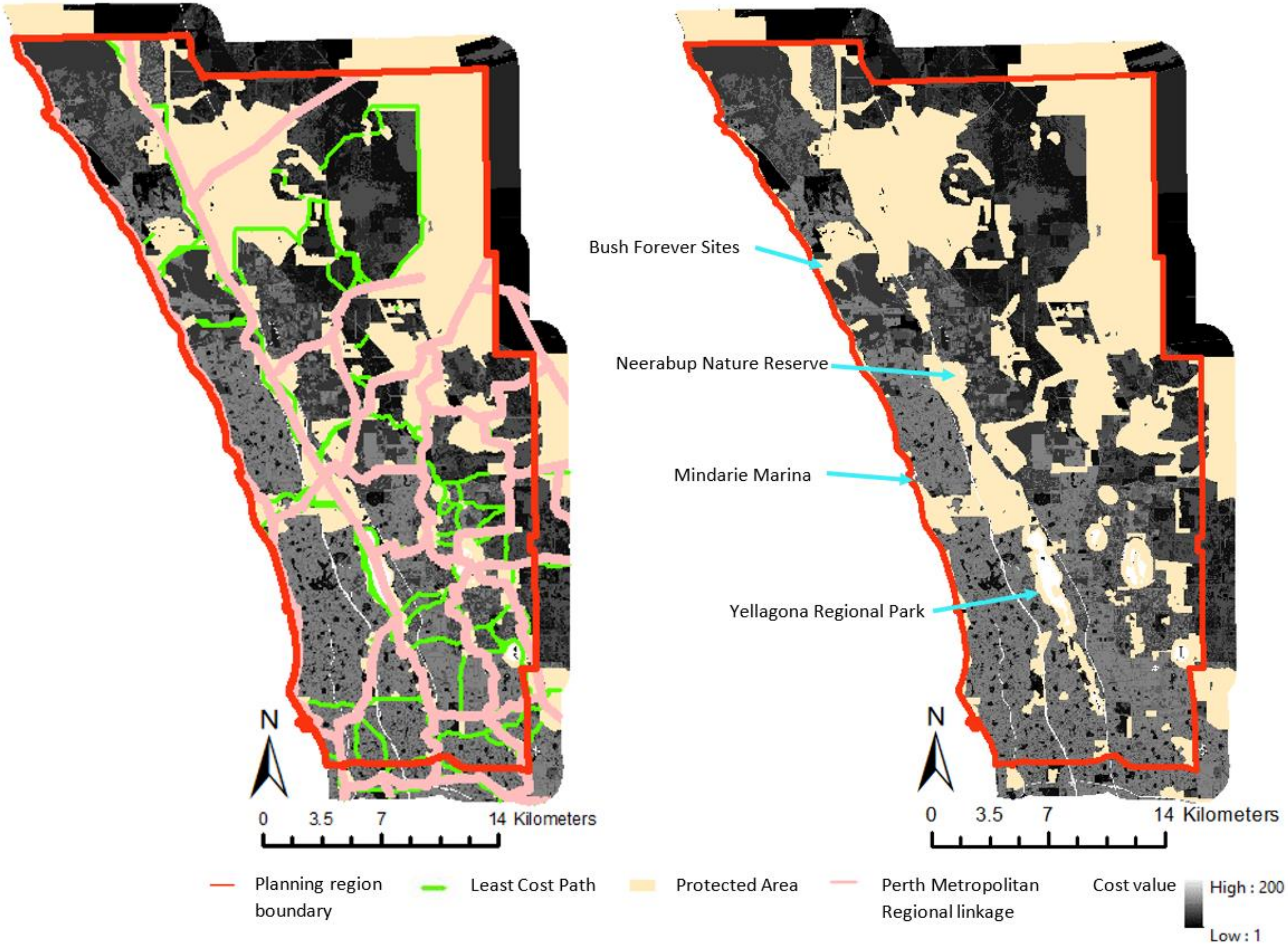

Figure 18. The North West Metropolitan Planning Region with a 2km buffer. The left image compares the ‘all’ protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004); the right image identifies different protected areas within the region.

The results in the North East MPR reveals the importance of protecting remnant vegetation in agricultural areas. The LCP modelling identified a small number of linkages to the east of the City of Swan when ‘all’ protected areas were incorporated, but none using only ‘formal’ protected areas, with the linkages skirting around the edge of the agriculture area. In contrast, the Perth Metropolitan Regional Linkages indicated many linkages through this agricultural area (Figure 19 and Figure 20) (Del Macro et el. 2004). Connectivity in the Swan Valley subregion of the City of Swan depends heavily on the Swan River, which provides a strong north-south linkage; only around the region’s periphery do other linkages occur (Figure 19 and Figure 20). More urbanised areas, such as Ellenbrook, rely on the river to form a north-south linkage, as well as small parks for east-west linkages (Figure 19 and Figure 20). Main Roads WA (2019) recently built a fauna bridge just north of Ellenbrook across Tonkin Highway that by chance the LCPs use to link two strict nature reserves (IUCN category 1a) (Figure 19 and Figure 20).

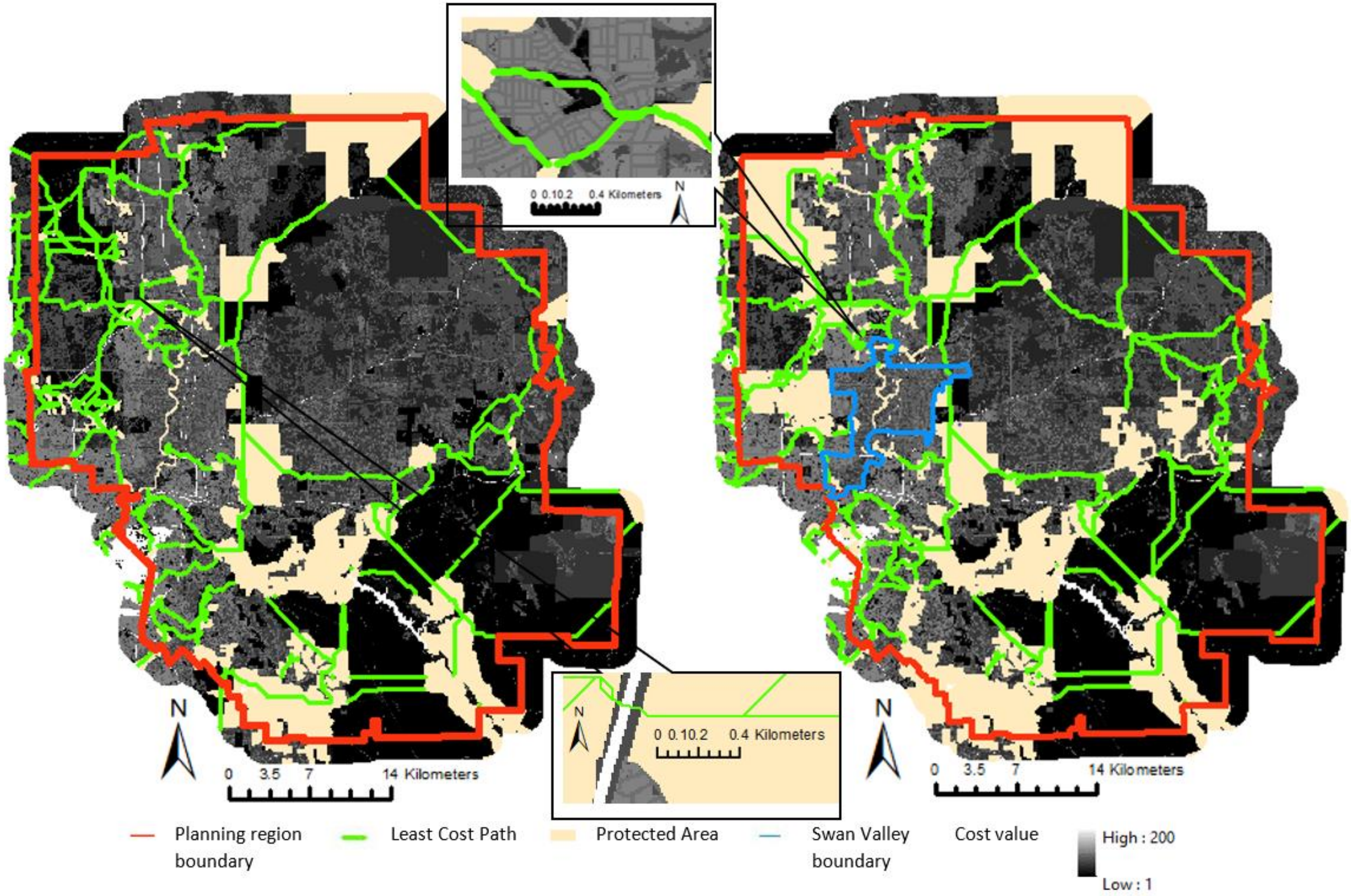

Figure 19. The North East Metropolitan Planning Region with a 2km buffer, the left image identifies the 'formal' protected areas with their least-cost paths; the right image identifies all protected areas with their least-cost paths. The top insert shows the least-cost paths using small parks through the suburb of Ellenbrook; the bottom insert shows a least-cost path crossing Tonkin Highway where a fauna bridge has now been built (Main Road 2019*).*

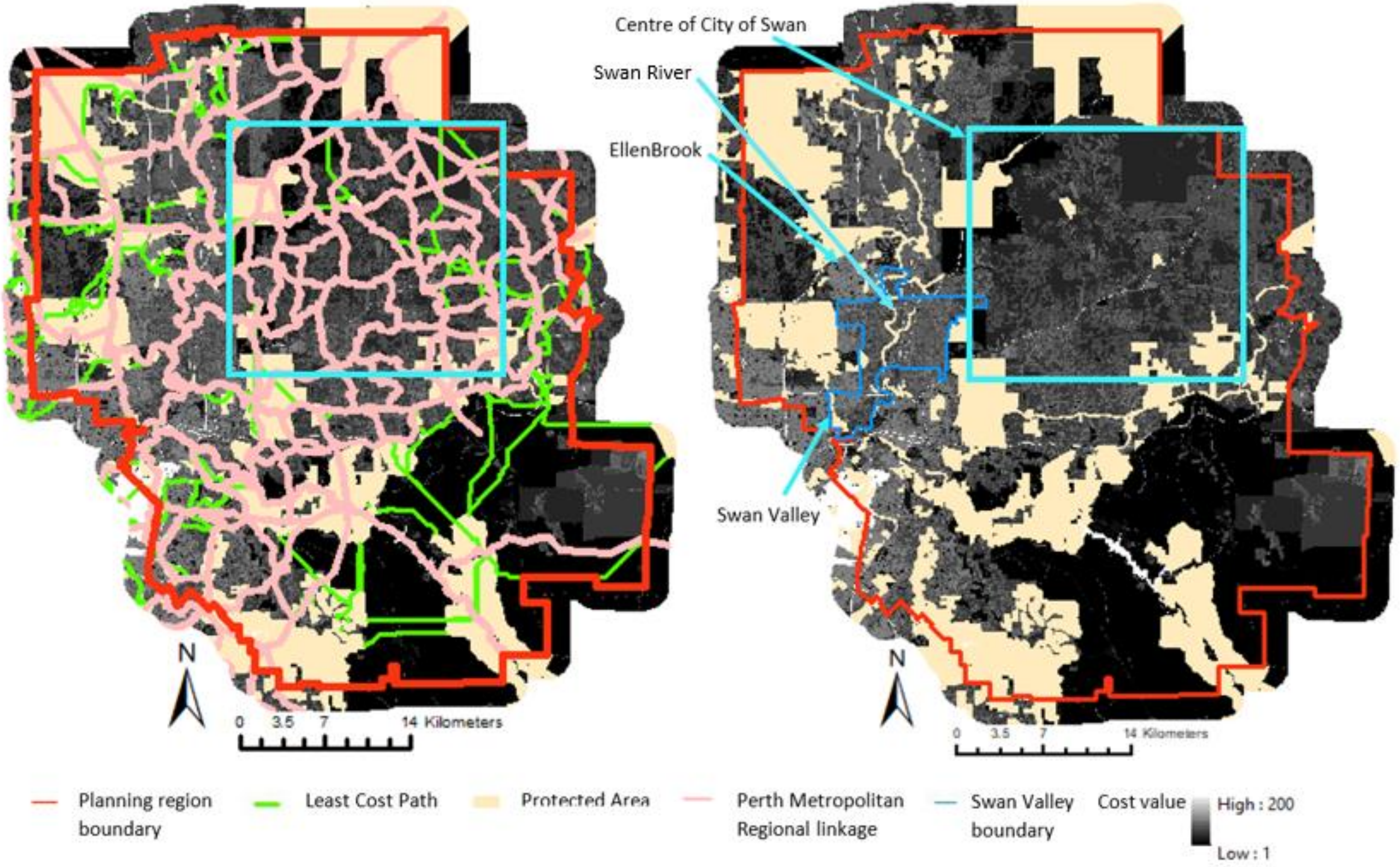

Figure 20. The North East Metropolitan Planning Region, with a 2 km buffer. The left image compares all protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004); the right image identifies different protected areas within the region. The blue squares highlights the large part of City of Swan where the Perth Metropolitan Regional Linkages (Del Macro et al. 2004) vary considerably from the least-cost path linkages.

The Central MPR is the most urbanised region within the study area. LCP linkages are heavily dependent on the Swan River for facilitating north-south and east-west linkages (Figure 21 and Figure 22). North of the river, Kings Park, Bold Park, and Herdsman Lake play an important role in forming a connected network to the west (Figure 21 and Figure 22). To the east there are few identified LCPs north of the river; these few depend on Yokine Reserve, Mount Lawley Golf Course and some small parks to provide passage through this built-up area (Figure 21 and Figure 22). At the very north of the Central MPR more east- west linkages are formed through areas such as Star Swamp Reserve, Trigg Bushland, Carine Regional Open space, and small parks (Figure 21 and Figure 22). There are few protected areas predominantly lining the rivers and airport to the east between the Swan and Canning Rivers. The LCP linkages north of the Canning River use widely separated small parks and Collier Golf Course. A similar situation exists south of the Swan and Canning Rivers. City of Fremantle and City of Melville have limited protected areas for species to move between, with City of Fremantle having just one protected area and Town of East Fremantle having no protected areas larger than ten hectares (Figure 21 and Figure 22). The linkages identified in the Perth Metropolitan Regional Linkages follow a similar trajectory as the ‘formal’ protected areas LCP analysis, however more paths are identified in the LCP modelling (Del Marco et al. 2004) (Figure 21 and Figure 22).

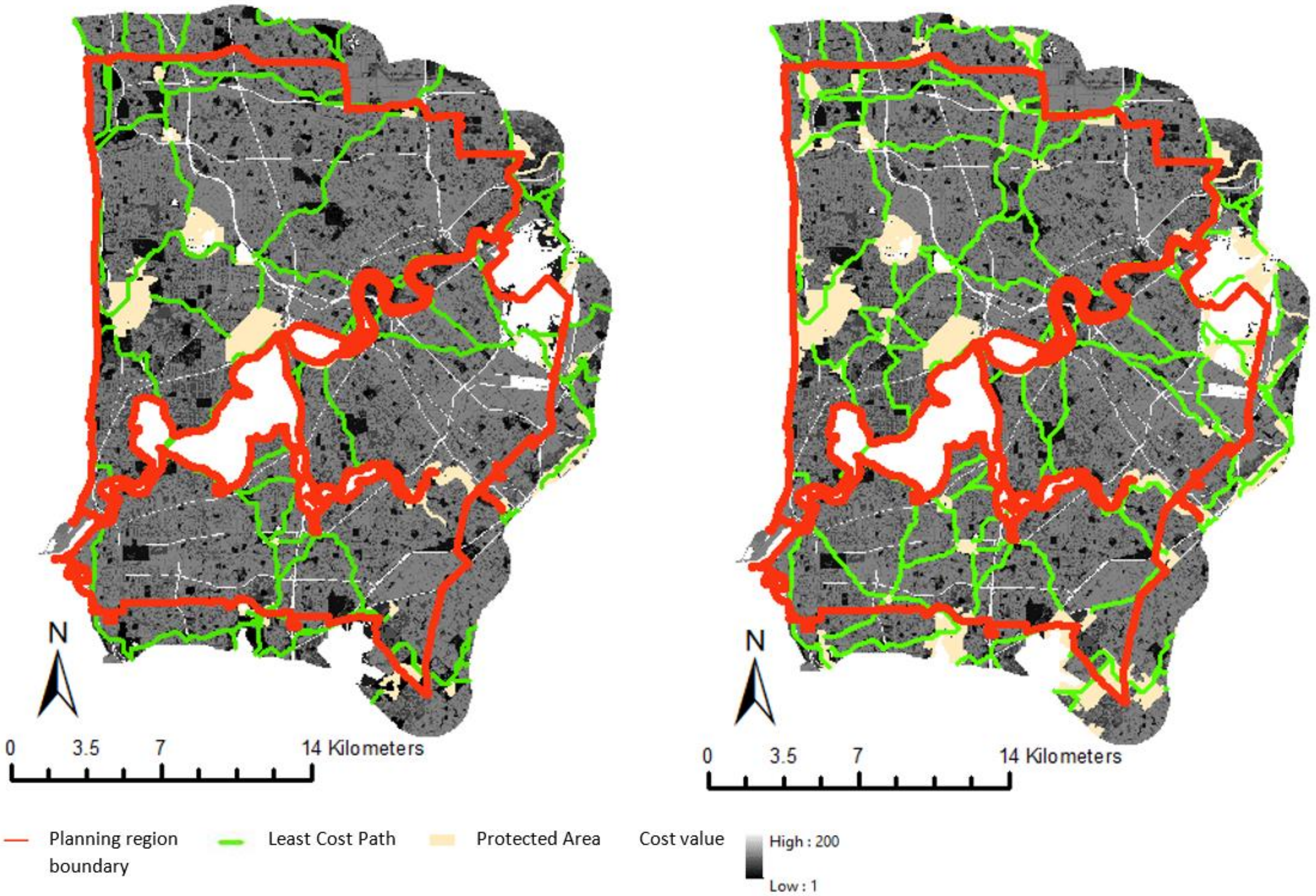

Figure 21. The Central Metropolitan Planning Region with a 2 km buffer. The left image identifies the 'formal' protected areas with their least-cost paths; the right image identifies all protected areas with their least-cost paths.

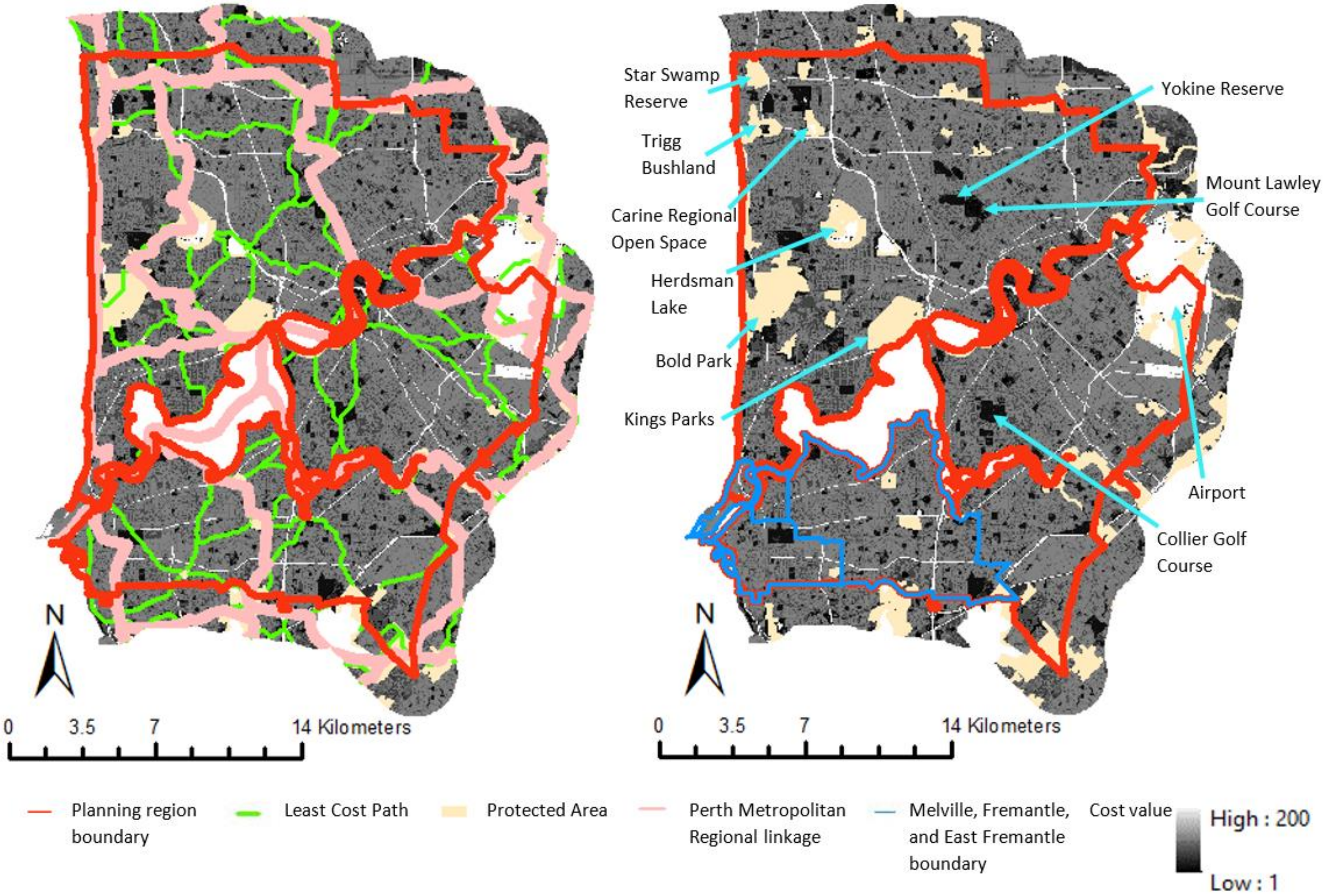

Figure 22. The Central Metropolitan Planning Region, with a 2 km buffer. The left image compares the all protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004); the right image identifies different protected areas within the region. The dark blue highlight identifies the local governments City of Fremantle, Town of East Fremantle, and City of Melville.

The South West MPR has good north-south linkages due to the large wetland system of Beeliar Regional Park, The Spectacles, Lake Cooloongup, and Lake Walyngup which runs through the centre of the region (Figure 23 and Figure 24). On the east side of the wetlands and lakes, many of the LCPs use vegetated roadsides to link protected areas through the agricultural landscape (Figure 23 and Figure 24). In the more urbanised areas to the west of the wetlands and lakes, linkages rely on natural areas that have been zoned for new roads or road expansion, with most LCPs avoiding dense urban areas due to their high associated costs (Figure 23 and Figure 24). Culverts were shown to be important for aiding species movement across the Kwinana Freeway in multiple areas where natural habitats occur on either side (Figure 23 and Figure 24). The Perth Metropolitan Regional Linkages identified similar linkages to the LCPs, but some occur areas that have subsequently been developed where the LCP linkages now take a slightly different route (Del Marco et al. 2004) (Figure 23 and Figure 24).

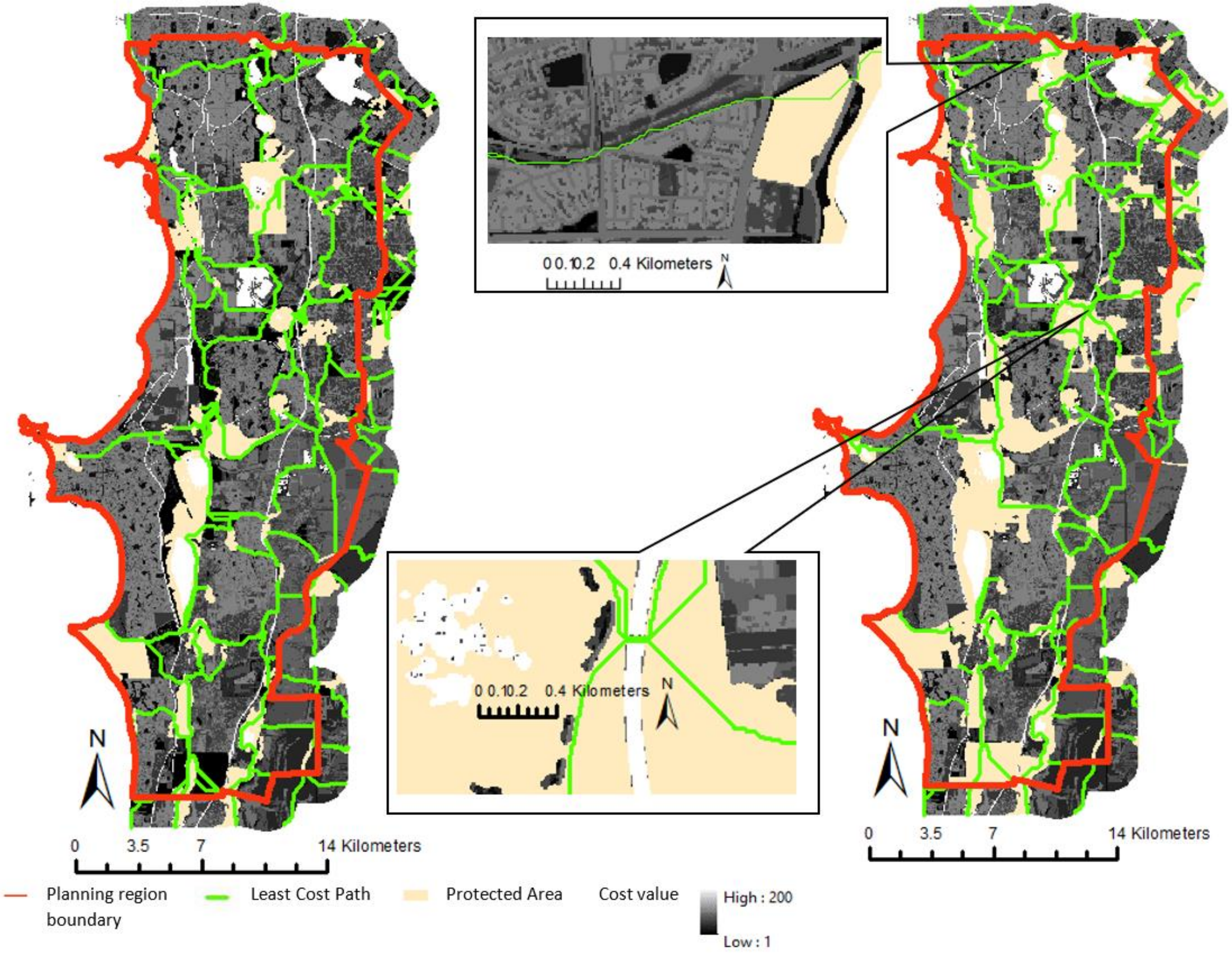

Figure 23. The South West Metropolitan Planning Region with a 2 km buffer. The left image identifies the ‘formal’ protected areas and their least-cost paths; the right image identifies all protected areas with their least-cost paths. The top insert shows where a least-cost path is using vegetation that in the past was zoned for a road expansion; the bottom insert shows the least-cost path using a culvert to cross the Kwinana Freeway.

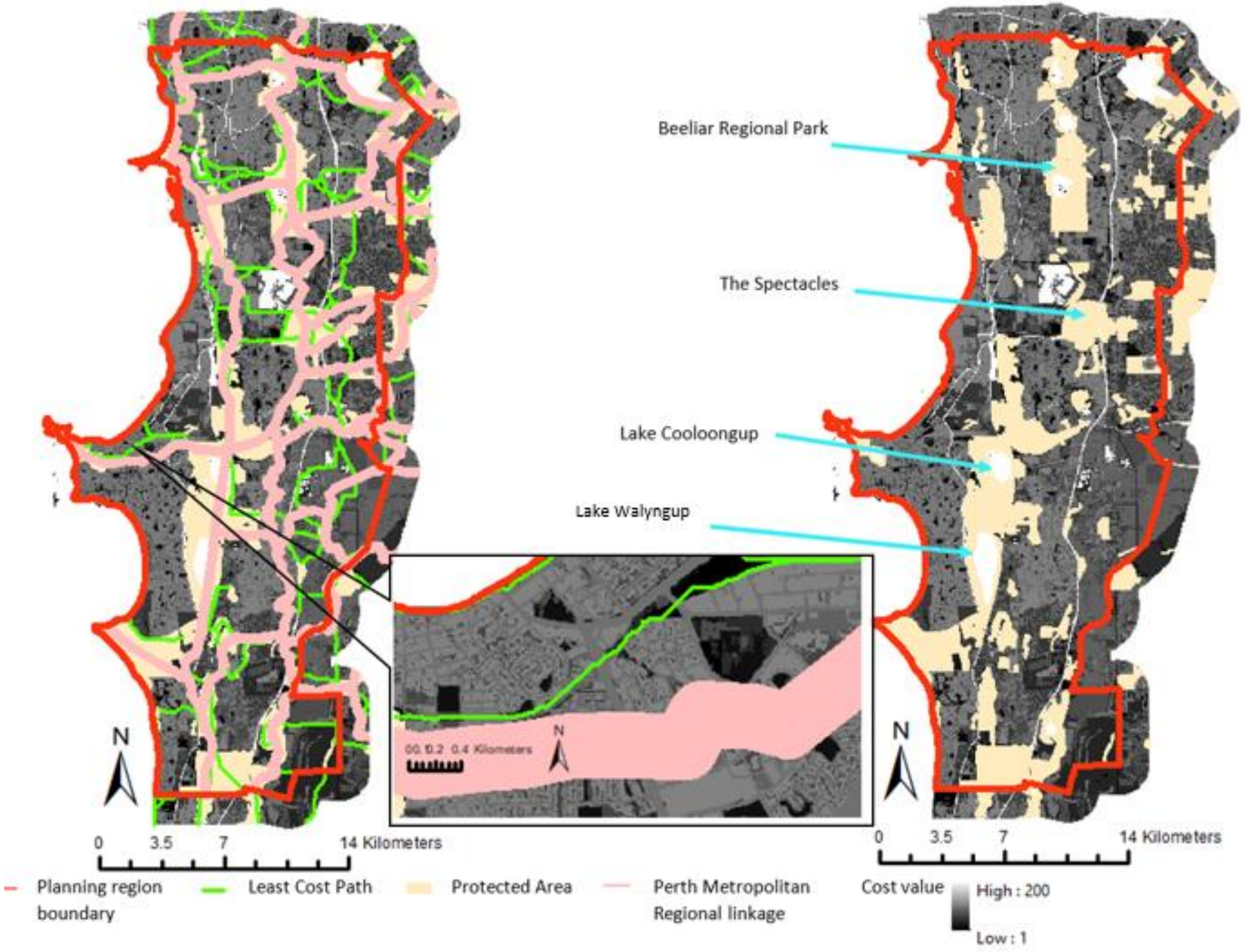

Figure 24. The South West Metropolitan Planning Region with a 2 km buffer. The left image compares all protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004); the right image identifies different protected areas within the region. The insert shows where least-cost paths take a slightly alternative route compared to the Perth Metropolitan Regional Linkages (Del Macro et al. 2004).

The north of the South West MPR is heavily urbanised. To the west, the Canning River forms a strong east-west linkage through the built-up area towards Banyowla Regional Park, as well as a north-south linkage connecting areas such as Harrisdale Lake Nature Reserve and Jandakot Regional Park (Figure 25 and Figure 26). The Brixton Street wetland at the top of the region also creates a strong north-south linkage through the dense urban matrix (Figure 25 and Figure 26). The north-east side of the region is quite well protected with large habitat areas such as Darling Range National Park, Wungong Regional Park, Korung National Park with state forest in between (Figure 25 and Figure 26). The south-east area also has large protected areas comprising the Serpentine National Park, and Monadocks Conservation Park, which again depends on the State forest to form linkages between them. The State forest is paramount for maintaining linkages on the eastern side (Figure 25 and Figure 26). The south-west area of the region presents a more agricultural setting, where LCPs predominantly use vegetated field edges and roads. Culverts were again important for connecting protected areas on either side of road barriers, which in this case is Great Eastern Highway (Figure 25 and Figure 26). The Perth Metropolitan Regional Linkages follow a similar layout to the LCPs, but more LCPs used the state forest (Del Marco et al. 2004) (Figure 25 and Figure 26).

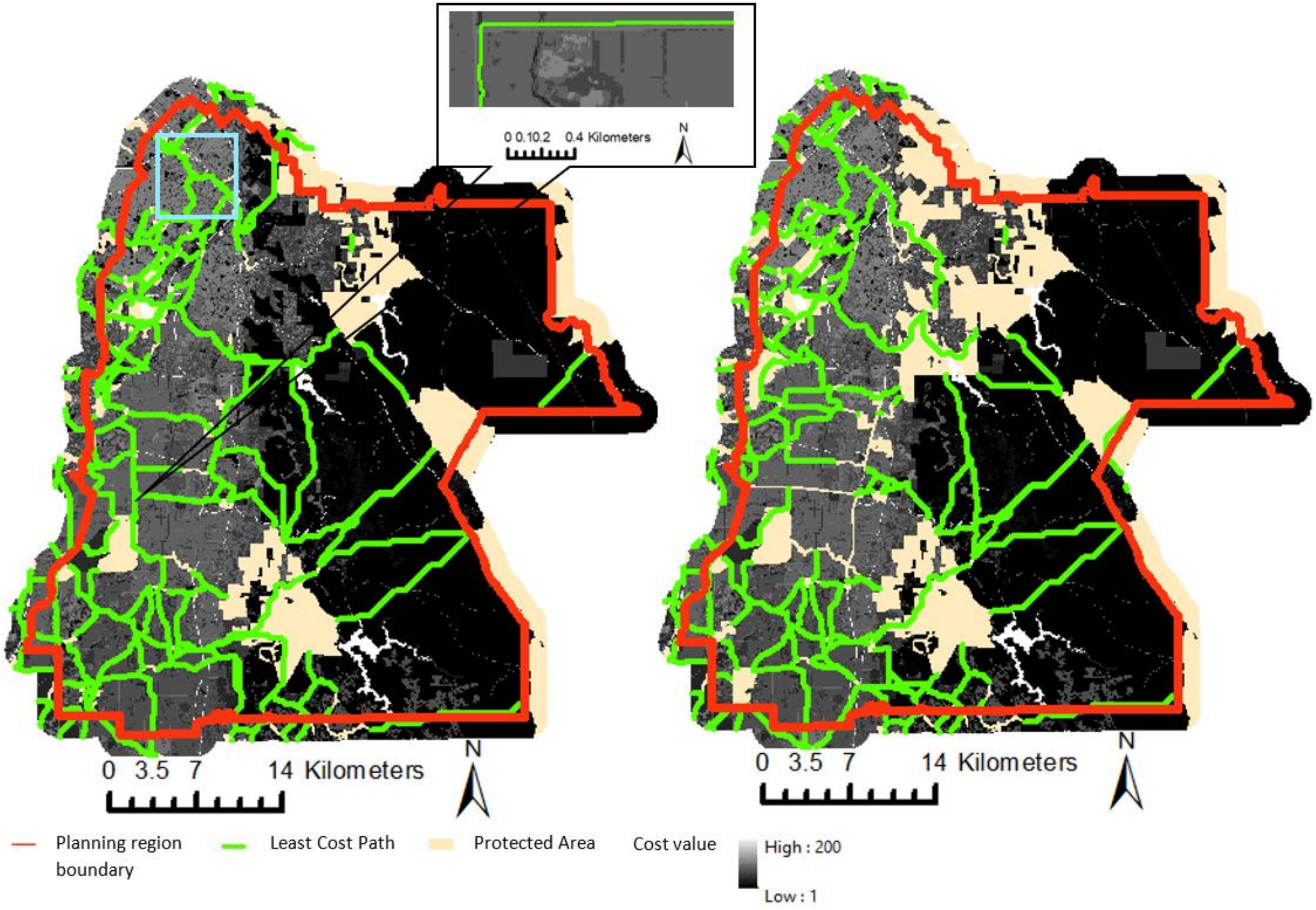

Figure 25. The South East Metropolitan Planning Region with a 2 km buffer. The left image identifies the ‘formal’ protected areas and their least-cost paths; the right image identifies all protected areas with their least-cost paths. The insert shows how the least-cost paths use vegetated road verges and field edges.

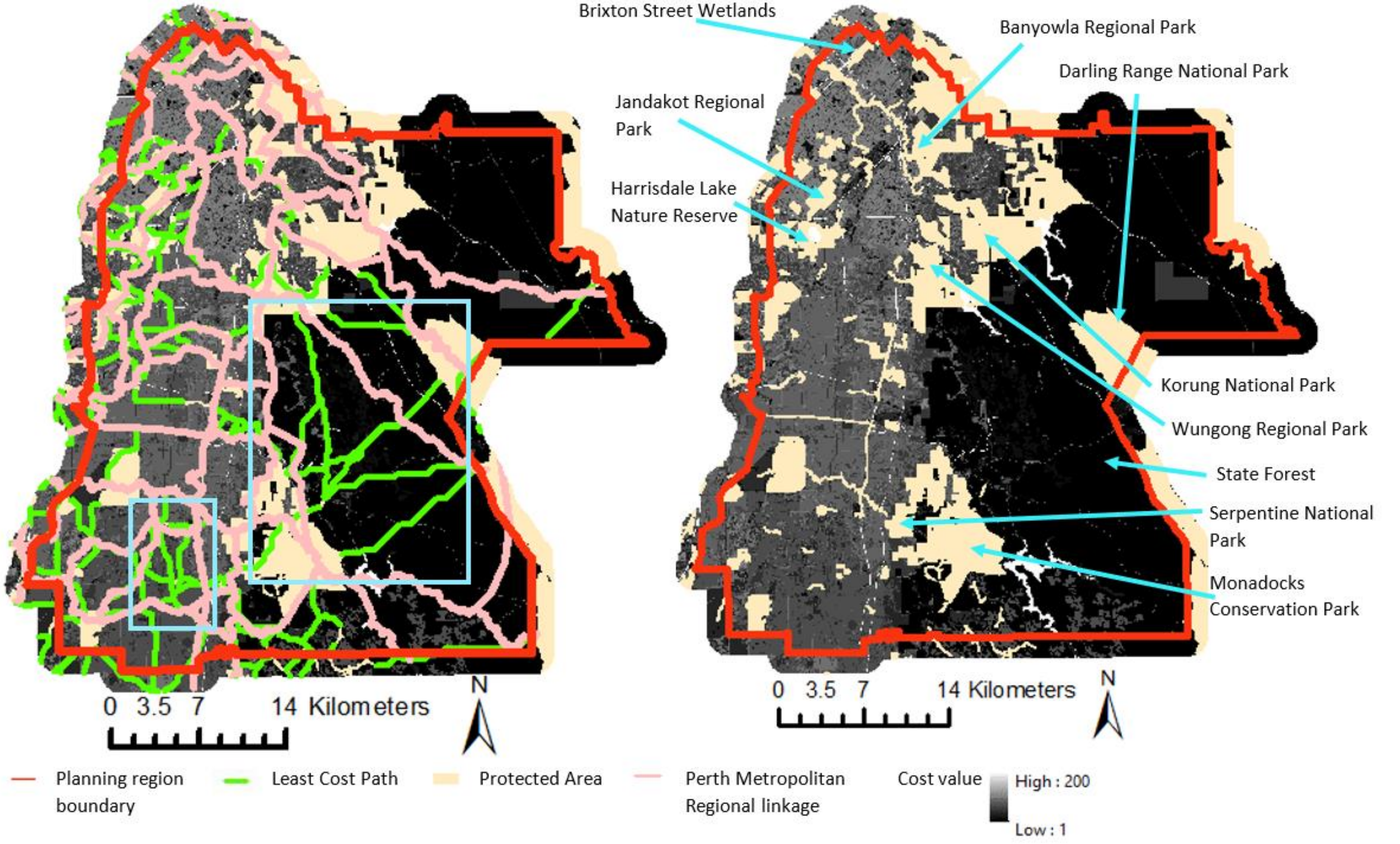

Figure 26. The South East Metropolitan Planning Region with a 2 km buffer. The left image compares all protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004), the blue squares identify the areas of greatest difference; the right image identifies different protected areas within the region.

The Peel planning region at the southern end of the study area is urbanised in the north-west towards the coast. The LCPs around the area depend on the coastline, Peel Estuary, and multiple river systems (Figure 27 and Figure 28). The Serpentine River creates strong connections to the north of the Peel Estuary, and the Murray River creates connections to the east towards the state forest to connect protected wetlands (Figure 27 and Figure 28). The south area of the Peel region has large protected areas to the west and east. On the western side, Yalgorup National Park has good north-south linkages to the Peel Estuary. Lane Poole Reserve on the east side depends on the state forest to link the protected area to the north, however connecting the two large areas are multiple river systems, Buller Nature Reserve, and vegetation along roads and fields (Figure 27 and Figure 28). The LCPs found more potential linkages than the South West Regional linkages. The South West Regional linkages are also heavily dependent on the river systems of this region but have fewer paths along vegetated verges and within the state forest compared to the LCPs.

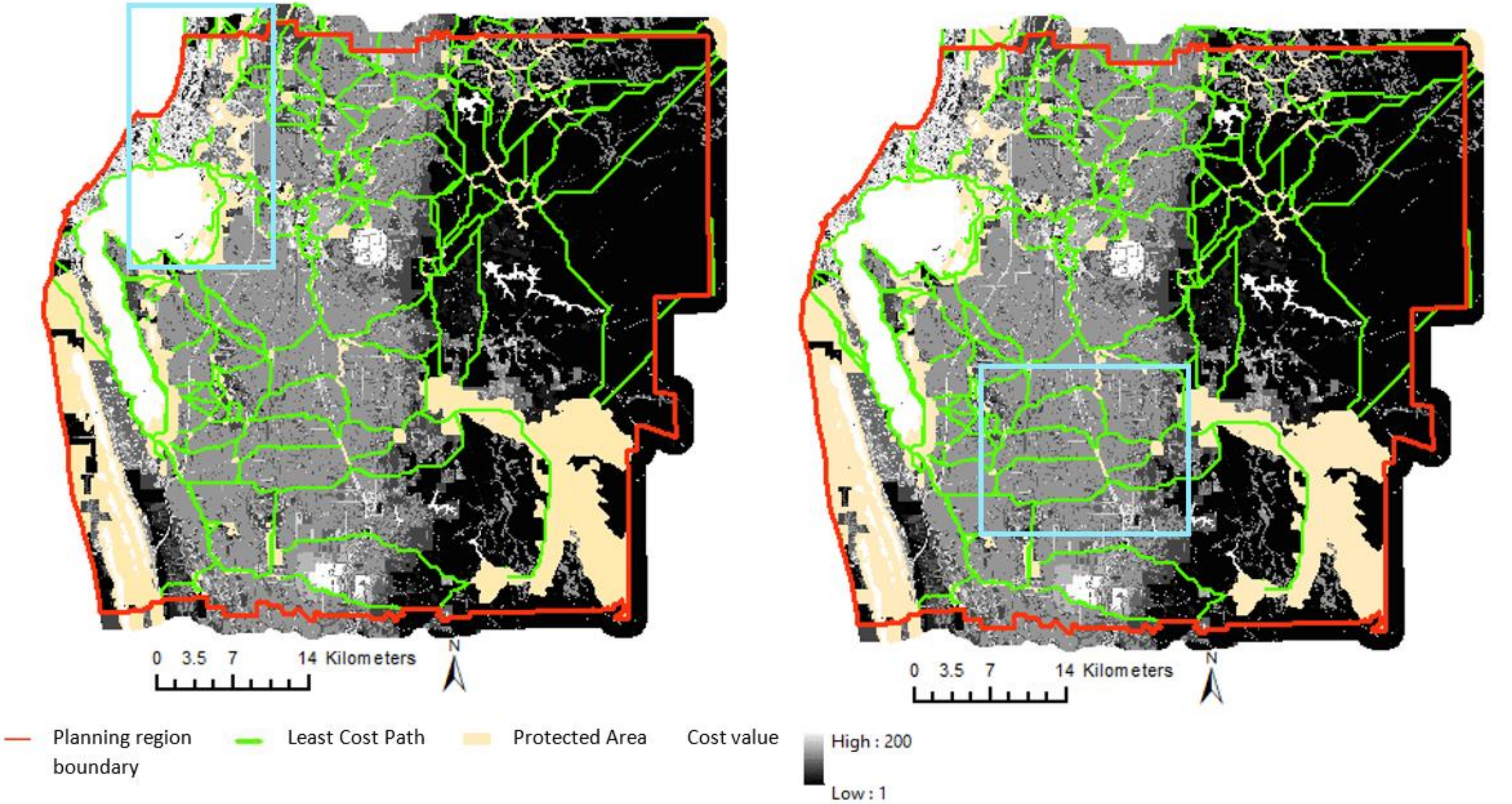

Figure 27. The Peel Planning region with a 2 km buffer, the ‘formal’ protected areas, and their least-cost paths. The blue rectangle in the left image identifies the least-cost paths which rely on rivers and wetlands; the right image identifies all protected areas with their least-cost paths with the blue rectangle identifying least-cost paths using vegetated road verges.

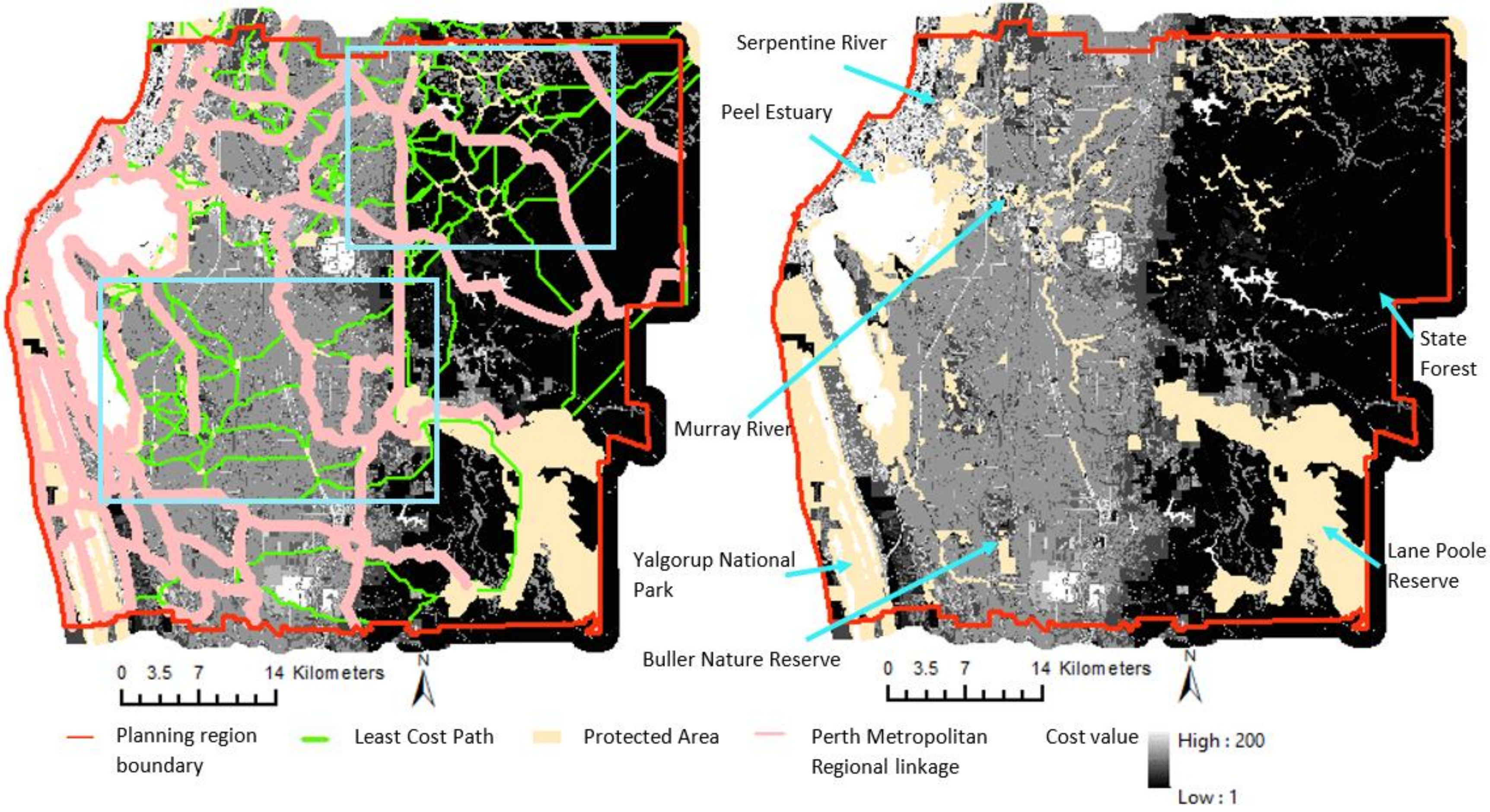

Figure 28. The Peel Metropolitan Planning Region with a 2 km buffer. The left image compares all protected areas and their least-cost paths with the Perth Metropolitan Regional Linkages (Del Macro et al. 2004), the blue squares identify the areas of greatest difference; the right image identifies different protected areas within the region.

5. Discussion

The importance of conserving and enhancing ecological linkages between protected areas within urban environments has increased in recognition internationally (Crooks and Sanjayan 2006; De Chanzal and Rounsevell 2009). This is particularly important for cities which reside in 'biodiversity hotspots' to help ease the current global biodiversity extinction crisis (Novacek and Cleland 2001; Levin and Levin 2002; Mittermeier et al.2011; United Nations 2019). The Perth and Peel region, in one such 'biodiversity hotspot', provides an example of species richness being lost due to increasing urbanisation. While protected areas such as those found within the Perth and Peel region are important for conserving biodiversity, to enhance species resilience to urban growth, linkages between protected areas are necessary for most species (Rudd et al. 2002; Harrison et al. 2014; Ramalho et al. 2017). The importance of connectivity in Perth has long been recognised (Chapter 2) with work across the Perth and Peel region investigating how to create ecological linkages. More recently this has evolved to focus more explicitly on the ecological viability of these connections (Chapter 2). However, the resources currently used (such as the Perth Metropolitan Regional linkages resource) was produced over 15 years ago (Del Marco et al. 2004) and the Southwest Regional linkages over 10 years ago (Molloy et al. 2009) while the region has continued to urbanise and change since. These previous resources did provide suitable potential linkages at the time but urban development has expanded and spatial data and technology has advanced, allowing for the hostility of the urban matrix between remnant vegetation patches to be accounted for.

This study then provides the next step in understanding where to place viable linkages in a rapidly changing landscape. Several metrics were used to estimate the current state of connectivity between ‘formal’ and ‘semi-formal’ protected areas, and least-cost path modelling (LCP) was undertaken to understand where linking protected areas will be most effective and efficient.

5.1 The degree of connectivity between protected areas

5.1.1 Overall level of connectivity

Providing a connected network of protected areas is an important strategy to maintain biodiversity in urban ‘biodiversity hotspots’. This study has shown that protected areas in the Perth and Peel urban region in the south-west Western Australia ‘biodiversity hotspot’ are insufficiently connected to support species movements at realistic ecological distance thresholds (EDTs), based on species dispersal distance capabilities. As each species has different capabilities for dispersal, protected areas need connectivity at a range of EDTs to be able to support the biodiverse range of species in the area. Doerr et al. (2011) found limited landscape connectivity is problematic for most local species, as native Australian species have an average EDT of around 106 m. At 100 m EDT, most ‘formal’ protected areas show poor connectivity with approximately one third isolated from any other ‘formal’ protected area and the largest linked network only containing ~4% of the protected areas in the landscape.

Estimating connectivity using the Integral Index of Connectivity (IIC) for the Perth and Peel region found at 50 m EDT connectivity was near 0, and even at 1500 m EDT the ‘formal’ protected areas had an extremely low proportion of connectivity of ~0.0005 (in a range from 0 = no connectivity to 1 = the whole area being protected). This is not surprising as only 11% of the study area is under ‘formal’ protection, and these protected areas are small and scattered.

True connectivity however does not rely only on the protected area themselves. The current state of biodiversity in formal protected areas benefits from being in an urban matrix that contains remnant vegetation at differing degrees of protection. Incorporating 'semi-formal' protected areas in the analysis indicated additional connectivity within the protected area network. The IIC values showed a substantial increase between the 'formal' and the 'all' protected areas from 0.0005 to 0.0016 (an increase of 220%), as the area protected in the landscape increased from 11%, to a total of 16%. Using the Betweenness Centrality (BC) metric, a greater number of shortest paths through protected areas occurred, at distances greater than 500 m EDT, when 'all' protected areas were considered, compared to only 'formal' protected areas. The increase in connectivity is especially prominent when using the Size of Component (SC) metric, as at 50 m EDT the number of protected areas in isolation dropped from 50% to 25%. At the 1000 m EDT, the number of protected areas within the largest linked network increased from ~25% to ~80%. This shows the value of 'semi-formal' areas in biodiversity conservation.

Using multiple metrics has been valuable in this study; an approach undertaken by previous authors (see Lechner et al. 2015, 2017; Qi et al. (2017)), and recommended by Baranyi et al. (2011) and Rayfield et al. (2016). While the metrics and their findings used in isolation could skew the connectivity perspective of the landscape, having multiple metrics (each of which analyse different characteristics of connectivity) provides some redundancy and a more robust outcome where multiple metrics indicate the same result, validating the overall findings.

There are few studies which estimate connectivity using these metrics, within an urban environment and situated in a 'biodiversity hotspot'. Fourie et al. (2015) assessed connectivity using SC and IIC in the species-rich South African rural grasslands in Mpumalanga. They found similar results to this study with connectivity increasing at larger EDTs, but they found high connectivity with ~90% of the habitat area being linked at a 50 m EDT. Perth, like other studies in Europe which assessed urban grasslands' connectivity, have been altered more extensively due to human development and illustrated lower connectivity values (Soons et al. 2005; Hejkal et al. 2017).

The connectivity values for this study would likely further increase if all remnant vegetation were included in the analysis, as remnant vegetation in private property, state forest, and other tenures encompasses over 50% of the Perth-Peel landscape area. Work done by Zang et al. (2019) supports this conclusion. When they assessed connectivity at 20 m EDT for all green spaces throughout the city of Detroit, their IIC values rose with increasing green space scenarios. It is important to note that the current quality of protected areas is being supported by this actual degree of connectivity in the urban matrix. There is little or no protection of these urban remnants and future clearing will reduce the capacity of our protected areas to support biodiversity.

This study used Euclidian distance (shortest distance) in the connectivity metrics, yet in reality species rarely move in straight lines, particularly in urban environments. This assumption therefore provides the most optimistic estimates of the degree of connectivity. As a modelling exercise, Euclidean distance provides a basic, unarguable representation of the spatial configuration of the protected area network that represents the highest possible degree of capacity for species movement. More realistic routes are considered in section 5.3 below.

5.1.2 Contribution of the Bush Forever sites

Existing connectivity between the ‘formal’ protected areas is largely dependent on patches of remnant vegetation that are not formally protected to enhance the connectivity network across the region. Bush Forever sites were shown to be critical in this study to improve connectivity within the protected area network; the number of protected areas isolated from each other at 50 m EDT declined from nearly 50% (for ‘formal’ protected areas only), to 25% (when both Bush Forever sites and ‘formal’ protected areas were included). This small-scale dispersal capacity is integral to retaining less motile elements of our biodiversity. At 1000 m EDT, the positions of the Bush Forever sites within the landscape allowed them to function as stepping stones between the ‘formal’ protected areas. The largest linked network of protected areas at 1000 m EDT grew from ~20% to nearly 80%. This study supported the retention of Bush Forever sites as being critical to maintain ecological viability of the Perth and Peel protected area network, as acknowledged in the 2000 Bush Forever Policy (Western Australia Planning Commission 2000).

Bush Forever sites were originally established in 2000 to retain 10% of each vegetation community and protect local biodiversity from land clearing (Western Australian Planning Commission 2000). This study provides further evidence of the validity the Bush Forever policy and the necessity of protecting these sites. Yet, under an amended state policy in 2010 Bush Forever sites can be cleared for urban infrastructure if the proposed development provides greater opportunity to fulfil economic, social, and recreational anthropogenic needs (Western Australian Planning Commission 2010). This clause means Bush Forever sites are not safe from land clearing and development, rendering the goal of Bush Forever sites and future conservation biodiversity of the region, insecure.

5.2 Effective Placement of Linkages

As shown in section 5.1, connectivity between ‘formal’ protected areas was low for realistic EDTs. This suggests reliance on protected areas, which have been shown to be highly fragmented and isolated, to protect biodiversity of the region is not realistic. Identifying linkages between protected areas can enhance the viability of the network for enabling species movement. To identify effective and efficient linkages, land planners and managers need tools which are neither too complex or time-consuming to make appropriate connectivity planning choices. Least-cost path (LCP) modelling is recommended by this study to provide this information. LCP modelling outlines effective placements for potential ecological linkages between protected areas which are least hostile to species movements. The 10 m resolution maps produced in this study incorporates the landscape features and the protected area network, identifying landscape elements which hinder or enable species movement. Providing this spatially explicit representation of the urban landscape and the ecological protected area network of the region enables land managers and planners to analyse local areas in a regional context when forming local planning decisions. This tool therefore empowers managers and planners to make suitable decisions that supports local biodiversity. The LCPs are characterised by thin lines on the map, which represent the general direction of the path. This does not mean that the vegetated areas around the LCP are not necessary for species dispersal but that this is simply the most efficient route for the model. The greater the size and number of native vegetation remnants present, the greater the number of options for species dispersal, the reduced risk for movement and a greater opportunity to support biodiversity (Ramakrishnan 2008). As the LCP linkages only identify routes which are least hostile for species movements, they can take many shapes and forms depending on the landscape features between the protected areas, not necessarily large strips of vegetation generally associated with wildlife corridors. The concept is to reduce the hostility of the urban matrix. For example, linkages may incorporate stepping stones which use vegetated gardens, verges, and parks in residential areas to increase the permeability for a species to move between two protected areas. This section will look at how the LCP resource can be used to create efficient and effective potential linkages by identifying where to: break barriers, create green enhancement, and protect native remnant bushland.

5.2.1 Break barriers

The LCP resource can be used to investigate where LCPs cross barriers. This identifies locations where strategies to aid species dispersal across barriers are appropriate. Barriers between conservation areas are ubiquitous within the Perth and Peel region, with many protected areas separated by transport infrastructure (Stenhouse 2004) (Appendix C). Transport infrastructure not only threatens flora and fauna by removing natural habitat and as a source of fauna mortality, but also by preventing species movement between close protected areas that might otherwise be easily accessible (Forman and Alexander 1998; Trombulak and Frissell 2000; Shepard et al. 2008). Culverts, fauna bridges, and underpasses are successful strategies that have been used to mitigate this issue (Kusak et al. 2009; Rytwinski et al. 2016). LCP modelling has been used as an approach to inform where to place bridges and underpasses, to improve the connectivity network for species (Cushman et al. 2014).

Fauna bridges have been implemented in some parts of the Perth Peel region, such as the possum bridge along Beeliar Drive that connects the Beeliar wetlands (Figure 29), and the fauna bridge Tonkin Highway that links two strict nature reserves (IUCN category1a) (Figure 30) (City of Cockburn 2019; Main Roads 20219). The value of these interventions was identified in the LCP modelling as they were integral to the LCPs in the areas where they occurred. The LCPs identify more areas within the Perth and Peel where road barriers could be broken, such as where Mitchel Freeway divides Bush Forever site 303 and 407 (Appendix C).

Figure 29. The possum bridge over Beeliar Drive connecting the Beeliar wetlands, over which possum movement would otherwise be hindered by this road barrier. Image supplied by author.

Figure 30. The fauna bridge over Tonkin highway links two IUCN class a1 nature reserves and is large enough to allow larger species movement (top) and an emu demonstrating how to use the fauna bridge (bottom). Image supplied by author.

Multiple marinas have presented themselves to be barriers for species movement across the Perth and Peel region, as identified by the LCPs (Appendix C), as most species cannot cross open water (Tremblay and St. Clair 2009). Marinas also include carparks, boat ramps, toilets, cafes, and shops, which heavily disrupt species movement and negatively impact surrounding bushland ecosystems (Fischer and Lindenmayer 2007). For existing marinas, adaptive urban design, which incorporates native flora in streetscapes to aid species movement would be a way to improve species movements through these areas (Felson et al. 2013). The Two Rocks Marina embodies this recommendation insofar as it divides the Bush Forever sites 397 to its north and south (Appendix C). Any new projects that develop marinas, such as the Ocean Reef Marina (City of Joondalup 2016), could easily incorporate natural elements that enable species movement along the coast.

5.2.2 Green enhancement

The LCP resource can be used to identify where green enhancement within the Perth and Peel region will improve linkages between protected areas. Re-introducing, restoring, and maintaining native flora on verges, roadsides, cycle paths and parks to increase the number and size of stepping stones used by the LCPs would benefit biodiversity (Appendix C). This is particularly important since research has shown that small isolated areas struggle to support species: reserves may appear to be maintaining populations because many species are long lived, but juvenile recruitment may no longer be occurring (Saunders et al. 1991; Ramalho et al. 2014). Vegetated verges have been found to support populations of certain flora and fauna species by reducing the required dispersal distance and thereby enhancing seed dispersal between adjacent populations, while also providing more foraging habitats for birds and increasing insect abundance (Suárez-Esteban et al. 2016; Villemey et al. 2018; Morelli et al. 2014). Incentives and education about the importance of planting local flora species are recommended, since private gardens have been found to help local pollinators, maintain local flora species, enhance ecosystem services, and provide habitats (Samnegård et al. 2011; Goddard et al. 2010; How and Dell 1994). Where there are limited protected areas and distances between protected areas are substantially greater than the capabilities of most species, as found in the City of Bayswater, City of Fremantle, the Town of East Fremantle, the City of Subiaco and the Town of Victoria Park, this provides a greater challenge (Appendix C). However, greening these suburbs will increase the permeability of the urban matrix while creating a beneficial greening that will improve people's physical and mental health (Sandifer et al. 2015). In other parts of the Perth Peel region, protected areas are closer together and ecological linkages will be easier to reintroduce, restore, and maintain, such as the area comprising Bold Park, Herdsman Lake, Lake Claremont, and Shenton Bushland (Appendix C).

Vegetation along roads in the agricultural areas of the Perth and Peel have been identified by the LCPs as being potential routes for species movement in the Peel planning region (Appendix C). Well-vegetated road verges in regional areas have been extensively documented to support small mammal movement between local habitats (Galantinho et al. 2020). These linkages within the Peel region are therefore important to link protected areas within the Swan Coastal Plain and towards protected areas in the Darling Scarp. It is important to have linkages that connect the two bioregions for species such as *Calyptorhynchus latirostris* (Carnaby cockatoo), and *Isoodon obeulus* (quenda) to take advantage of both habitat types (Peck et al .2018; Friend 1990). Reintroducing, restoring, and maintaining vegetation on road verges and field edges within linkages identified by the LCPs is a way to improve connectivity in the more agricultural areas of the Perth and Peel region.

5.2.3 Protect native remnant vegetation

Protecting small remnant patches

The LCP modelling can be used to determine where providing further protection to remnant vegetation will improve the protected area network. For example, LCPs run through small inner-city parks such as Charles Riley Memorial Reserve which links two protected areas: Star Swamp reserve and Trigg Bushland reserve within the Central

Metropolitan Planning Region (MPR) (Appendix C). Endowing these inner-city parks with protection and enhancing the biodiversity within them will help to ensure their preservation as stepping stones between the protected areas. Preservation of these linkages within the dense urban areas will help sustain local native populations. For instance, urbanisation of the Perth and Peel has fragmented the predominant endemic vegetation community of *Banksia* woodlands to the point that it is now an ecological threatened community, with the average patch being only 0.16 hectares (Barret and Towers 2017 (Appendix C). These habitats have been found to become degraded when they are reduced to under 10 hectares (Ramalho et al. 2014). Protecting parks which help to link these habitats (thereby increasing their effective size) is therefore important to support their ecological viability and to sustain biodiversity. The idea that smaller inner-city parks are unworthy of protection due to their lesser species richness when compared to outer city larger reserves cannot be a justification for their removal to build additional urban infrastructure (Stenhouse 2004). Quite apart from the integral role they play in retaining species in these areas they are essential for people’s experience of biodiversity, benefiting the physical and mental health of inner-city dwellers.

Remnant bushland in less dense urban areas is equally essential in facilitating species movement. This is seen in the North West MPR where the LCP links Bush Forever site 397 and 130 through Tamala Park. In the North East MPR, LCPs use non-protected continuous native remnant vegetation to link Walyunga National Park and Avon Valley National Park (Appendix C). These areas of remnant vegetation provide strong connections and facilitate movement between protected areas for local species, reducing the distance they have to transverse through the urban matrix. Many species are more likely to move through areas that are representative of their habitat rather than the urban matrix, due to the safer and familiar routes they present (Pulsford 2017; Püttker et al 2011). Providing protection to remnant vegetation within LCPs, will secure vegetated safer routes for all species when dispersing to different protected areas.

Least-cost paths in Forest

State Forests play a key role in facilitating movement along the Darling Scarp of the North East MPR, South East MPR, and the Peel planning region. The large National and Conservation Parks such as Bellu National Park, Korung National Park, Kalamunda National Park, Helena National Park, Midgegooroo National Park, Monadnocks Conservation Park, Serpentine National Park, and Lane Poole Reserve, are all situated within the Jarrah and Marri State Forest and depend on it to facilitate movement between them (Appendix C). This region is estimated to have a species richness of 400-600 species/km^2, with high degrees of endemism in around John Forrest National Park and Helena National Park (Williams and Michell 2001). Historically, this forest has been heavily logged; Jarrah trees that were predicted to live for between 800-1000 years now rarely make 100 years due to the logging rotations (Williams and Michell 2001). However, the most recent Forest Management Plan for the Jarrah Forest recognises the need for sustainable practices to maintain the forest for future generations and identifies the importance of maintaining connectivity between their reserves and minimising fragmentation (Conservation Commission of Western Australia 2013). The LCPs that are found to connect protected areas within the Jarrah State Forest can provide foci for protection from anthropogenic practices such as logging in accordance with the Forest Management Plan (Conservation Commission of Western Australia

2013) (Appendix C). The LCPs within the forest take the shortest routes between protected areas because of the landscape's homogeneity of cost values (Appendix C). Linkages between protected areas that only use the state forest do not necessarily need to follow the exact LCP, provided there is effective linkages occur.

Riparian connections

Riparian areas often provide linkages (Hilty and Merenlender 2004; Fremier et al. 2015; Rouquette et al. 2013) because they are pre-existing linear elements that support flows of water, energy, and biota across the landscape. For example, Hilty and Merenlender (2004) found mammal predators preferred to disperse through riparian linkages than move through vineyards in the Sonoma wine region of California. The LCPs highlighted the importance of rivers and wetlands within all regions including Yellagonga Regional Park, the Swan and Canning Rivers, Beeliar Regional Park, Murray River, and Serpentine River (Appendix C). Wetlands support a wide range of species and keeping them linked supports regional diversity (Amezaga 2002). The Swan Coastal Plain like other parts of the world have seen major losses in their wetland systems due to vast urbanisation (Mao et al. 2018), with over 70% lost. The protection of the riparian connections identified by the LCPs, will thereby help to support dispersal needs of local species.

5.2.4 Collateral benefits

Breaking barriers, enhancing green spaces, providing protection to bushlands, forests, and waterways facilitates linkages between protected areas and provides not only linkages for flora and fauna but also multiple social benefits. Having more natural areas throughout a city gives opportunity for passive recreation such as walking and bird watching for residents, creates a sense of place, and enhances ecosystem services

(Wolch et al. 2014). Around the globe, ‘biodiversity hotspots’ have lost at least 30% of their original native vegetation, thus rendering those vegetation complexes threatened (Myers et al. 2000). Local governments within the Perth and Peel Region within their local biodiversity strategies have therefore set aims of retaining 30% of each natural vegetation community in order to maintain biodiversity (Del Marco et al. 2004). The integration of biodiversity targets within the linkages identified by the LCPs multiplies the efficacy of work to the benefit to both humans and other species in the Perth and Peel regions.

5.2.5 Caveats of LCP modelling

LCP modelling, as with any modelling, is only as good as the input data included within the model. This research incorporated as much landscape information as possible through data from the Department of Planning, Lands and Heritage and online publicly available data. This model could have been improved if there were datasets present on fence locations as they increase ecological costs as a significant barrier to most species’ movement (Hayward and Kerly 2009). Data sets that identify differences within urban plantings such as parks which are outside of native remnant vegetation, such as species composition would also have improved the model’s application. To minimise these effects satellite image data from spring 2019 and summer 2020 was used to identify perennial and annual vegetation (Drusch et al. 2012).

LCP modelling also relies on the costs given to each landscape feature, which in this study and in many others rely heavily on expert opinion (Etherington 2016). Selecting meaningful ecological cost values for the cost-surface is a difficult aspect of this approach due to the challenges of researching species movements. To mitigate potential biases this study reviewed the literature, and where suitable, applied corresponding cost values to the model. Even with these limitations the LCP modelling has outperform other simpler models and been as effective as more complex models (Pascual-Hortal and Saura 2006; Etherington 2016; Balbi et al. 2019).

Urban landscapes are constantly changing and evolving to keep up with human demands. The LCP modelling resource can readily be updated as landscape changes occur and as new data is released, to allow land managers and planners to make biodiversity conservation decisions based on the most recent information.

Whilst connectivity can enable invasive species and disease movement, multiple studies have demonstrated that increased linkages and habitats is better for overall biodiversity conservation (Hannah et al. 2002; Shafer 2014 Fremier et al. 2015). Invasive species and diseases need to be managed with connectivity. Increasing the area in which species have to move between habitats has also been found to potentially ameliorate these negative impacts by increasing population resilience (Hadded et al. 2014). The integration of potential linkages within highly fragmented landscapes is therefore an integral process in supporting biodiversity.

5.3 Future work

The Perth and Peel region has an large number of species and while the LCPs identified 1,268 potential linkages between all the protected areas, this network may not encapsulate all the biodiversity of the region. This research only identifies where the protected areas are and provides strategies and recommendations to link them based on the landscape features between. Studies such as ‘gap analysis’ or similar assessments of biodiversity by the regions protected areas can be conducted to identify the biodiversity ‘gaps’ (Kandel et al. 2016). Once these ‘gaps’ have been identified, a systematic conservation planning exercise could be undertaken to determine priority sites given their biodiversity assets and associated costs. Then, only once these sites are known, LCP modelling can be used to identify linkages between them.

The LCPs identified potential linkages a species could use based on the ‘low costs’ associated with the permeability of the landscape features, rather than actual linkages a species take, as some may migrate to particular habitat types. For example, a species may disperse to a certain habitat for breeding, such as wetlands, even if the cost is lower in other directions (Buhlmann and Gibbons 2001). Therefore, future work to monitor and evaluate whether the LCPs are being used, and by which species, should be undertaken to provide a prioritisation of linkages for management. This research would also identify paths which are not used and will help to determine whether alternative routes are being used by species and why, in order to provide further recommendations to land planners and managers.

6. Conclusion

To conserve biodiversity in urban environments, land planners and managers need to go beyond protecting small areas of habitat in isolation, to providing opportunities for species to move between them. This research identified that the ‘formal’ protected area network within the Perth and Peel region, situated in south Western Australia’s ‘biodiversity hotspot’ are not sufficiently connected to support species movement at a range of ecological distance thresholds (EDT). The ‘formal’ protected areas are too far apart for many native Australian species which typically have EDT of ~100 m. The current network relies on the permeable landscape features between the formal protected areas such as Bush Forever sites to improve connectivity. Enhancing the landscape features to increase the degree of connectivity between protected areas should therefore be a planning priority. To do this land planners and managers need tools to make appropriate connectivity planning choices, which are not too complex or time consuming, and are dynamic and applicable. The least-cost path modelling illustrated in this study identified landscape features which facilitate species movement between protected areas and the routes that take advantage of them providing comprehensive 10 m resolution maps, to allow efficient and effective actions to improve connectivity. Tailored recommendations which include ways to break barriers, enhance appropriate green spaces, and provide adequate protection to natural areas have been created from this research’s findings, with acknowledgment to previous connectivity frameworks within the region to ensure their economic and social relevance. This resource will need to be updated as the landscape changes to continue to provide decision makers with appropriate strategies for biodiversity conservation. This research contributes to an understanding of connectivity urban areas across the globe, with applicable solutions, will also help to ease the growing biodiversity extinction crisis.

7. References

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Appendix

Appendix A. Betweenness Centrality maps (begins next page)

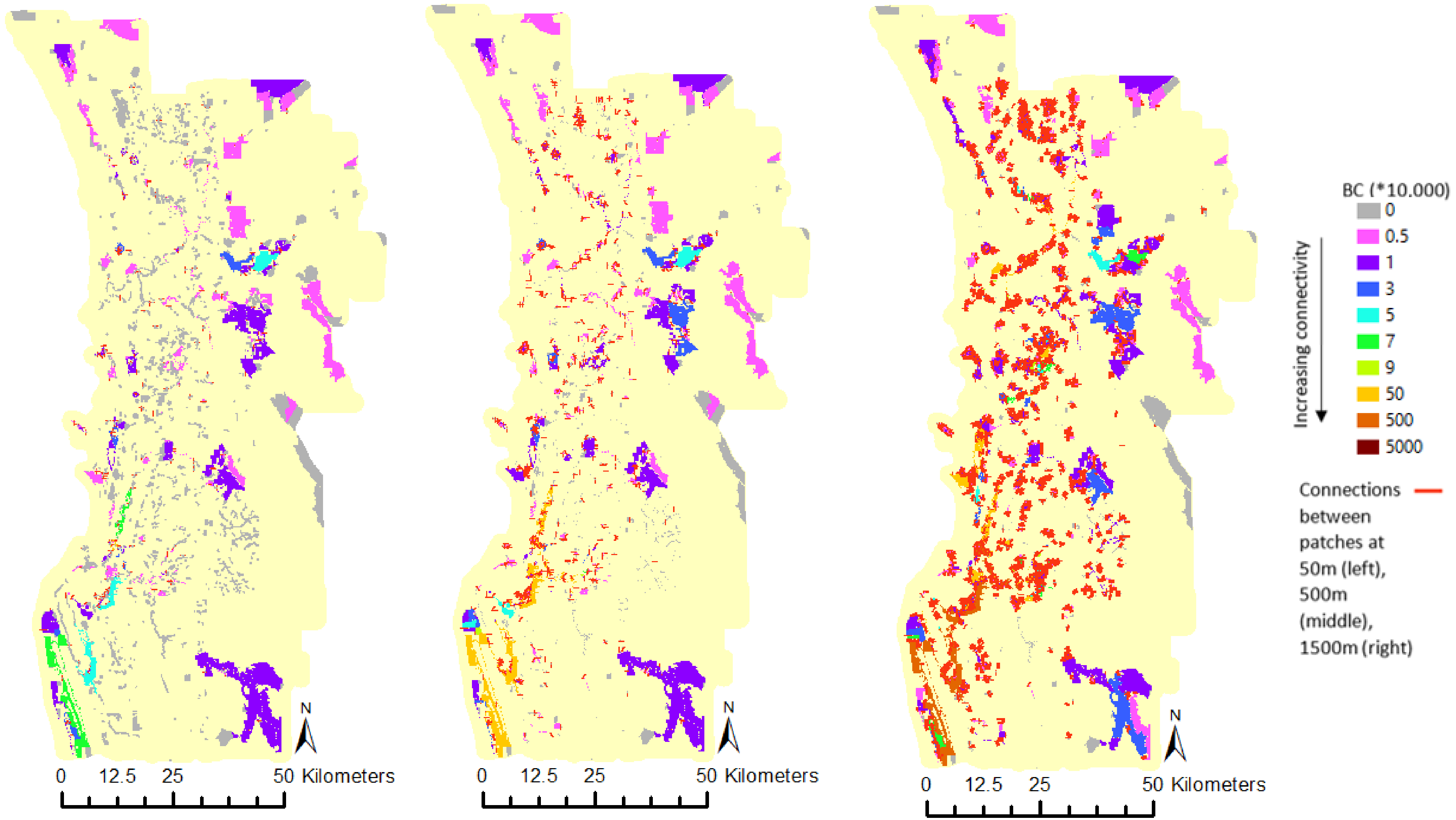

Figure 1. The individual role of 'formal' protected areas in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 100m (left), 300m (centre), and 1,000m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

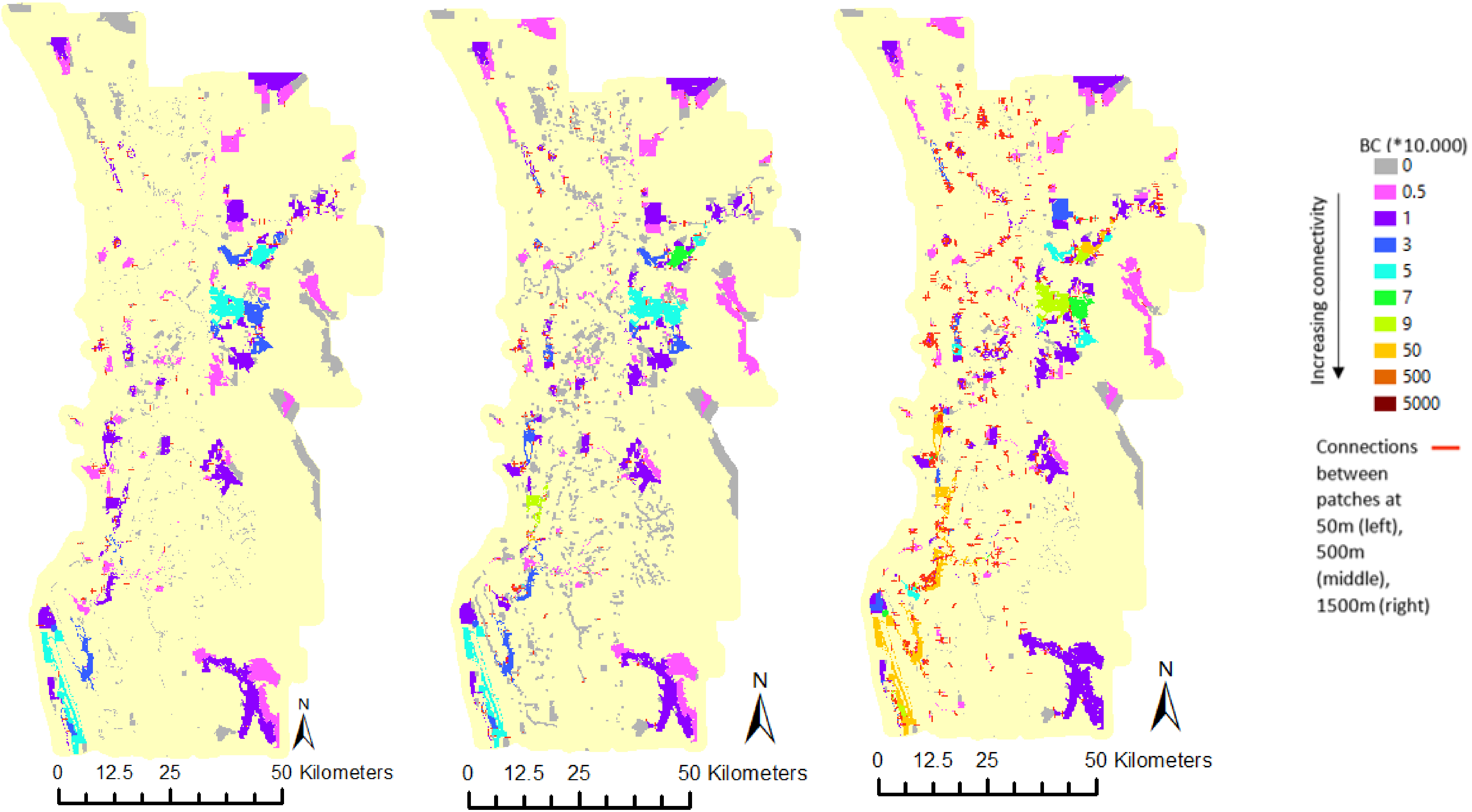

Figure 2. The individual role of 'formal' protected areas and Regional Parks in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

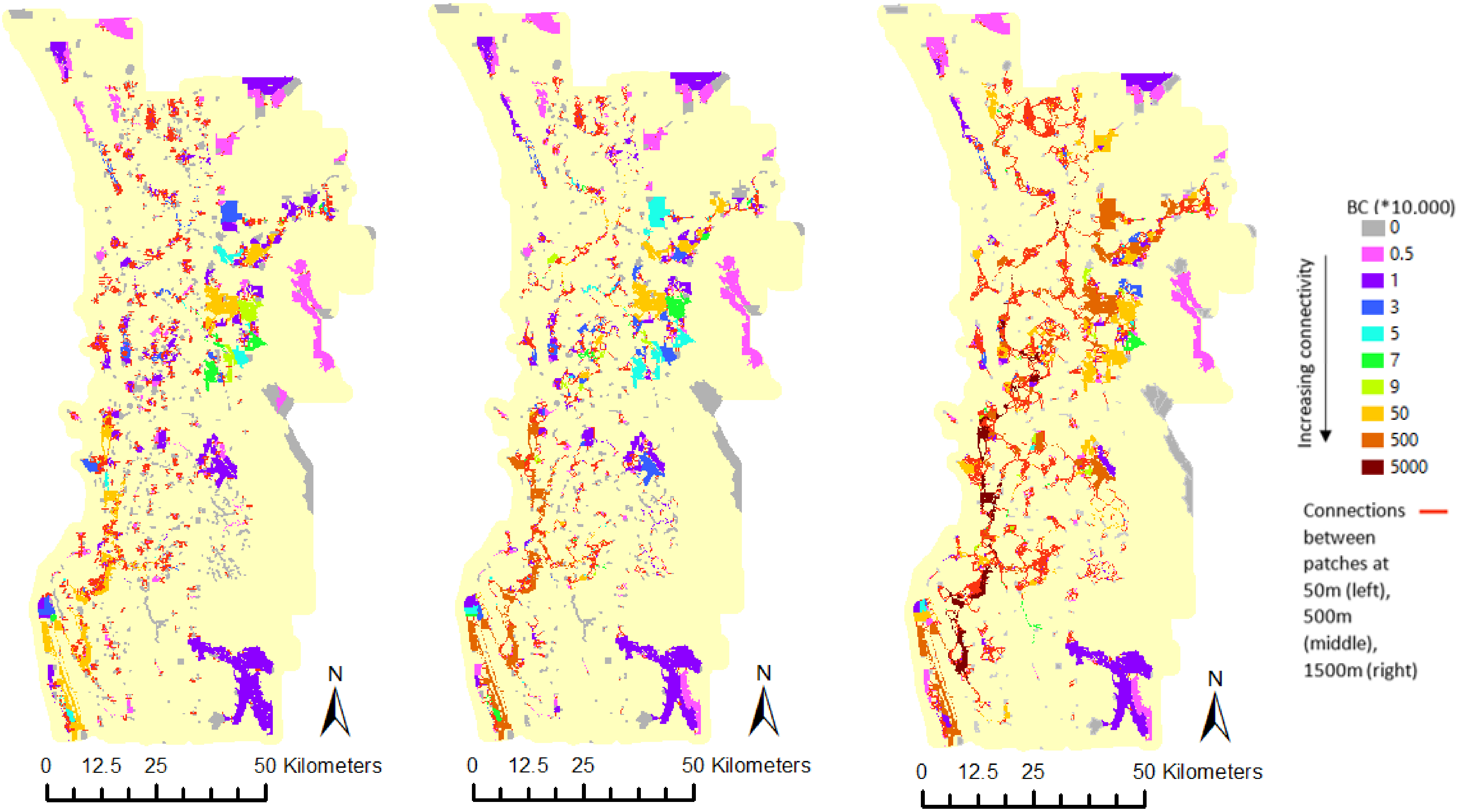

Figure 3. The individual role of 'formal' protected areas and Regional Parks in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 500m (left), 1,000m (centre), and 1,500m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

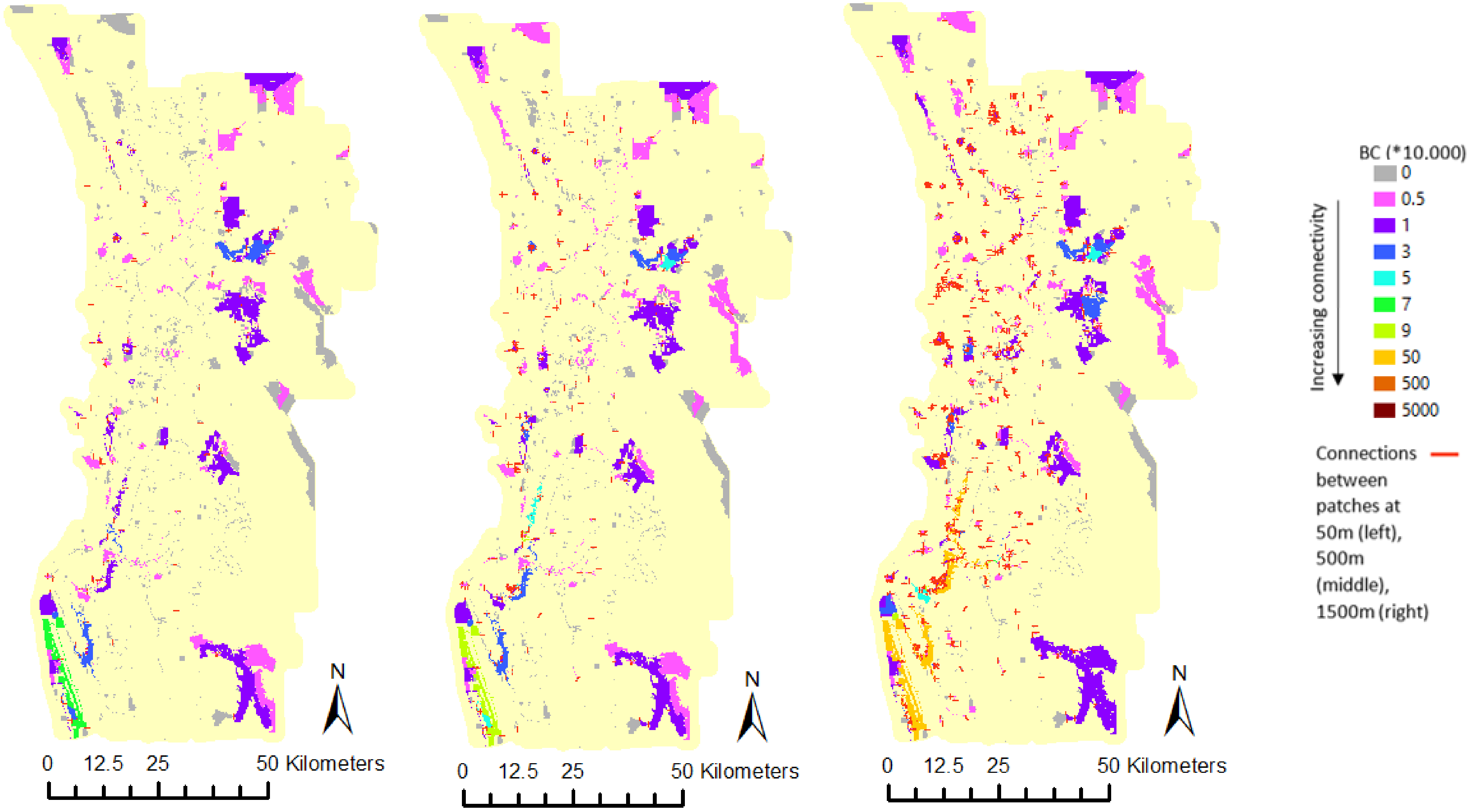

Figure 4. The individual role of 'formal' protected areas and Class 'A' Reserves in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

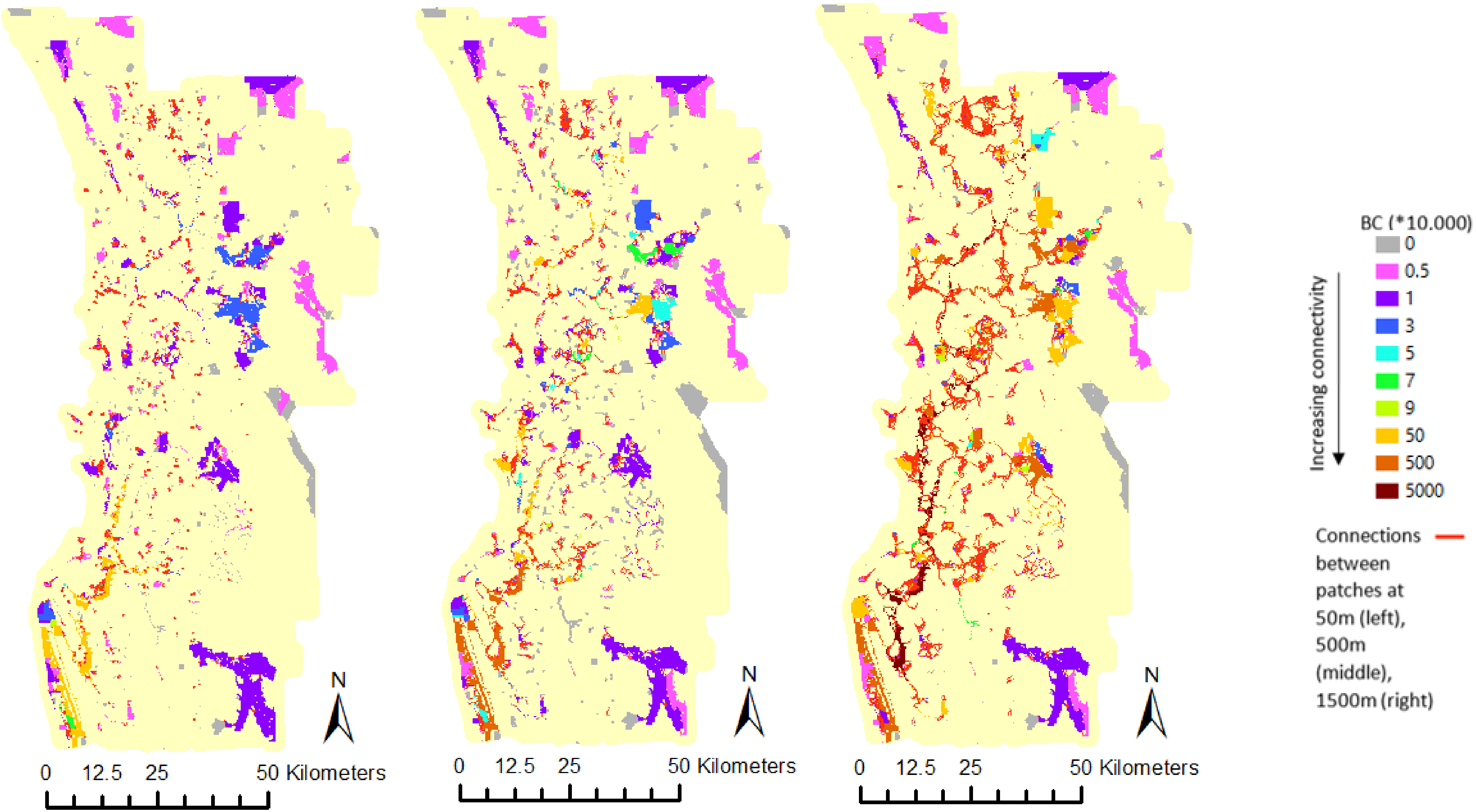

Figure 5. The individual role of 'formal' protected areas and Class 'A' Reserves in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 500m (left), 1,000m (centre), and 1,500m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

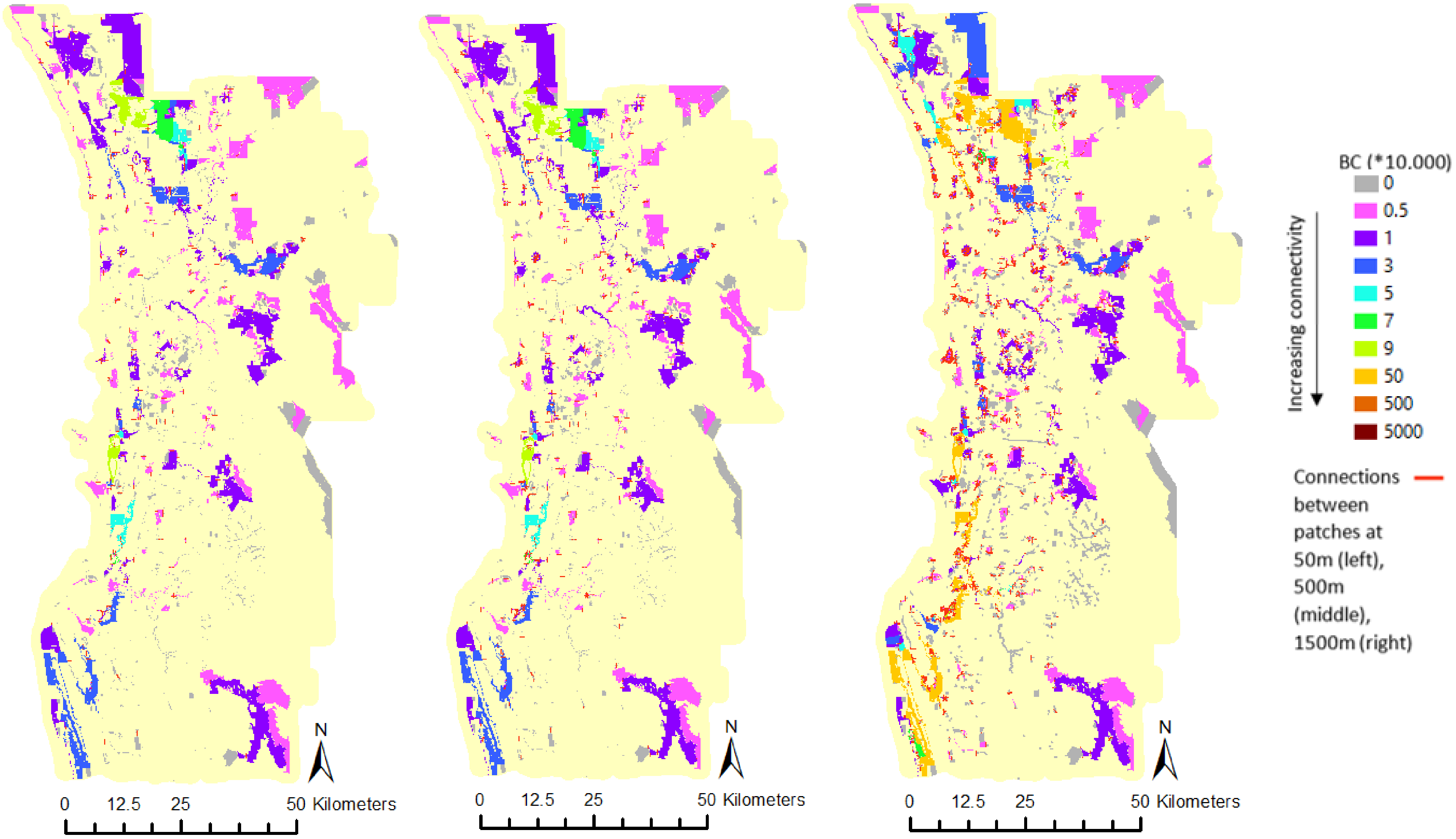

Figure 6. The individual role of ‘formal’ protected areas and Bush Forever Sites in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

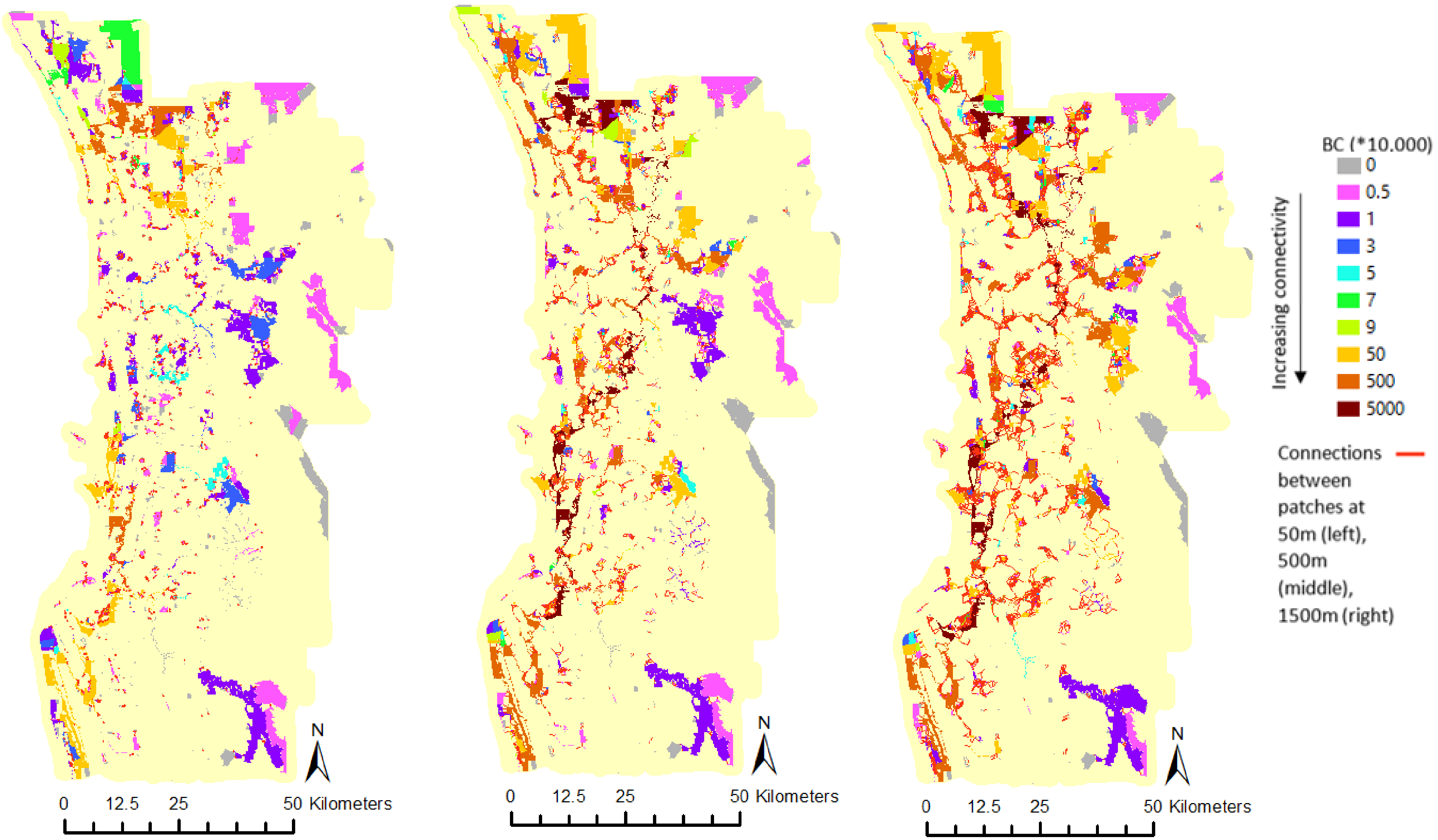

Figure 7. The individual role of 'formal' protected areas and Bush Forever Sites in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 500m (left), 1,500m (centre), and 1,500m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

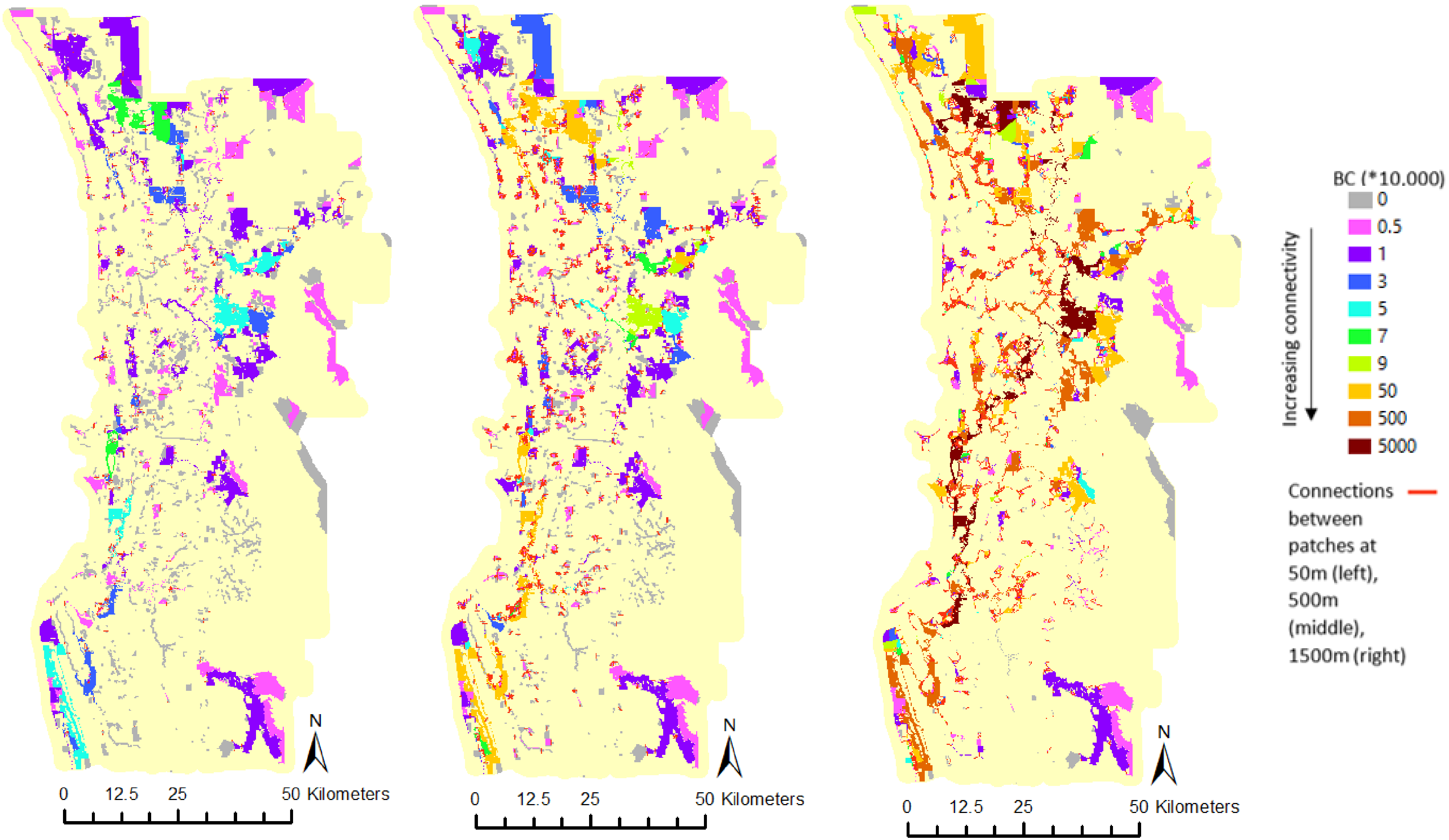

Figure 8. The individual role of 'all' protected areas in enabling species movement from one protected area to another based on the number of shortest routes through an individual protected area (Betweenness Centrality, BC) at different EDTs that species can move: 100m (left), 300m (centre), and 1,000m (right). The protected areas borders have been emphasised to enhance the visibility of the protected area and their BC result

Appendix B. delta Integral Index of Connectivity maps (begins on next page)

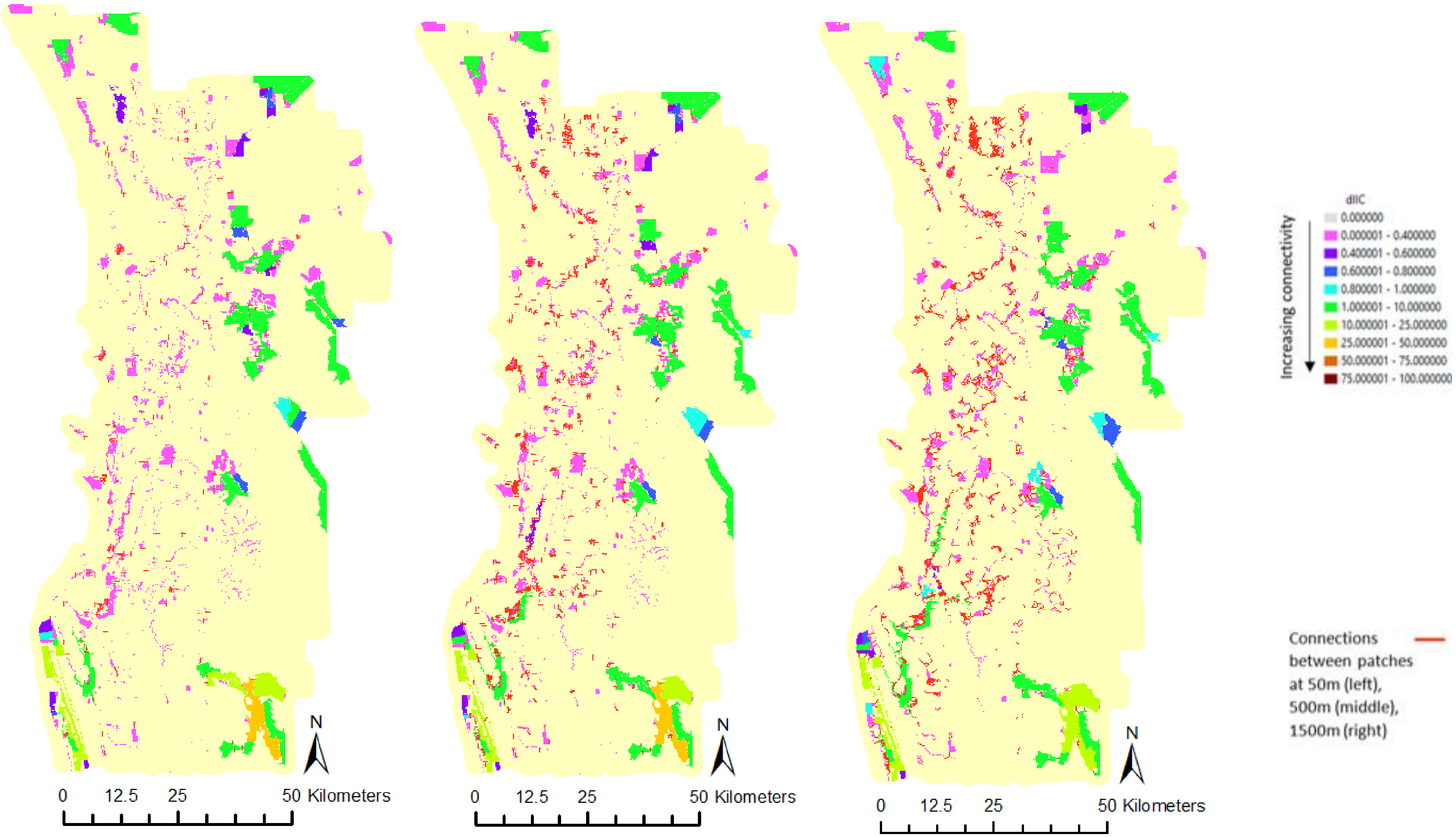

Figure 9: The individual role of the 'formal' protected area in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 100m (left), 300m (centre), and 1,000m (right).

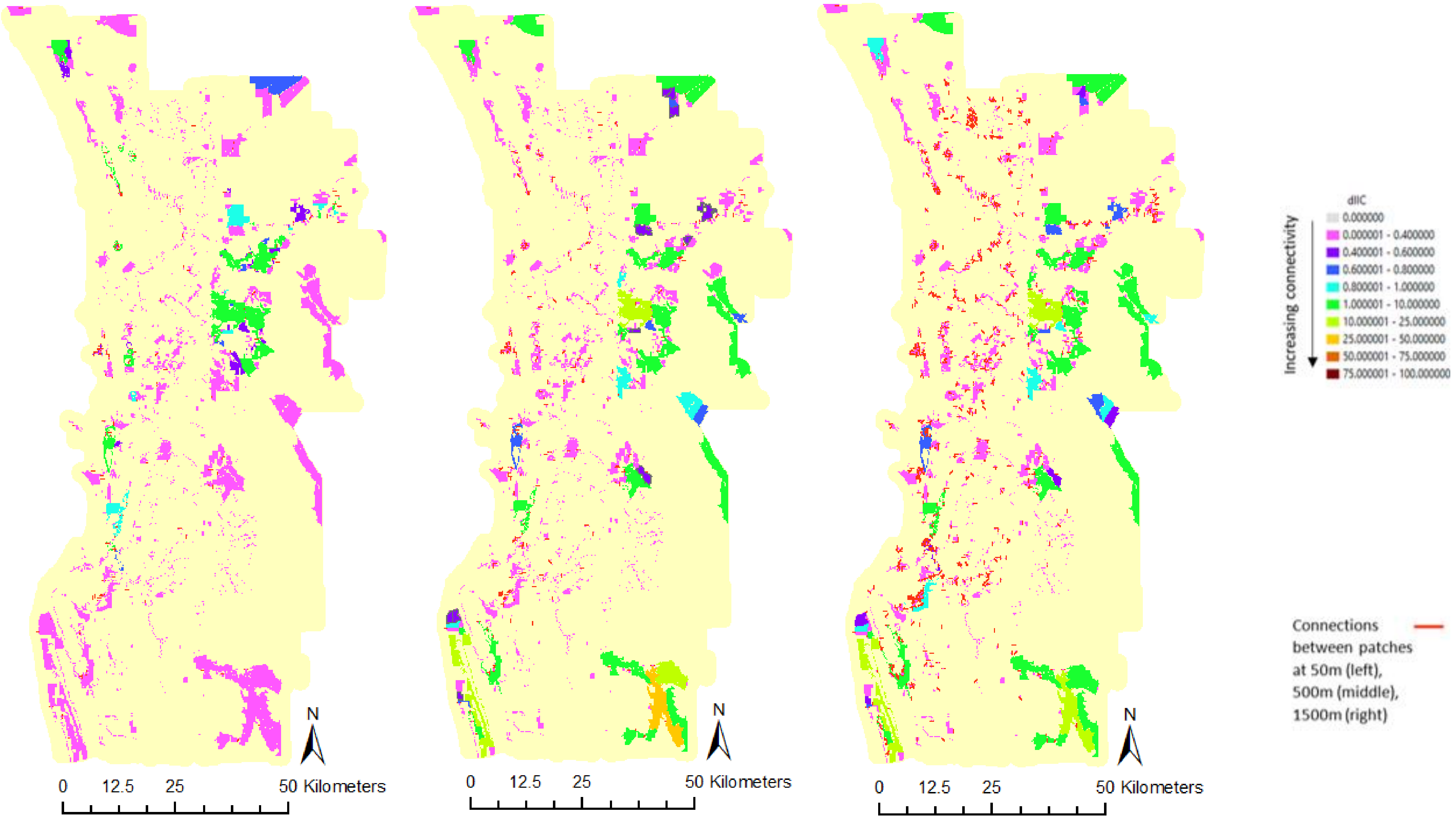

Figure 10: The individual role of the 'formal' protected area and Regional Parks in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right).

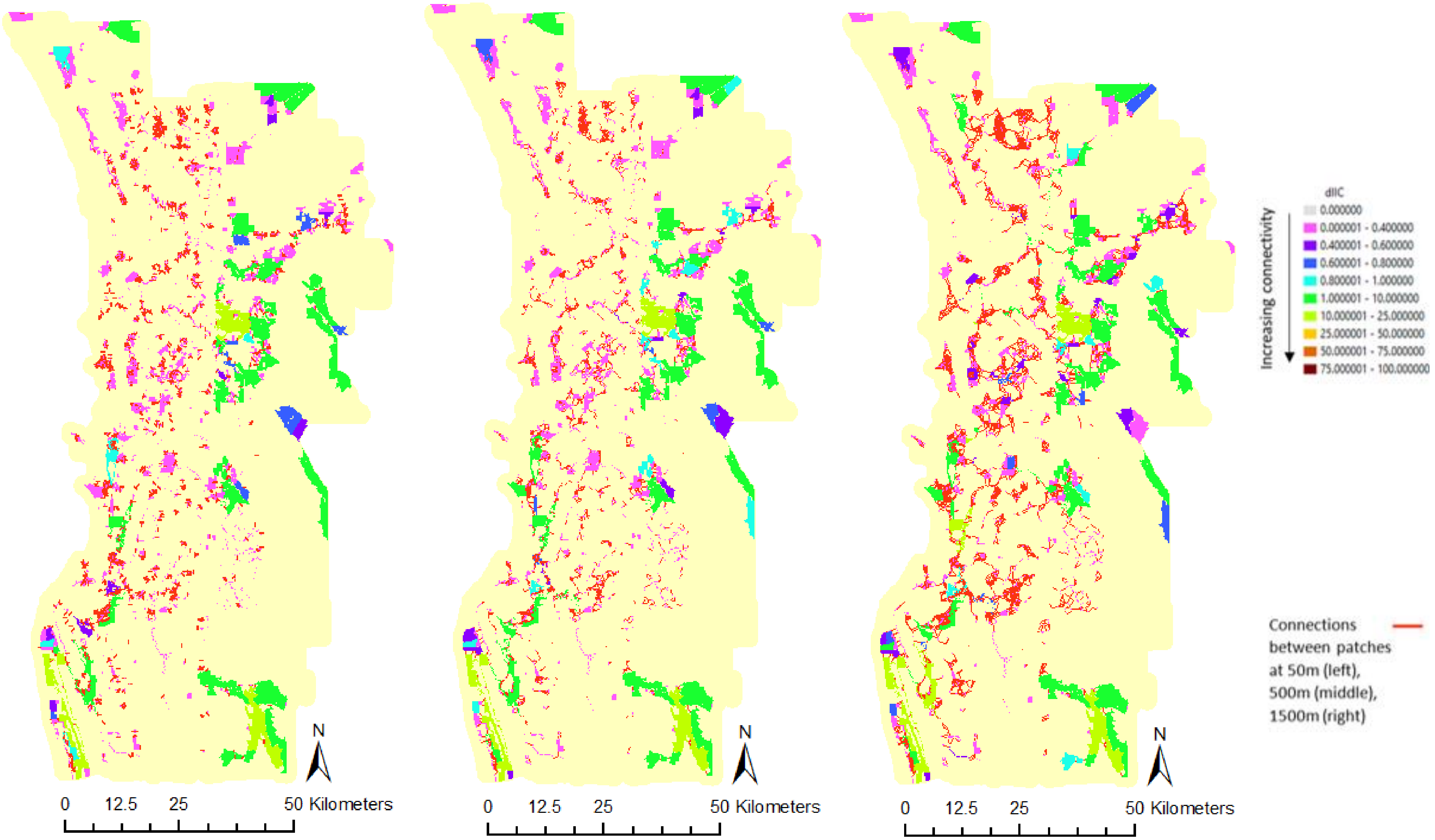

Figure 11: The individual role of the 'formal' protected areas and Regional Parks in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 500m (left), 1,000m (centre), and 1,500m (right).

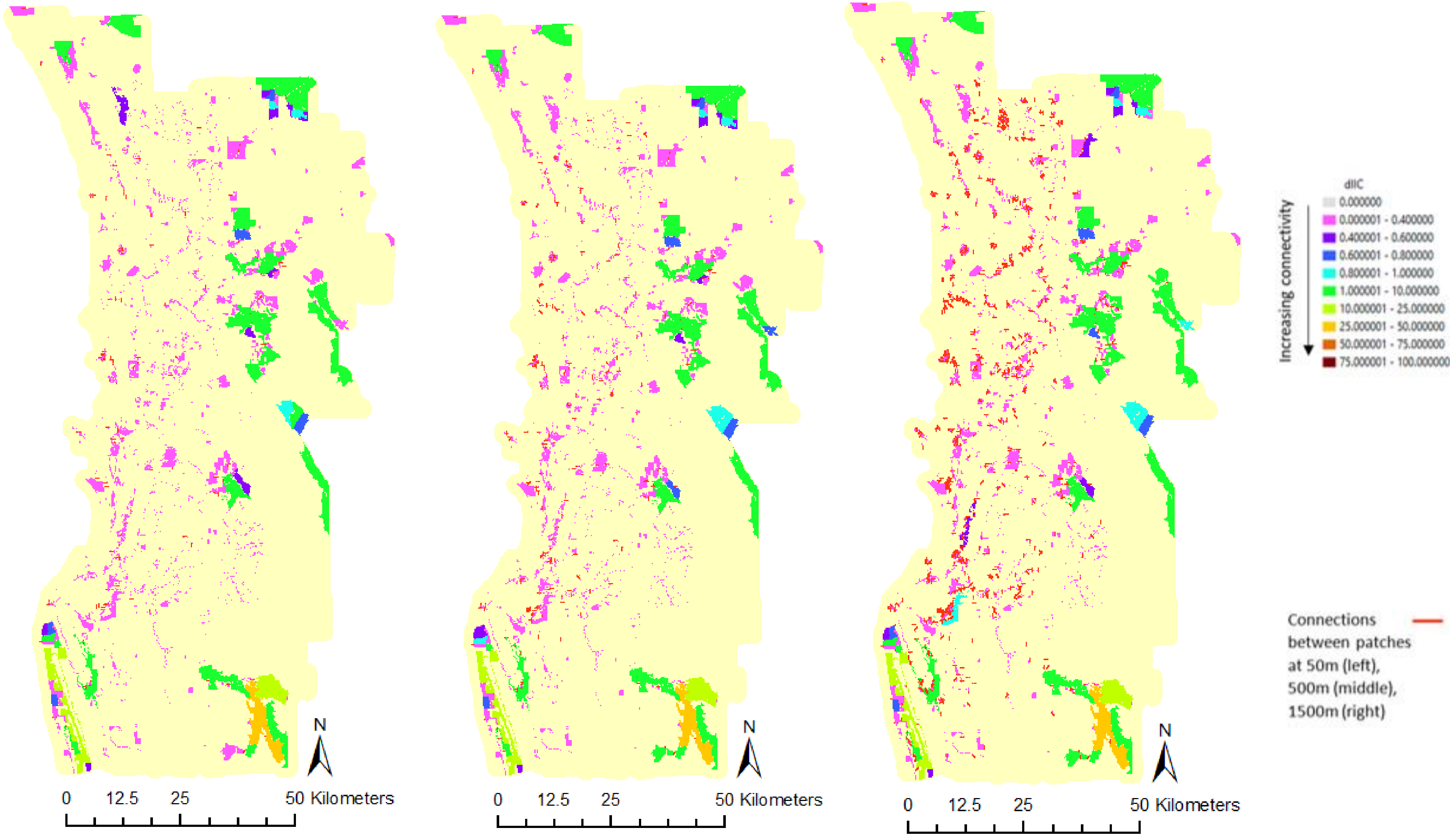

Figure 12: The individual role of the 'formal' protected araes and Class 'A' reserves in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right).

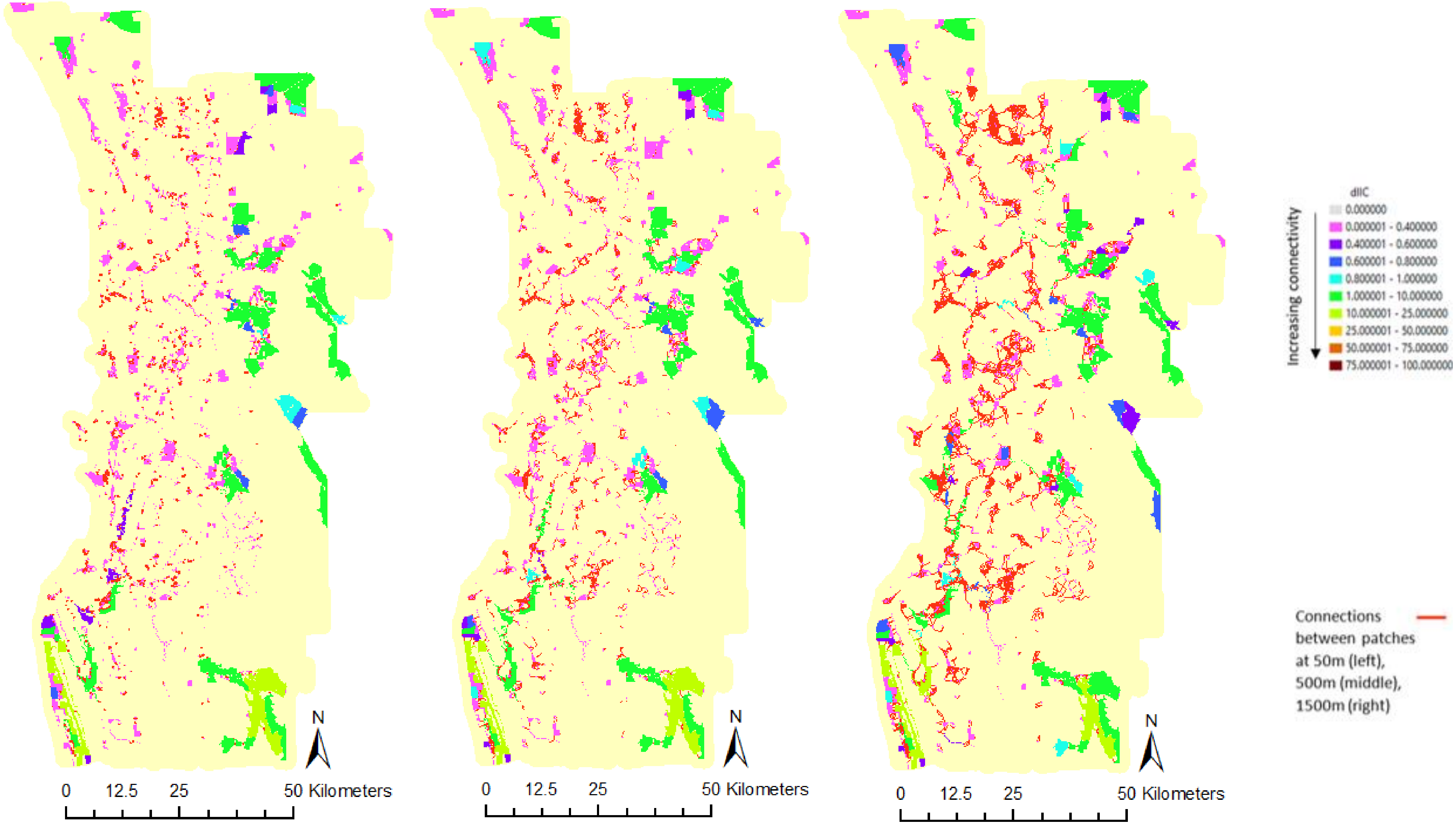

Figure 13: The individual role of the ‘formal’ protected areas and Class ‘A’ reserves in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 500m (left), 1,000m (centre), and 1,500m (right).

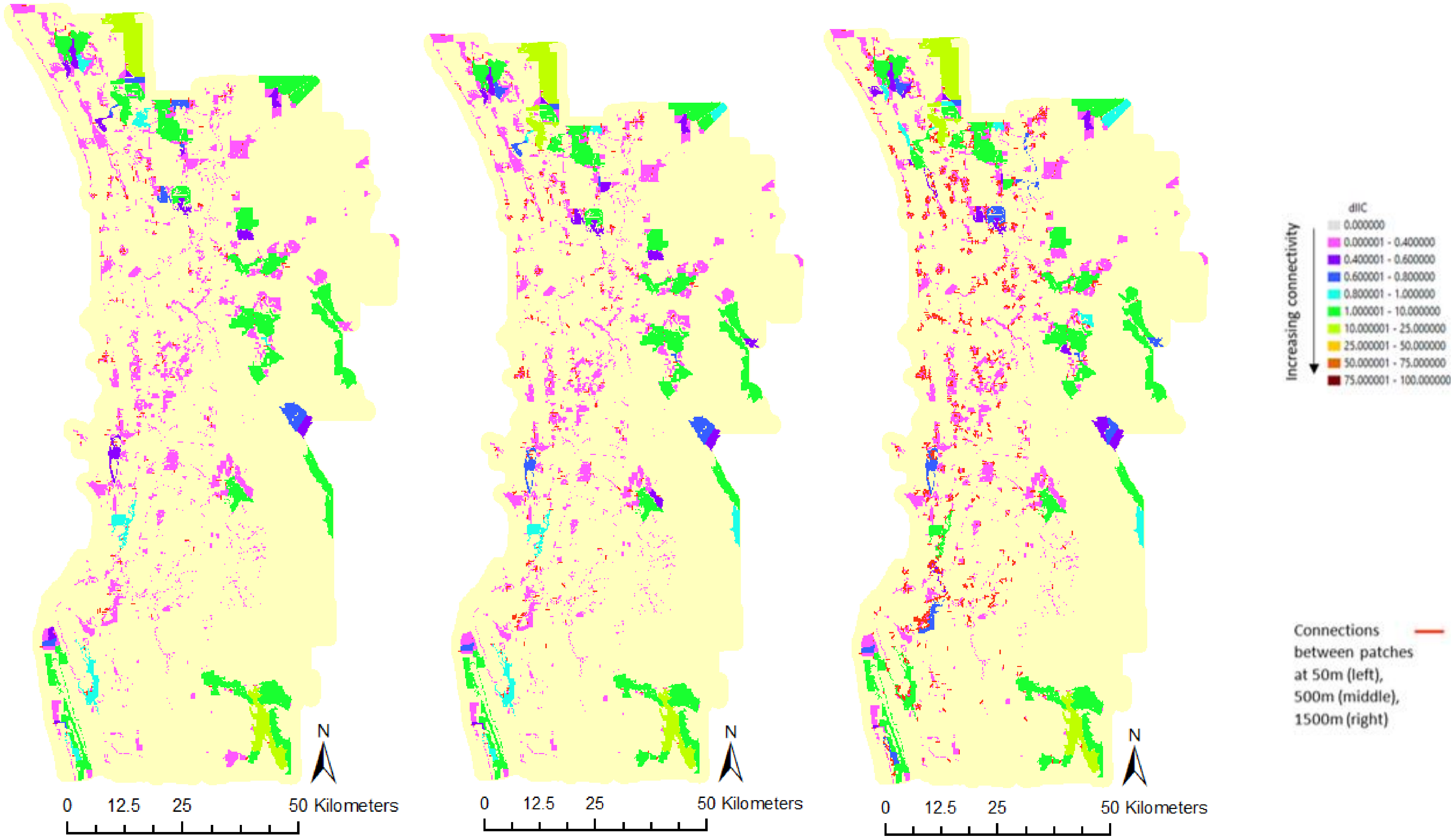

Figure 14: The individual role of the 'formal' protected areas and Bush Forever sites in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 50m (left), 100m (centre), and 300m (right).

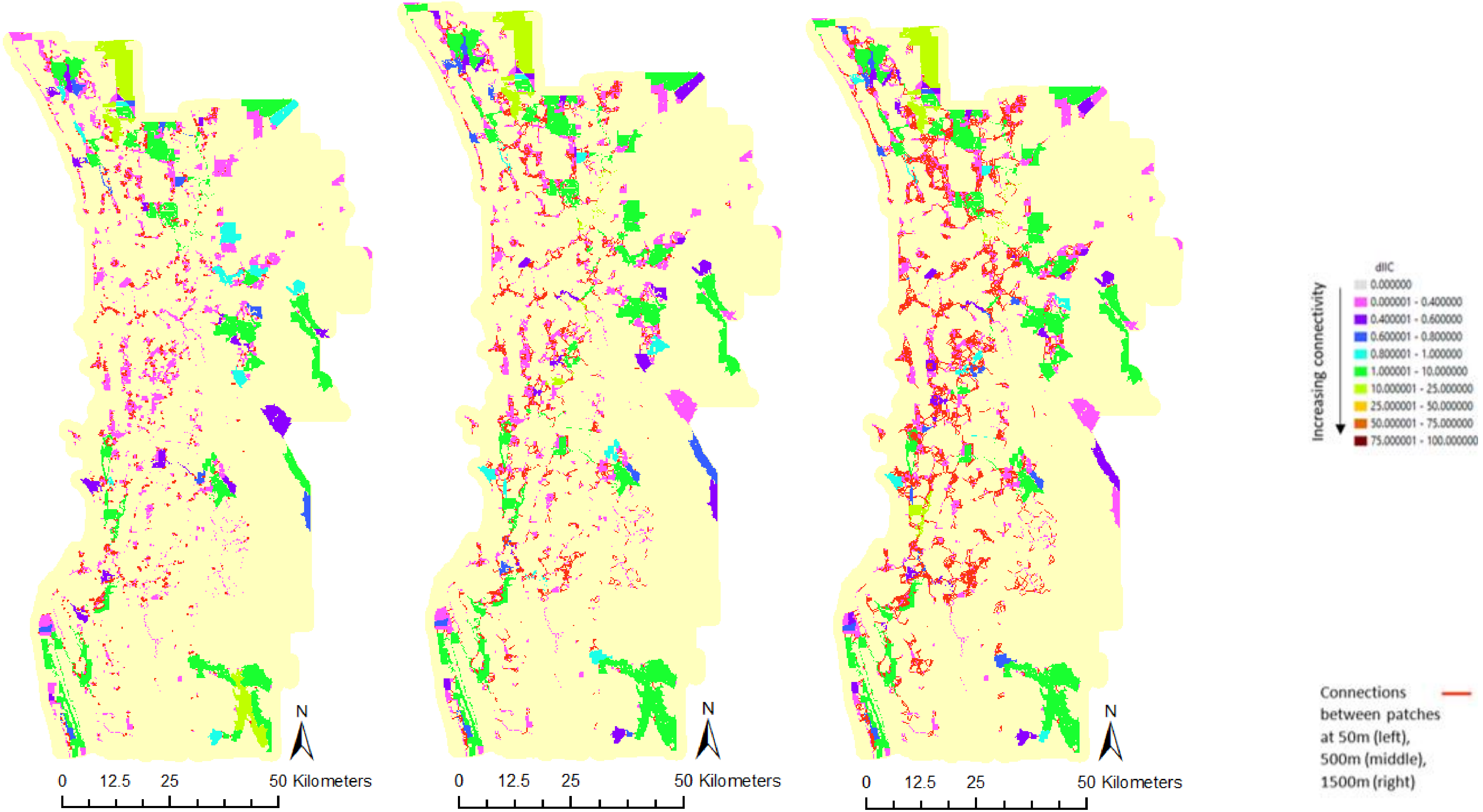

Figure 15: The individual role of the 'formal' protected areas and Bush Forever sites in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 500m (left), 1,000m (centre), and 1,500m (right).

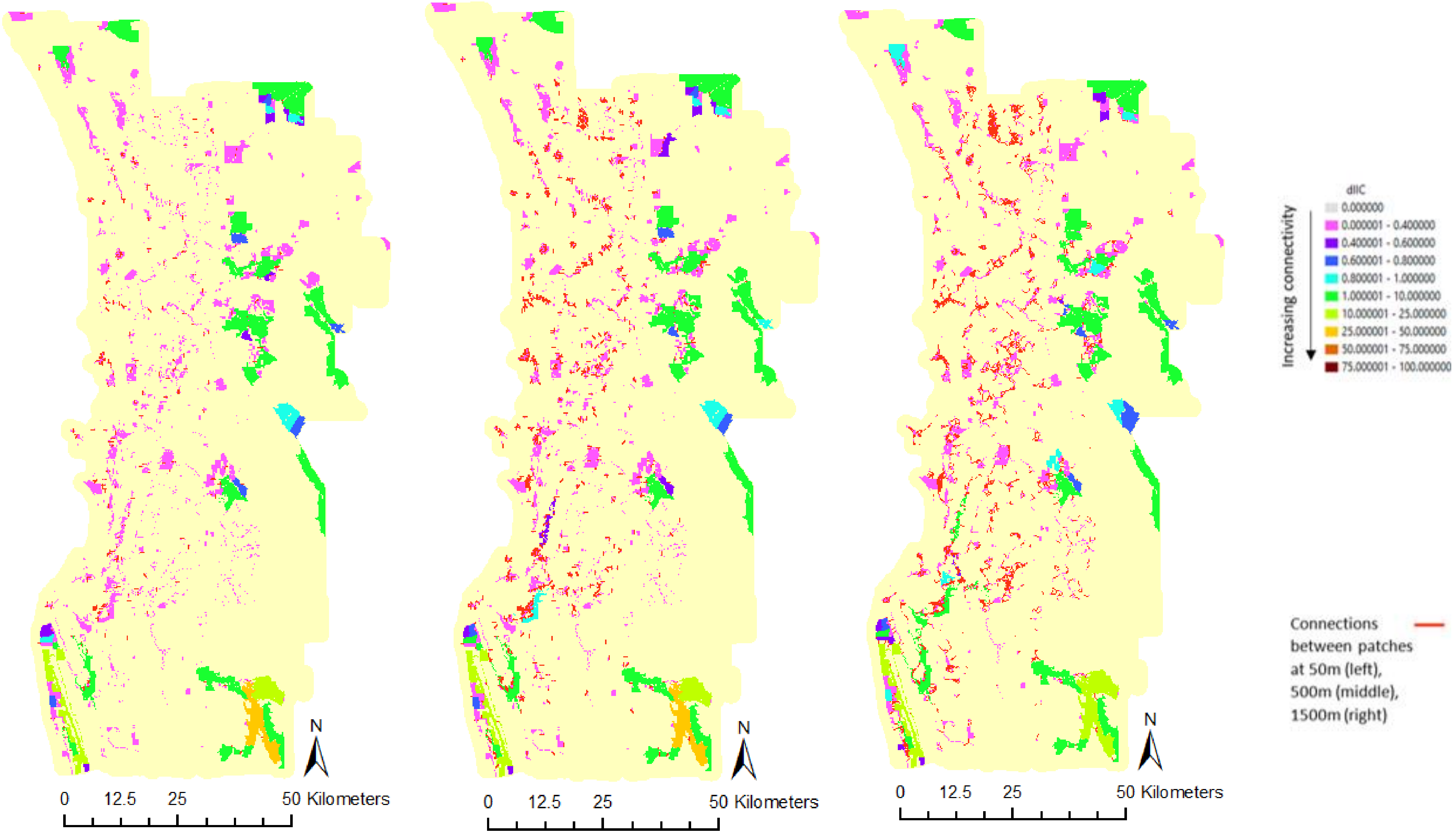

Figure 15: The individual role of the 'formal' protected areas and Bush Forever sites in enabling species movement from one protected area to another based on a protected areas importance for maintaining connectivity within the landscape (delta Integral Index of Connectivity; dIIC) at different EDTs that species can move: 100m (left), 300m (centre), and 1,000m (right).

Appendix C. Zoom in least-cost path modelling maps to highlight recommendations (begins on next page)

North West Metropolitan Planning region recommendations

- On the Coast where the Marina's create barriers use adaptive urban design to incorporate native flora in streetscapes to aid species movement (Figure 1)
- Where Major transport infrastructure forms a barrier to fauna movement between two conservation areas, installation of underpasses and overpasses are required to mitigate the impacts. For example, Figure 2
- In established urban areas reintroduce, restore, and maintain native vegetation within parks and on verges along the identified LCPs (Figure 3)
- Protect and enhance remnant bush land that is not protected such as land by the Broadcast Australia Transmitting Station which facilitates east west linkages (Figure 3)
- Protect remnant bush land that is not protected and has not yet been developed on towards the north of the region with priority given to those that have LCPs running through
- Towards the south of the region where LCPs go through dense urban areas reintroduce, restore, and maintain native vegetation within parks and on verges (Figure 3)
- Where LCPs use a cycle path to connect Bush Forever site 39 reintroduce, restore and maintain vegetation to along the path (Figure 4)

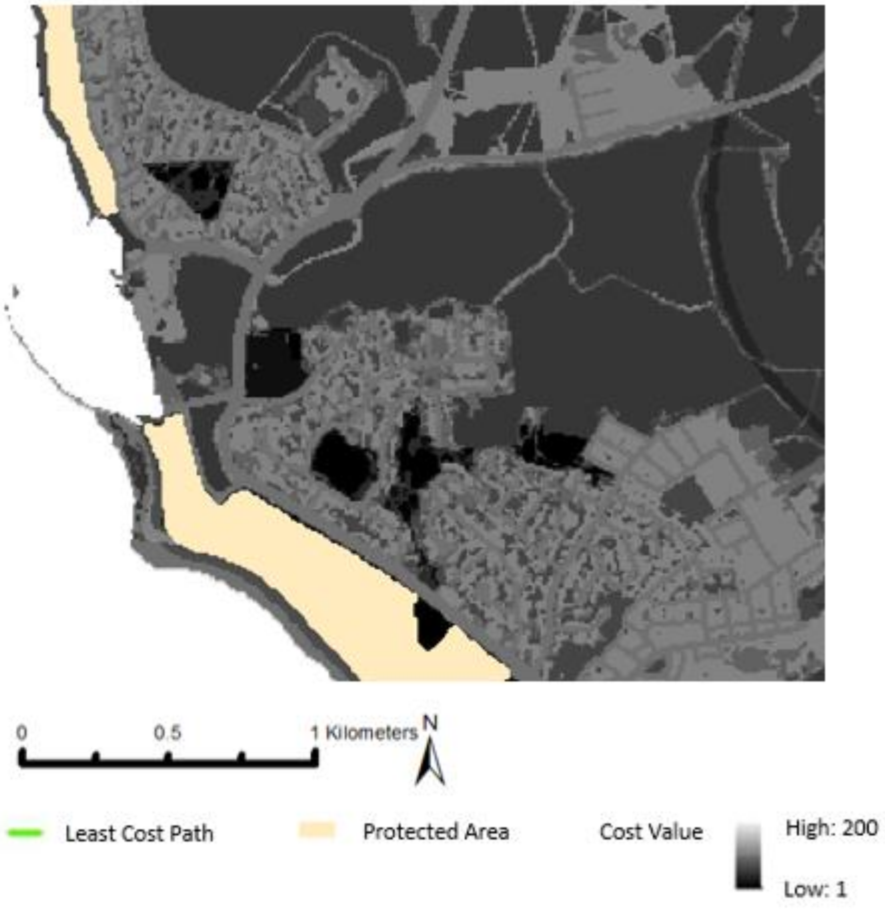

Figure 1: Two Rocks Marina creating a major barrier for species movement between the protected areas on either side

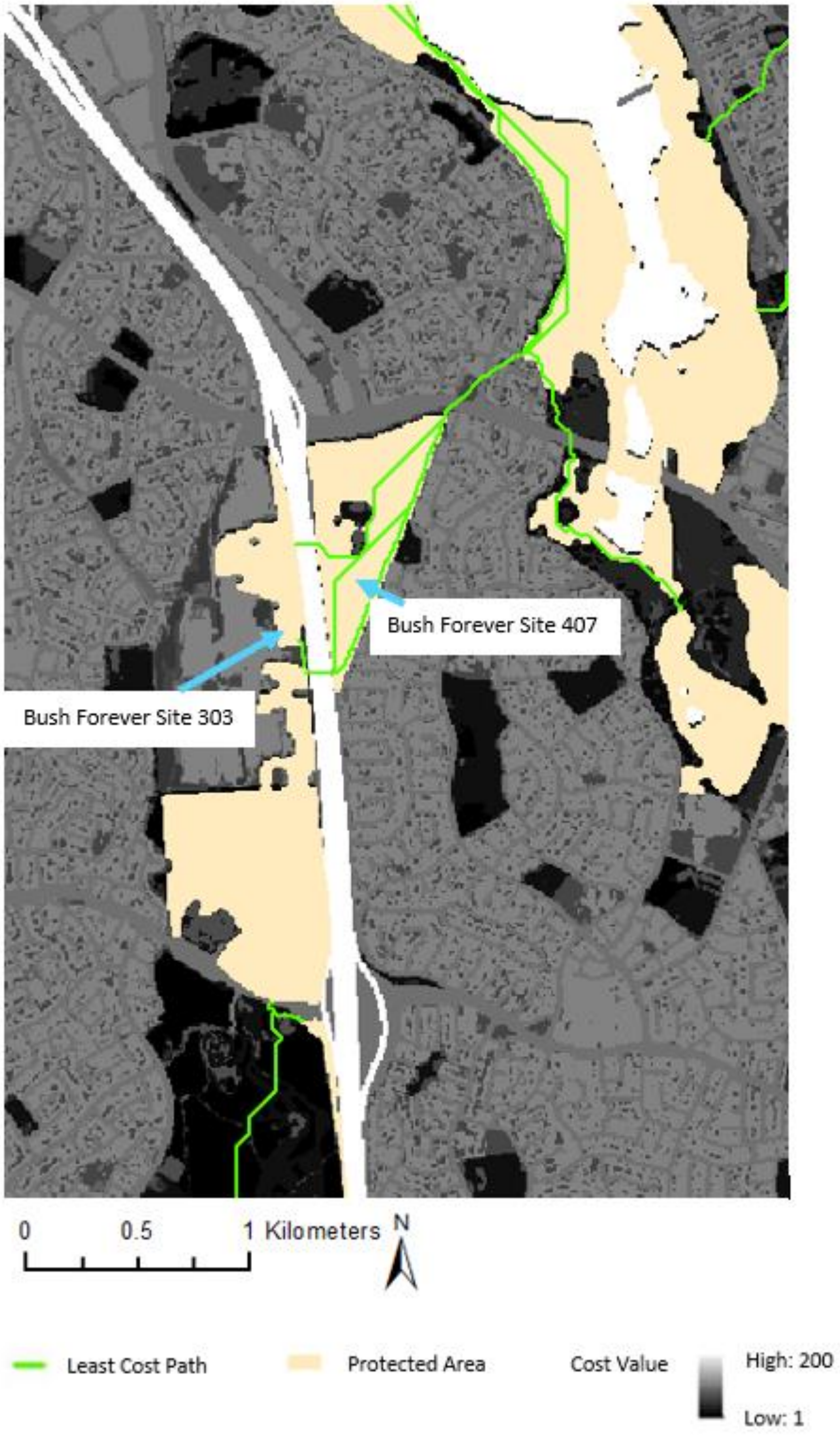

Figure 2: Mitchell Freeway creating a major barrier for species movement between Bush Forever sites 303 and 407

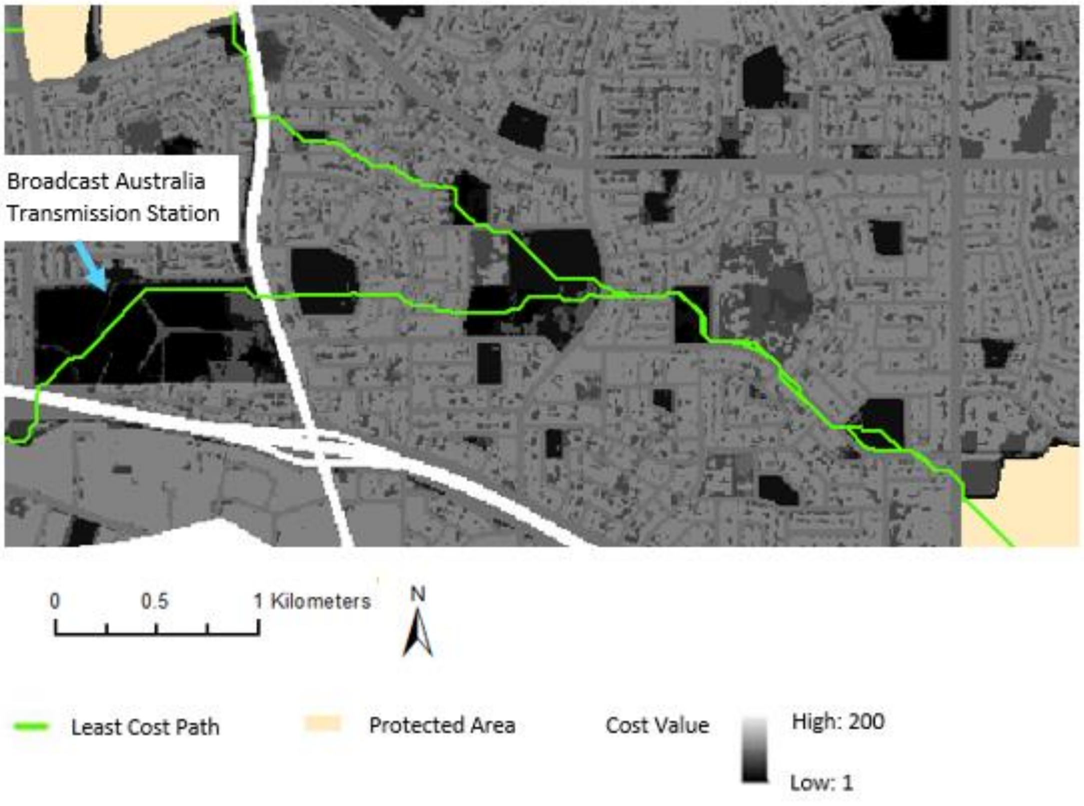

Figure 3: The Broadcast Australia Transmission Station and small parks being used as stepping stones to link protected areas in the dense urban area of the North West Metropolitan planning region

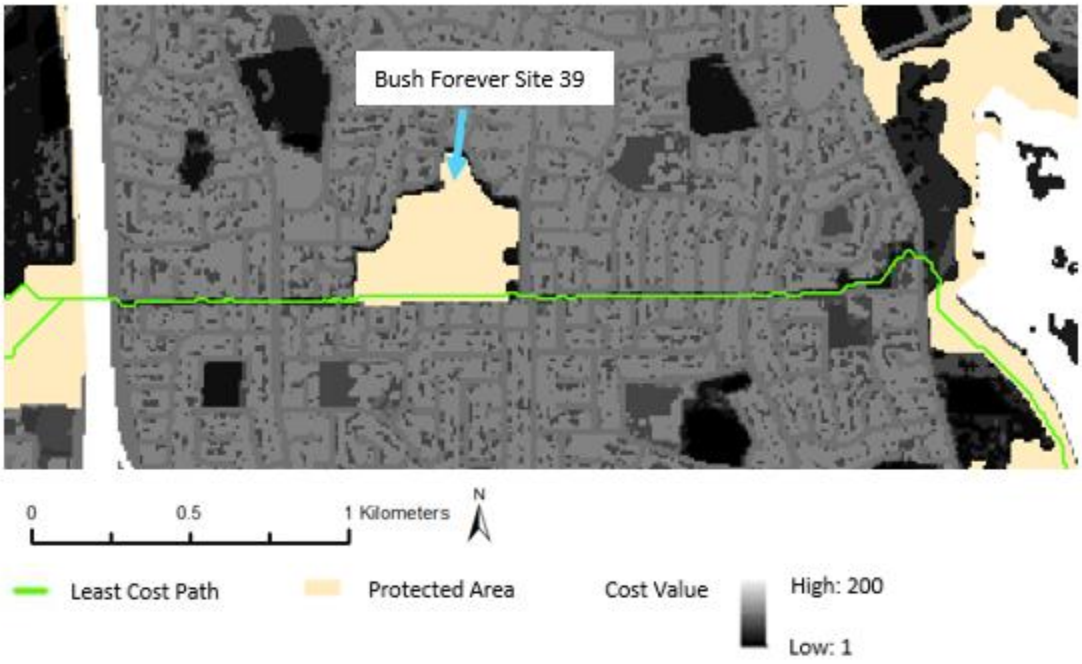

Figure 4: The cycle path which aids species movement form Bush Forever site 39 to other protected areas as seen by the least cost path

North East Metropolitan Planning region recommendations

- Zone and protect areas of Greenmount State Forest, and Mundaring State Forest where LCPs run through connecting protected areas either side of the forest (Figure 5)
- Reintroduce, restore, and maintain native vegetation along the Swan River the only major linkage in the Swan Valley (Figure 6)
- Incentives local wineries and farms within the region to plant native flora species to create more east west linkages
- Provide remnant vegetation within the central City of Swan with protection to ensure their preservation to provide habitats and linkages as recognised in/ the PMR linkages (Figure 7)
- Limited the number of houses per property in peri-urban areas as their higher vegetated areas provide linkages between Mundy National Park, Kalamunda National Park, and Gooseberry National Park (Figure 8)
- Where Major transport infrastructure forms a barrier to fauna movement between two conservation areas, installation of underpasses and overpasses are required to mitigate the impacts. For example, where Tonkin Highway divides Bush Forever site 304
- Within the Denser Urban areas reintroduce, restore, and maintain parks and road verges LCPs run through (Figure 9)

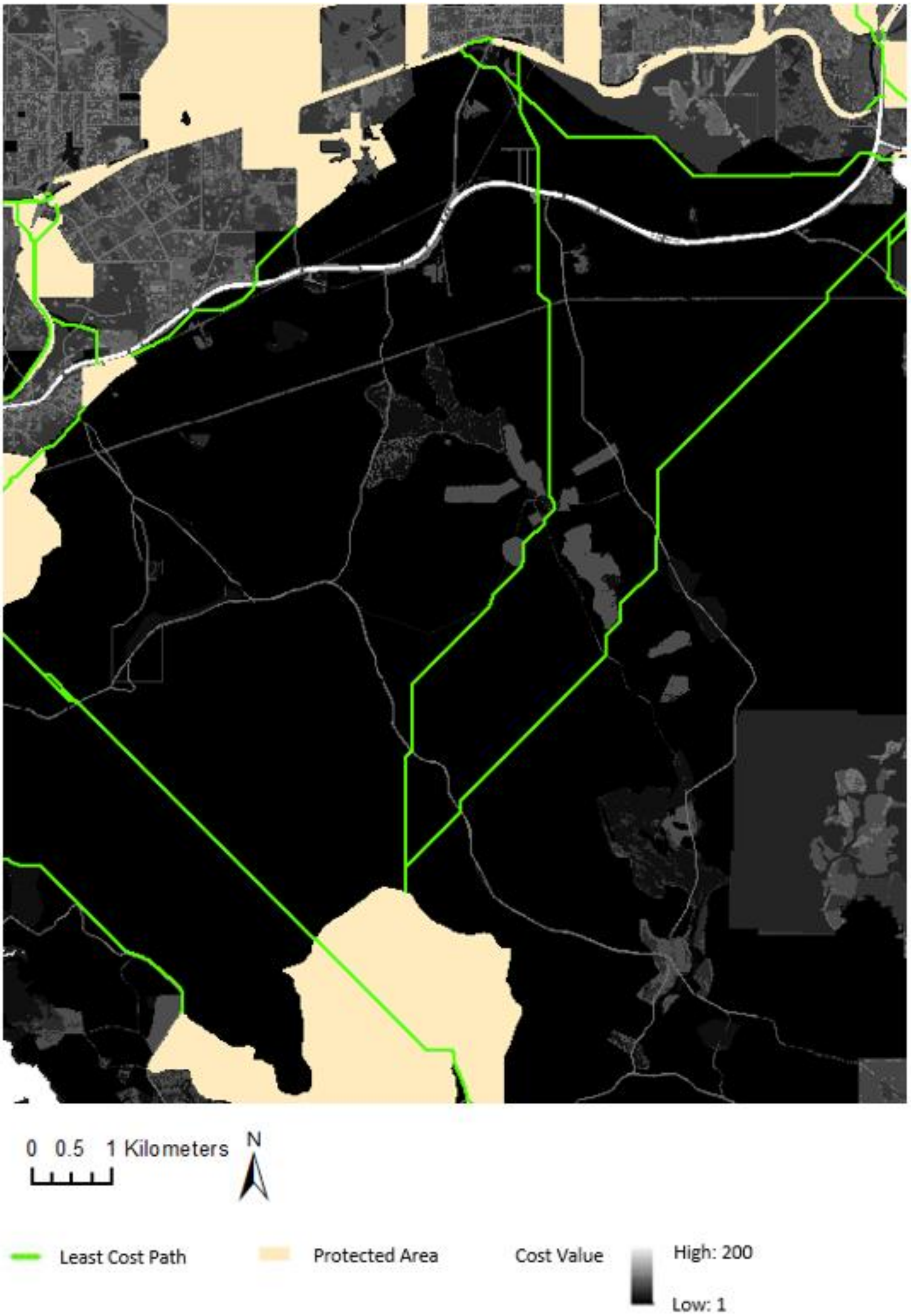

Figure 5: Least cost paths using Greenmount State Forest to link multiple protected areas

Figure 6: The Swan River creating a strong north south linkage in the Swan Valley with no least cost paths creating east west linkages in the centre

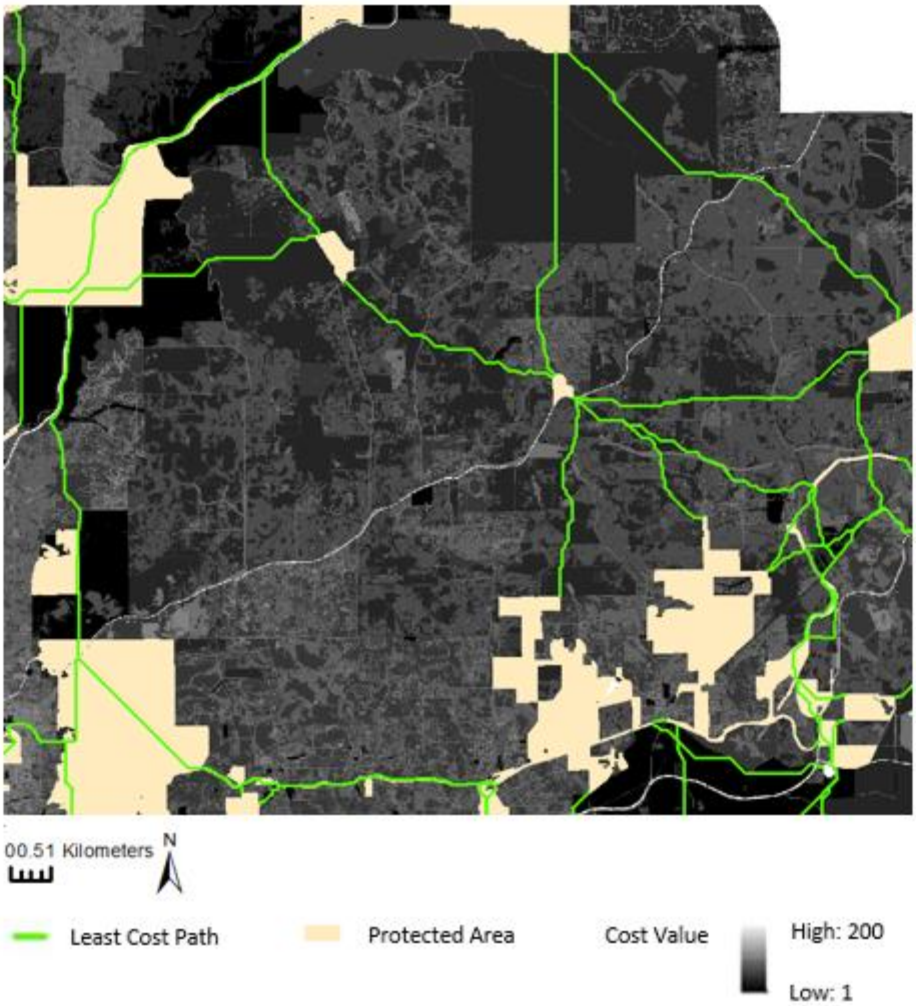

Figure 7: The centre of the City of Swan where there are high levels of native vegetation as identified in the PMR linkages but that are not protected and therefore susceptible to clearing

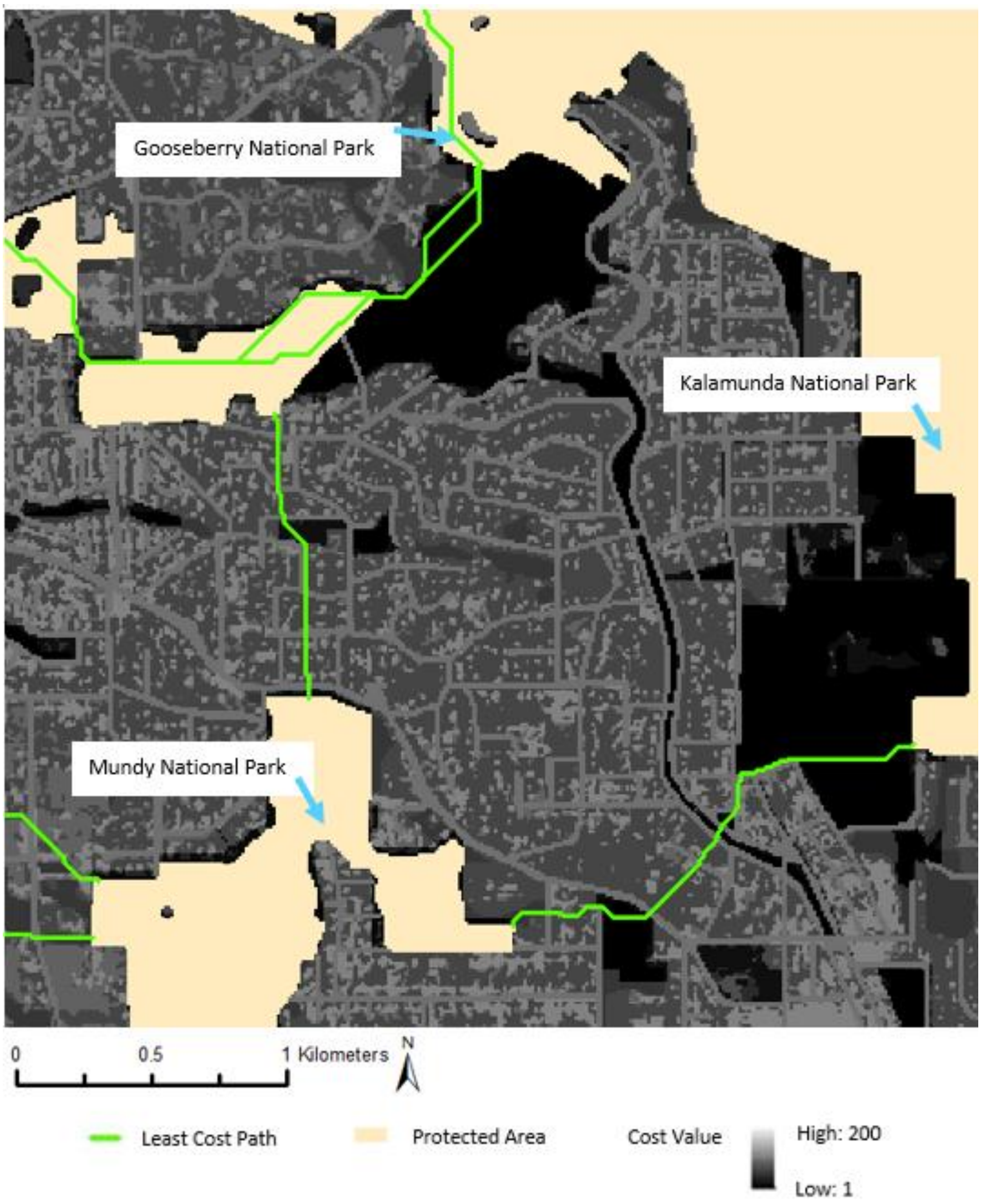

Figure 8: Least cost paths using peri-urban areas that to link Mundy National Park, Kalamunda National Park, and Gooseberry National Park

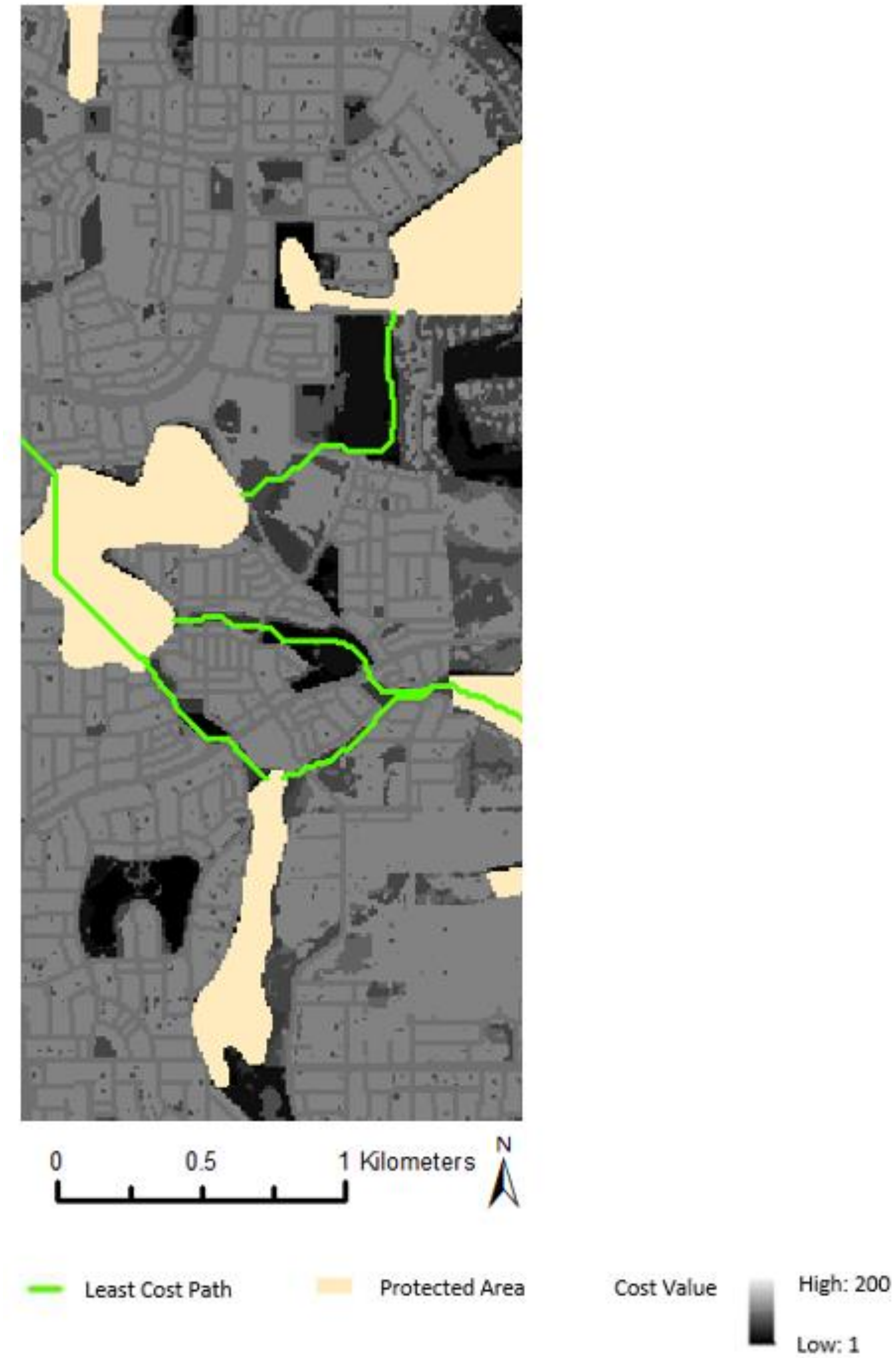

Figure 9: Small parks being used as stepping stones by least cost paths within a dense urban area to aid species movement between protected areas in the North East Metropolitan planning region.

The Central Metropolitan planning region

- Reintroduce, Restore and maintain the Swan River, Estuary, and Canning River which facilitates most of the LCP linkages.
- Restore and maintain all protected areas
- Reintroduce, restore, and maintain native vegetation within parks acting as stepping stones
- Incentivise and educate stake holders to plant native vegetation to create a more permeable surface across the dense urban area
- Small fragmented Bush Forever sites are throughout this region, ensure their protection as without these sites refuges for wildlife is limited as seen in Figure 14
- Incentivise Mount Lawley Golf Club and the West Australian Golf Club to plant native flora species as they are major stepping stones for LCPs in north central part of the region (Figure 10)
- Incorporate culverts to link Bush Forever sites 337 and 339 across Leach Highway (Figure 11)
- Incorporate a culvert to link Bush Forever site 338 where leach highway divides the site (Figure 11)
- Incorporate a culvert to link Bush Forever site 331 and 336 across Canning Highway
- Reintroduce, restore and maintain native flora in Walter Road Reserve, Yokine Reserve, and Breckler Park as that are major stepping stones for LCPs in north central part of the region
- Reintroduce, retore, and maintain native flora in cemeteries such Karrakatta Cemetery and Fremantle Cemetery (figure 12)
- Protect smaller parks acting as stepping stones between protected areas Such as Figure 13 and Figure 14
- Incorporate native vegetation along verges where LCPs run through as well as their surrounding areas this will be easier in some cases rather than others (Figure 13 and 15)

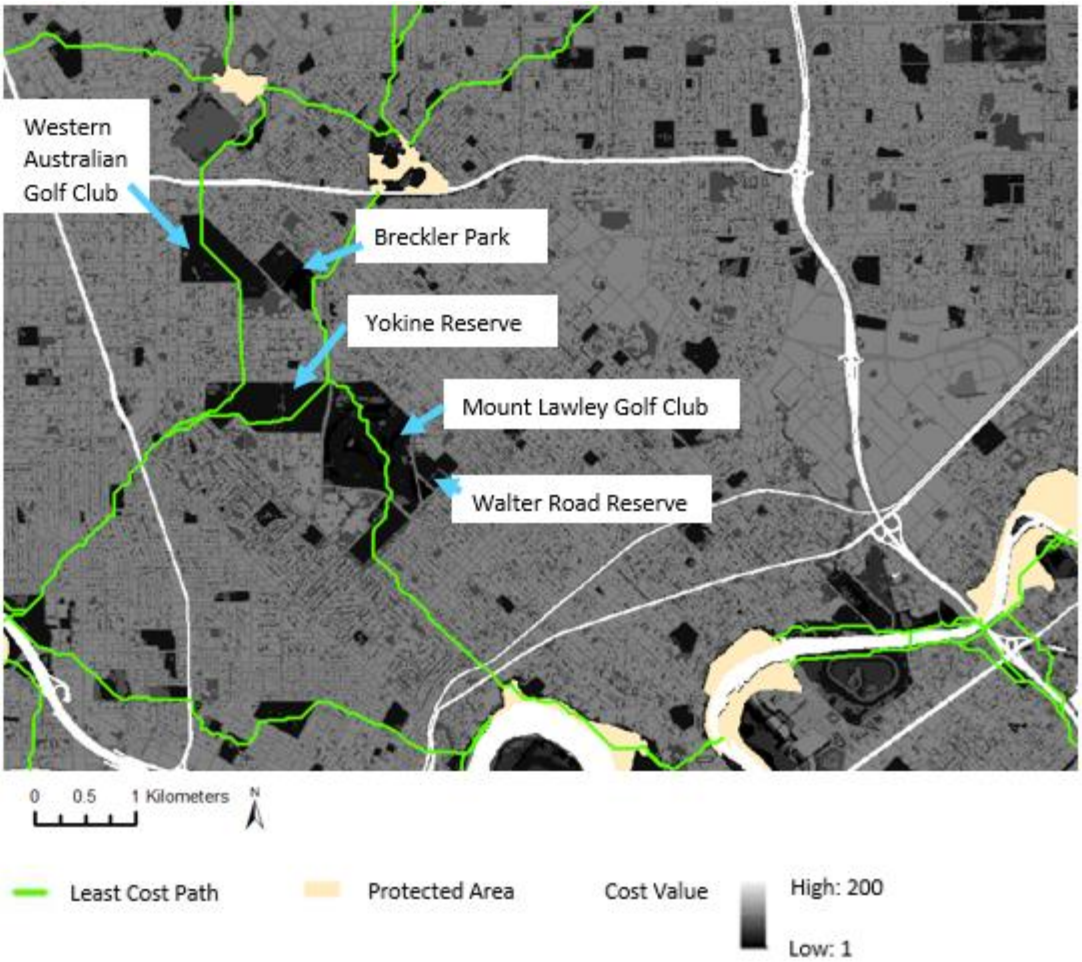

Figure 10: Least cost paths using parks and Golf Courses as stepping stones to link protected areas in a dense urban area of the Central Metropolitan planning region

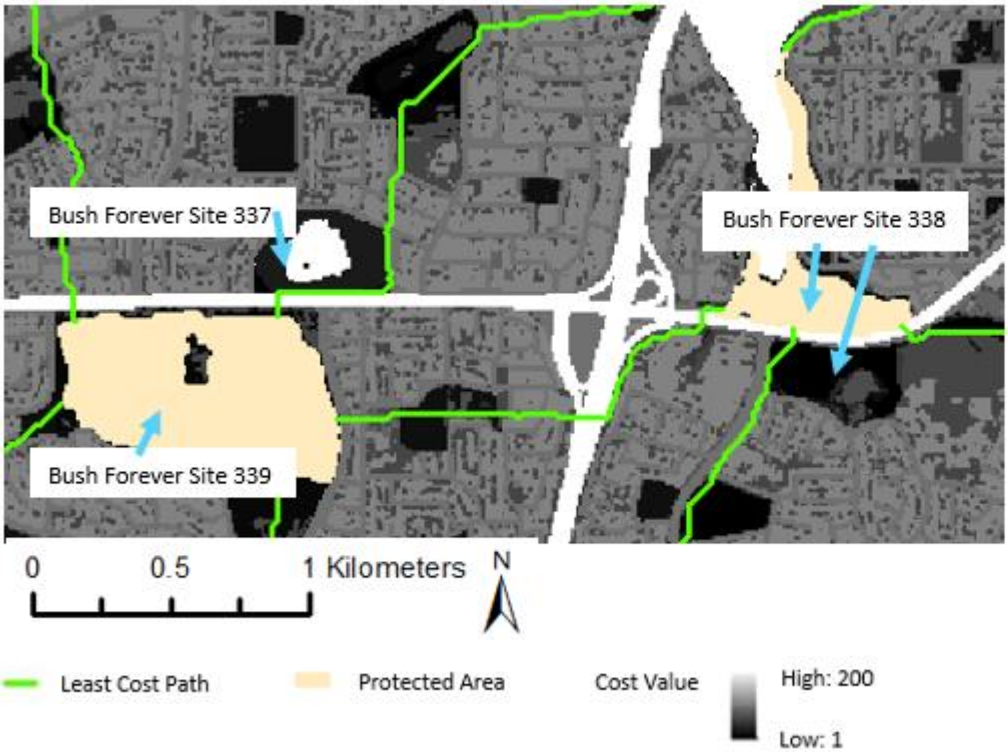

Figure 11: Species movements would benefit by incorporating culverts in leach highway to aid species movement between the Bush Forever sites

Figure 12: Karrakatta Cemetery being used by least cost paths to aid species movement

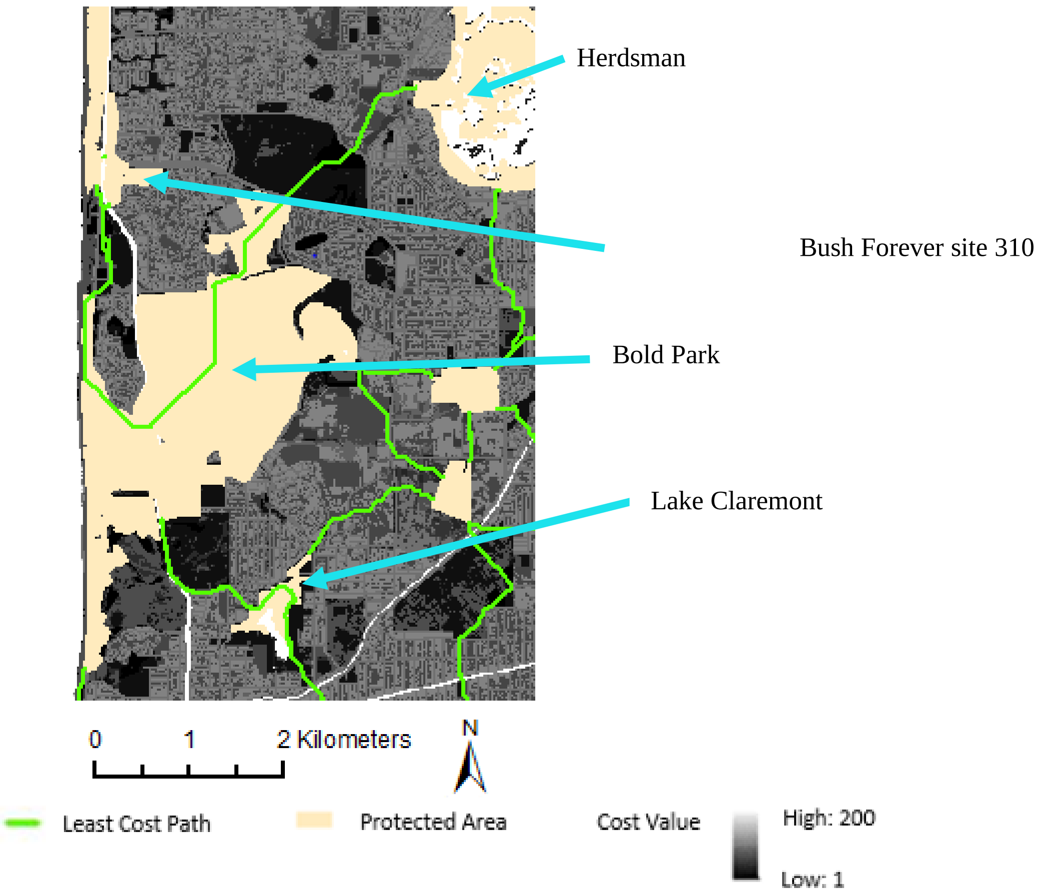

Figure 13: Parks helping to connect protected areas in dense urban area of the Central Metropolitan planning region

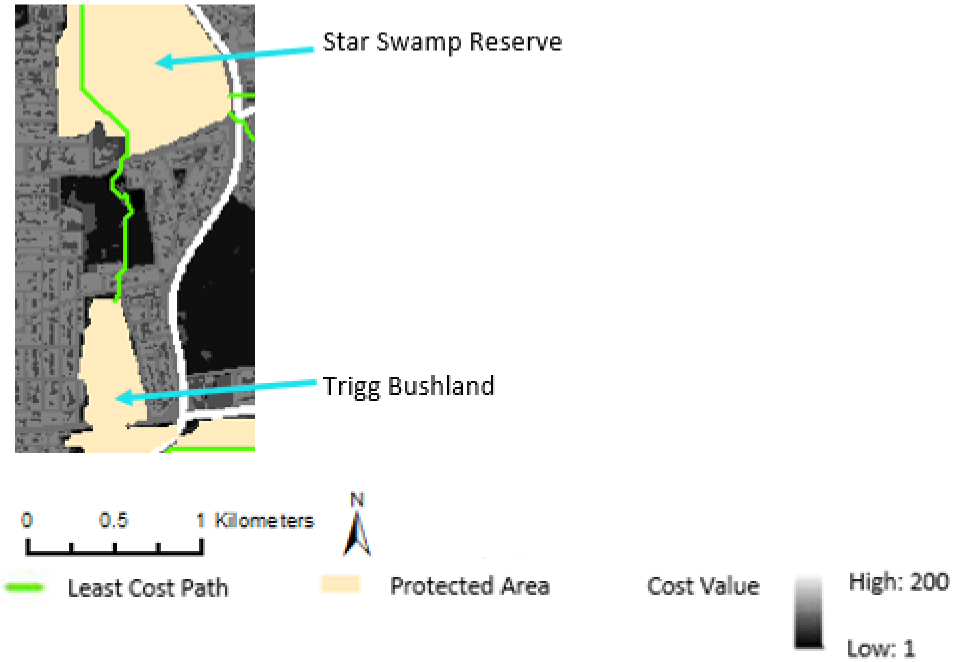

Figure 14: A small park connecting Star Swamp Reserve and Trigg Bushland

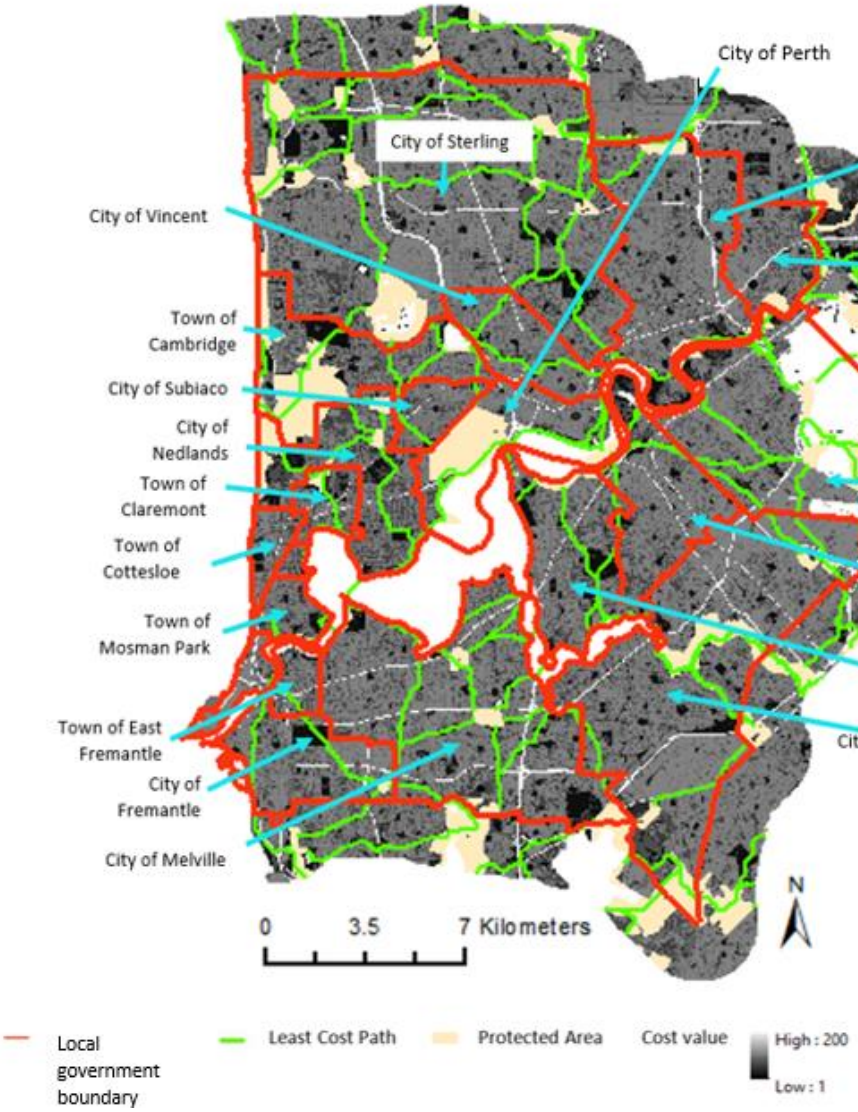

Figure 15: The Central Metropolitan planning region with its local government boundaries outlined, indicating where protected areas are.

The South West Metropolitan planning region

- Keep the Roe 8 and Cockburn Community Wildlife Corridor as a class ‘A ‘reserve and do not reverse it back to be zoned as a road, this will keep a strong east west linkage from Bibra lake to Manning Park (Figure 16)
- Reintroduce, restore, and maintain the Roe 8 corridor that was cleared in in 2017, to preserve a strong east west linkage
- Restore and maintain the vegetation opposite Lewington Reserve south of Patterson Road including the strip of vegetation between the industrial sites, and the vegetation to the west through the residential area. This vegetation provides a route for species from Point Peron to Alumina reserve and Leda Nature reserve (Figure 17)
- Reintroduce, restore, and maintain the vegetation along Serpentine River which is connecting protected areas to the south east of the region (Figure 18)
- Reintroduce, restore, and Maintain vegetation under overhead powerline corridors which the LCPs use (Figure 18).
- Restore and maintain coastal vegetation as they provide alternative north south routes to the ones provided by the expansive lake system running through the middle of the region
- In the peri-urban areas limit the number of houses per property as their higher vegetation helps to provide LCPs between protected areas such as Denis De Young Reserve, Wandi Nature Reserve, Jandakot Regional Park, Banksia Eucalypt Woodland Parks, Shirley Balla Swamp Reserve, Bosworth reserve, Emma Treeby Reserve, Rose Shanks Reserve, Mitzi Swamp Reserve, Gill Chadwell Reserve and the Bush Forever site 389 (Figure 19)

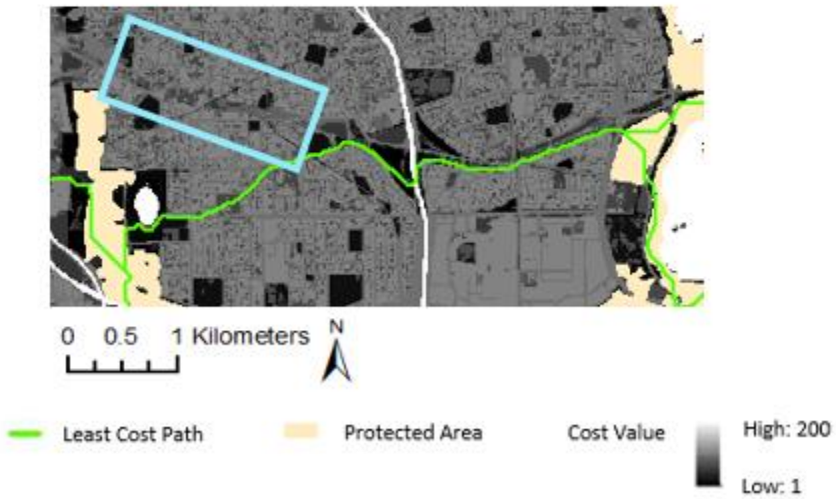

Figure 16: A least cost path using Cockburn Community Wildlife Corridor to aid species movement from Manning Park (left protected area) and Bibra lake (right protected area). The Blue box highlights where clearing has taken place for the Roe 8 extension which has now been overturned with the current government. The rehabilitation of the cleared are will give species a strong linkage to move through in a dense urban area

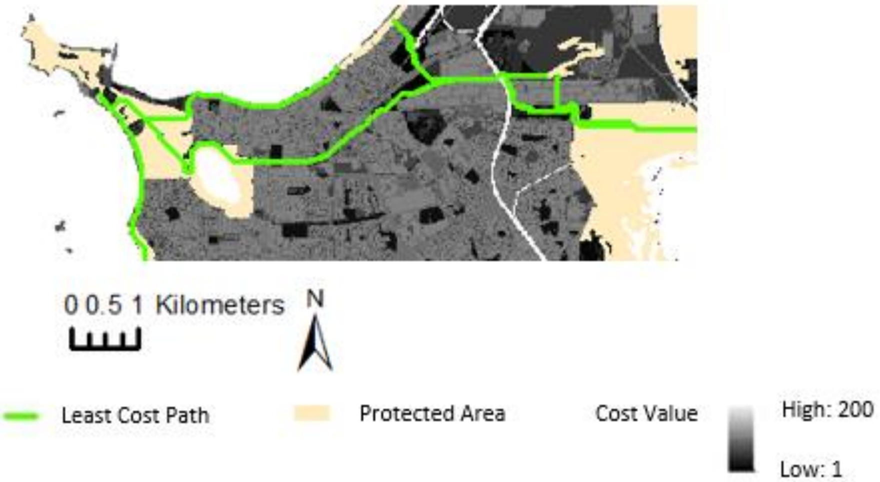

Figure 17: A least cost path linking Point Peron (left protected area) and Leda Nature Reserve (right protected area), using a vegetation strip that runs through a residential area and industrial area. The maintenance of this strip will provide species with an opportunity to move between the protected areas

Figure 18: A least cost path within the right blue box identifies serpentine river as a landscape feature that aid species movement in the agricultural area. The least cost path within the left blue box identifies an overhead transmission corridor to aid species movement as this landscape feature was given a lower cost due to work done by Wagner et al. 2019

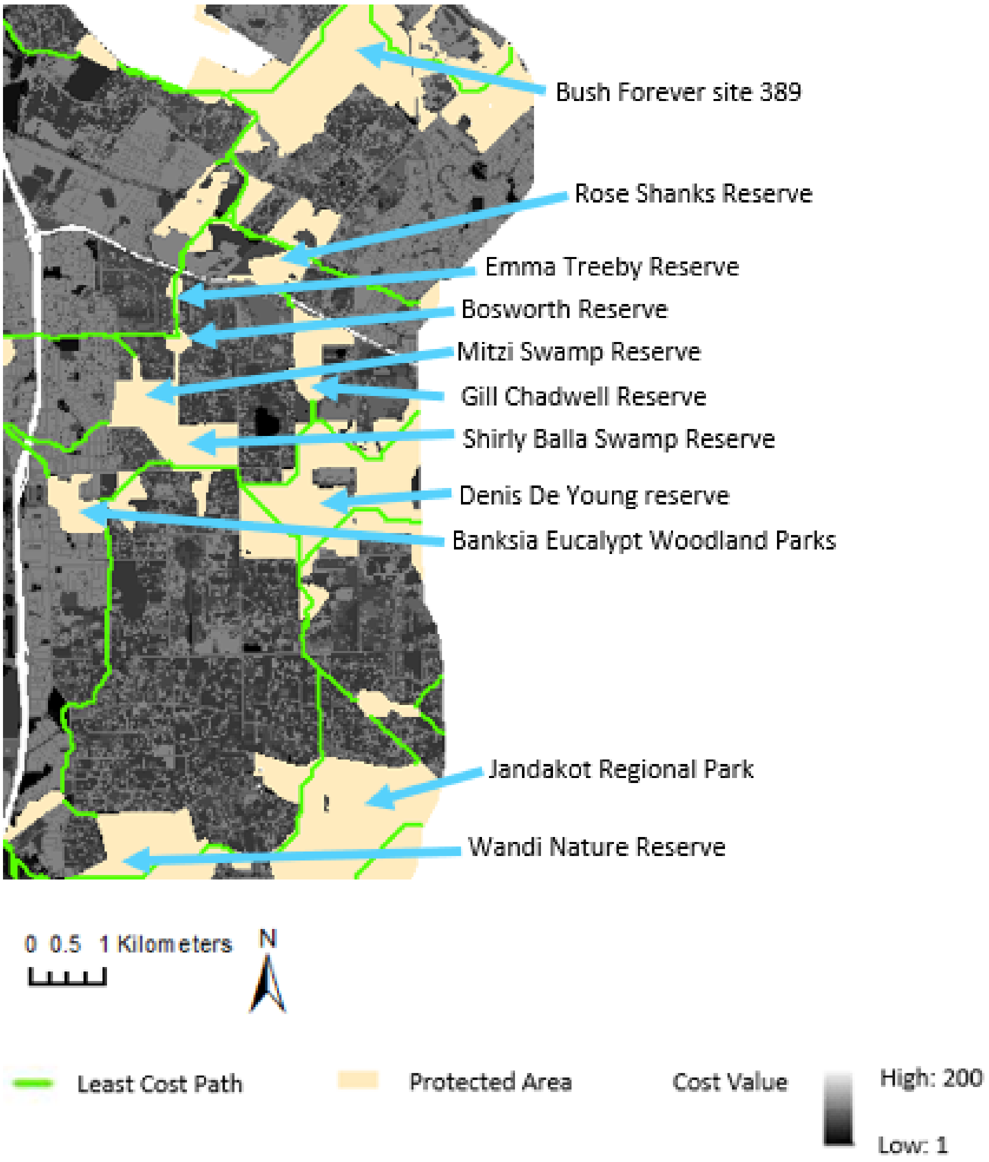

Figure 19: Least cost paths moving through peri-urban areas to link several protected areas in the South West Metropolitan planning region.

South East Metropolitan planning region

- Zone and protect areas of the Mundaring State Forest and Jarrahdale State Forest where LCPs run through to link protected areas (Figure 20)
- Reintroduce, restore, and maintain vegetation along roads in agricultural areas
- Incentivise Farmers to plant native vegetation along field verges as this will help to maintain the east west LCPs within the south west of the region
- Restore and maintain the vegetation strip that links Piara Nature Reserve and Bush Forever site 342
- Reintroduce, restore, and maintain vegetation strips and other vegetation, such as the carpark of the Aspiri Sports Pavilion to link Piara Nature Reserve with Rose Shank Reserve (Figure 21)
- Protect and maintain native vegetation in small parks that are stepping stones used by the LCPs in the dense urban areas such as Brookland Greens and Greentree Drive Reserve to aid species movement (Figure 22)
- Reintroduce, restore, and Maintain vegetation under overhead powerline corridors which the LCPs use (Figure 23).
- In the peri-urban areas limit the number of houses per property as their higher vegetation helps to provide LCPs between protected areas such as Jandakot Regional Park, Denis De Young Reserve, and Forrestdale Lake Nature Reserve (Figure 23)

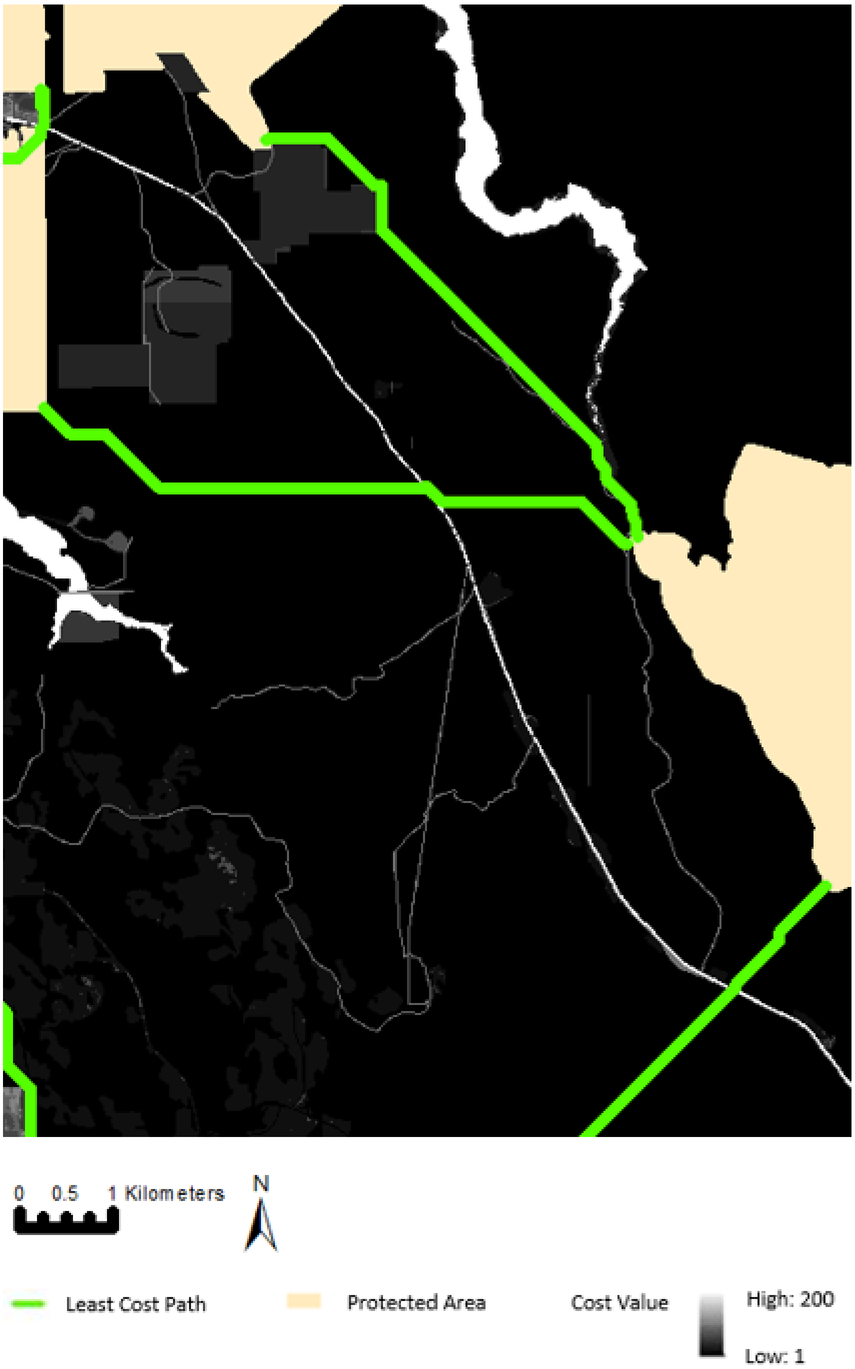

Figure 20: Least cost paths using Jarrahdale State Forest to link multiple protected areas

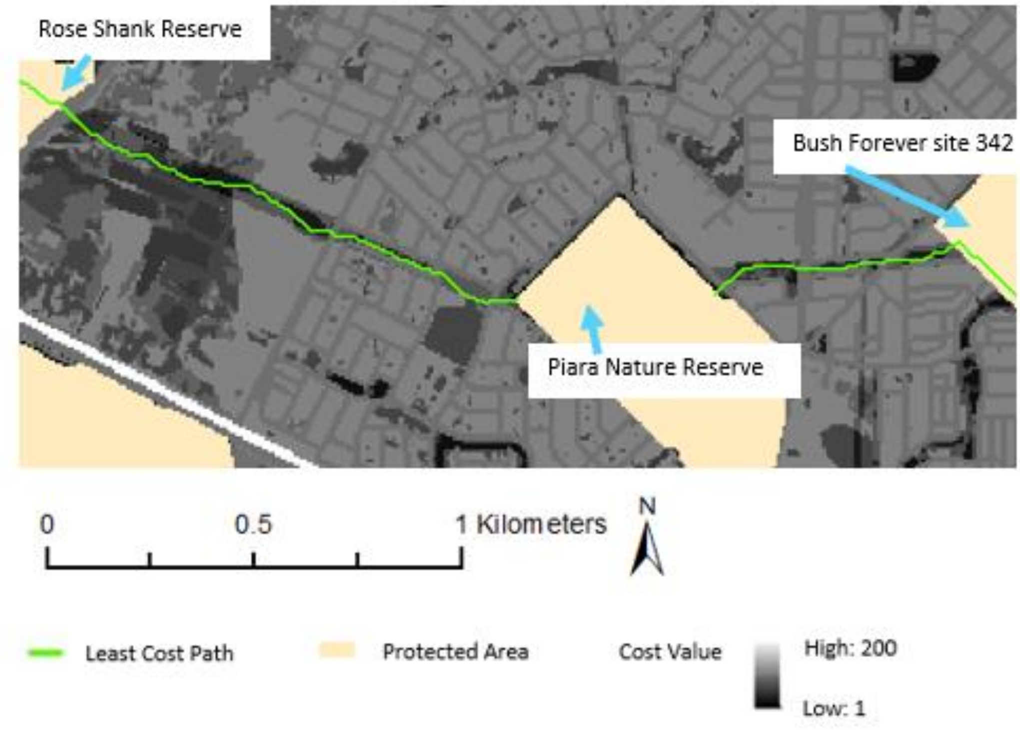

Figure 21: Least cost paths using vegetation strips to link protected areas in a dense urban area of the South East Metropolitan planning region

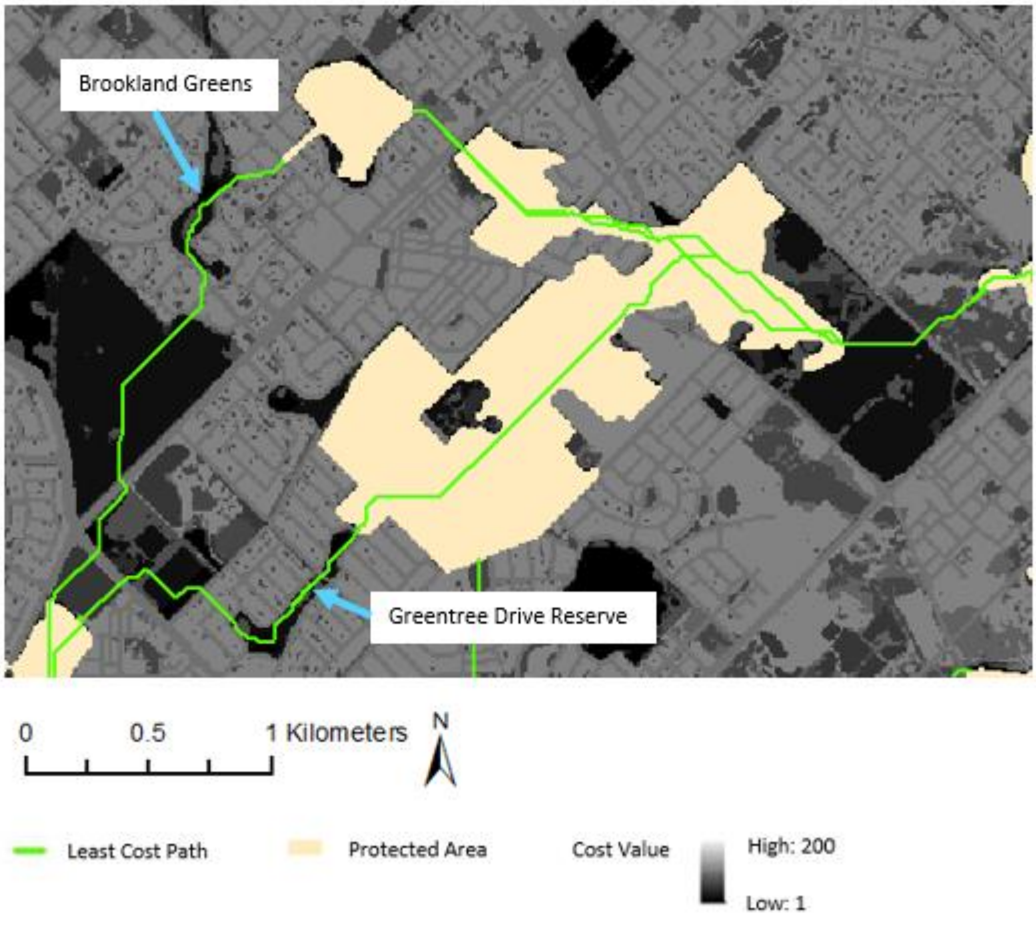

Figure 22: Small parks being used as stepping stones by least cost paths to link protected areas in a dense urban area of the South East Metropolitan planning region

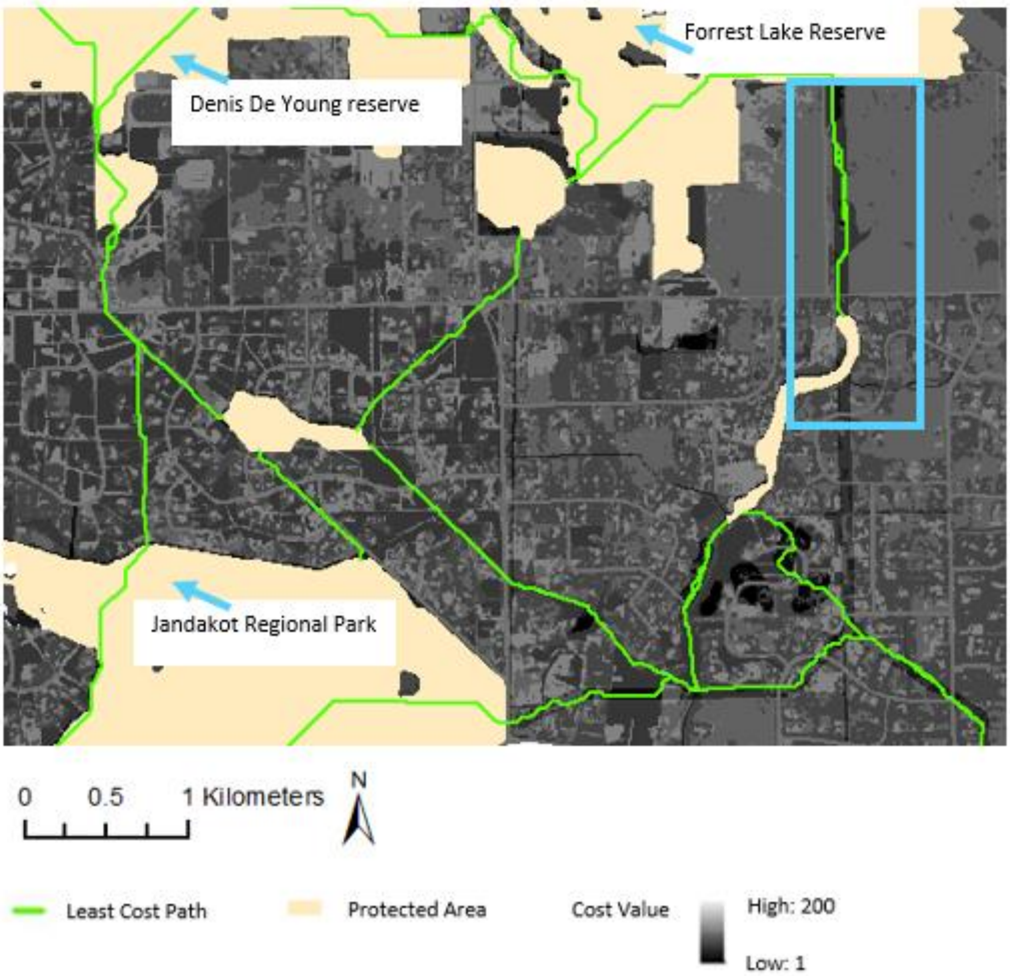

Figure 23: Least cost paths moving through peri-urban environments to link several protected areas. The least cost path highlighted in the blue box identifies an overhead transmission corridor to aid species movement as this landscape feature was given a lower cost due to work done by Wagner et al. 2019.

Peel planning region recommendations

- Reintroduce, restore and maintain native vegetation and wetlands within the mega network to the east of the region consisting of Yalgorup National Parks, Peel estuary, Serpentine River and Murray River
- Reintroduce, restore, and maintain native vegetation along roads in the agricultural areas of the middle of the region to aid east west species movement, there is very little native vegetation left in this area therefore species are reliant on verges and river systems for movement (Figure 24)
- Incentivise farmers to plant local vegetation around field edges to help aid the east west linkages and north south linkages in the middle of the region
- Protect, restore, and maintain remnant vegetation around the Nine Mile Lake Nature Reserve (Figure 25) and Buller Nature Reserve
- Restore and Maintain the Murray River and the River leaving the most southern tip of the Peel Estuary that links with Buller Reserve as they are critical in creating east west connections in this area (Figure 26).
- Zone and protect areas of the Marrinup State Forest, Jarrahdale State Forest, Dwellingup State Forest, and Harris River State Forest where LCPs run through to link protected areas (Figure 27)
- Restore and maintain the Lane Poole Reserve

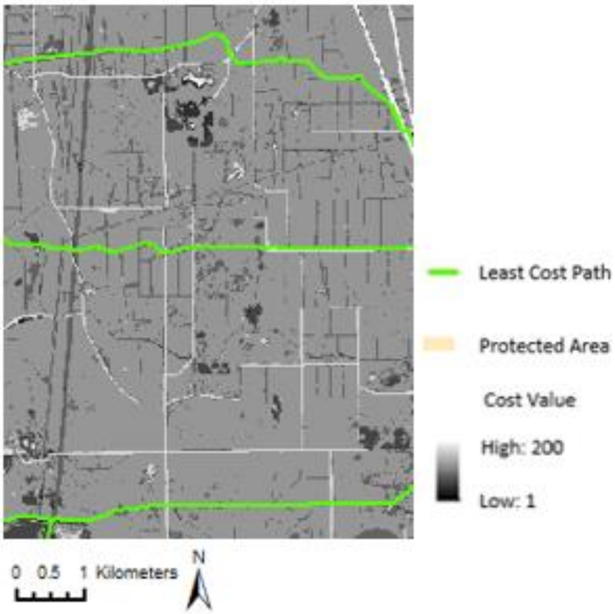

Figure 24: Least cost paths using road verges and vegetated lined fields in the agricultural area of the Peel region

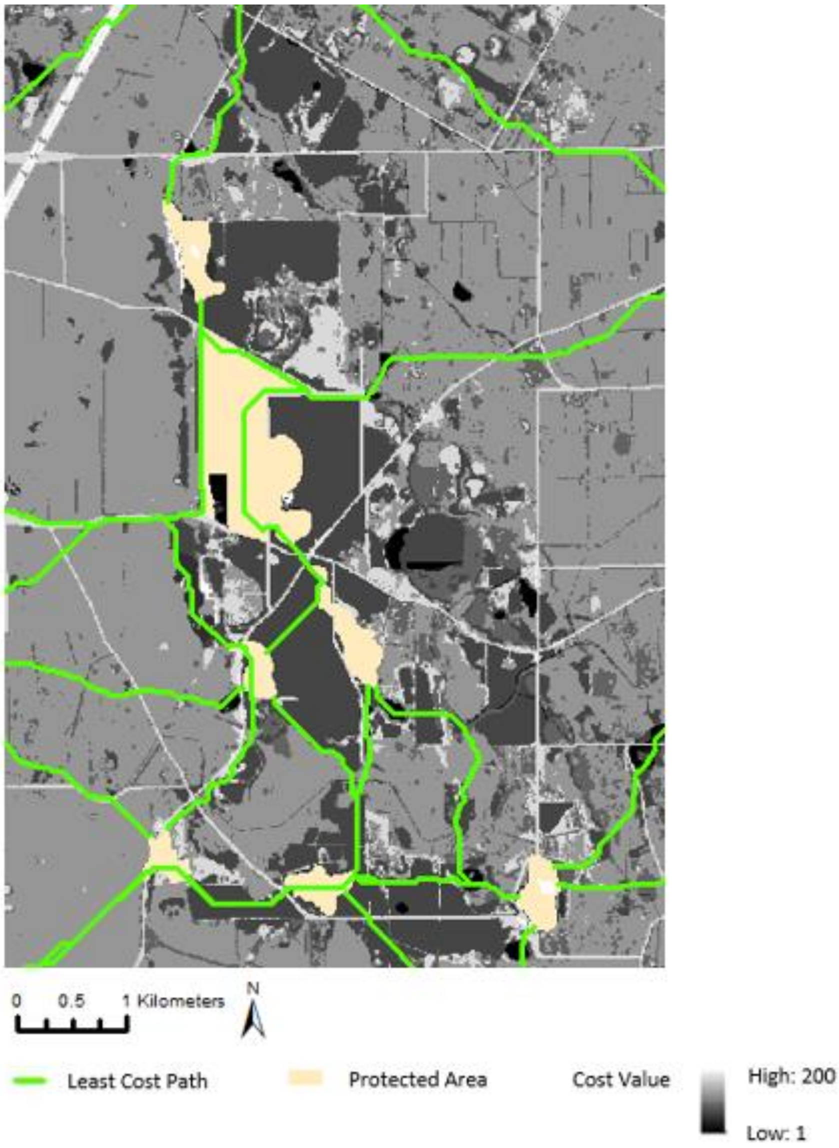

Figure 25: The Nine Mile Lake Nature Reserve and the surrounding vegetation

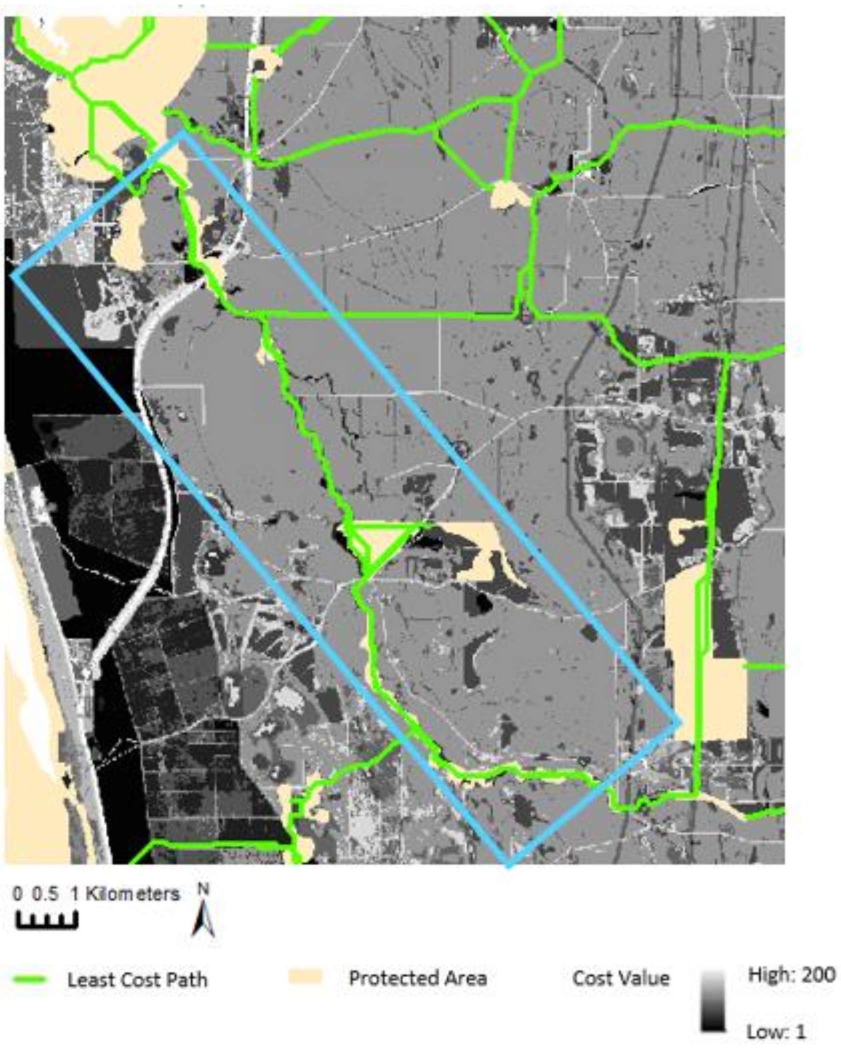

Figure 26: The river system highlighted by the blue box at the southern end of the Peel Estuary providing a strong linkage across agricultural land

Figure 27: Least cost paths using Marrinup State Forest to link Lane Poole Reserve at the South and conservation category wetlands towards the north.

Recommendations applicable to all regions

Break Barriers

- Culverts, fauna underpasses, and fauna bridges to be implemented where suitable LCPs cross the freeway and highways
- When designing and planning transport infrastructure incorporate elements that allow species crossing such as culverts, fauna underpasses and fauna overpasses.

Green enhancement

- Where LCPs cross dense urban areas and use small parks as stepping stones assess where native vegetation can be reintroduced, restored, and maintained
- Incorporate native flora verges into street planning
- Reintroduce restore and maintain native species along road verges and cycle paths
- Assess where park structures can be altered to incorporate a greater range of native flora
- When deciding on flora species to incorporate into urban planning prioritise species local to the area as a standard practice
- Employ expert advice when undertaking restoration to ensure the incorporation of priority species needs
- When reintroducing local native flora species incorporate a large range of species which include ground covers, shrubs, and trees
- Use the least cost path modelling resource identified in this study to aid decision making for an effective ecological network
- Restore and Maintain native remnant vegetation, wetlands, and river systems

- Restore and maintain state forest areas that link protected areas
- Use KPIs to help monitor and evaluate restoration sites, protected areas, and linkages

Protect native remnant vegetation

- Protect remnant vegetation, wetlands, and river systems that are not already protected
- Bush Forever sites that are government owned to be protected as a Class A reserve for conservation purposes and passive recreation, rather than protected for parks and recreation, as the amount of vegetation that can be cleared for recreation facilities can have detrimental effects on the local ecosystems affecting their ability to support species populations and movements
- Where Bush Forever sites are either in private, commercial, or unknown ownership to be acquired by government when available as stated in the Bush Forever Plan 2000

Community engagement

- Educate residents of the benefits of native gardens
- Provide incentives for residents to create native gardens
- Provide incentives for businesses to reintroduce, maintain, and restore local native flora species
- Support local stakeholders in establishing ecological linkages through incentives and advise
- Educate residents and businesses on the best ways to deal with various species that may enter private gardens Educate residents on responsible pet ownership

Appendix D: Literature Review

Improving connectivity in a rapidly urbanising landscape: Best application of landscape ecology theory to inform adaptive urban planning

1. Introduction

Urban environments are constantly evolving to meet human needs, but vast systematic infrastructure threatens biodiversity. The development of man-made infrastructure expose species to hazards such as predators and traffic, reduces available food and water resources, and blocks traditionally taken pathways, thereby, fragmenting natural habitats and forming barriers which impede species movement (Fahrig 2003; Bonte et al. 2012). With increasing urbanisation, the size of habitat remnants decreases, the distance between them increases, and the urban matrix situated between can become increasingly hostile for species seeking to move between (Fahrig 2003; Shochat et al. 2006). Small patches in isolation may host low biodiversity, but when these patches form a connected network, populations are able to move across multiple patches thus increasing the area and resources available, aiding biodiversity preservation (With and Crist 1995; Fahrig 2003). Habitat linkages are then necessary to sustain biodiversity in urban environments, without them organisms cannot move across the landscape, inhibiting genetic flow, breeding, foraging, recolonization, migration and dispersal (Cushman and Lewis 2010; Stephens et al. 2007; Clobert 2012; Dingle 2014). This may ultimately lead to species extinctions. The degree to which the landscape enables or hinders species movement from one habitat patch to another is termed landscape connectivity (Taylor et al. 2003).

1.1 Hotspots

Cities tend to be built in areas with high biodiversity as soil productivity and water resources, which attract humans to live there, also support many other species (Grimm et al. 2008; Miller and Hobbs 2002). More than half of Earth’s living species live within just 2.3% of the planet’s surface. These Biodiversity hotspots are internationally recognised for their high number of endemic species and the rate at which they are becoming endangered or extinct (Mittermeier et al. 2011). There are 35 ‘biodiversity hotspots’ acknowledged globally and all contain urban landscapes (Mittermeier et al. 2011), with at least 146 cities situated either in or directly adjacent to ‘biodiversity hotspots’ (e.g. Chicago, New York, Mexico City, Brussels, Frankfurt, Cape Town, and Perth (Cincotta et al. 2000; Mittermeier et al. 2011)). For example: Perth within the South Western biodiversity hotspot of Australia has the highest species richness of the region (Gioia and Hopper 2017). The Perth area has 372 flora and 159 fauna species of priority status for conservation (DCBA 2018; DCBA 2019).

1.2 Informed urban planning is vital for biodiversity

The need for urban conservation is particularly pronounced when the range of a species is now completely encapsulated within an urban matrix. Soanes and Lentini (2019) have identified 39 threatened species in Australia whose whole distribution is now entirely restricted to urban areas. Without adequate urban conservation planning, these species will not exist into the future (Soanes and Lentini 2019). Research in urban areas for biodiversity conservation is still an emerging area, as previously urban environments were considered ‘worthless’ for biodiversity (Soanes et al. 2018; Miller and Hobbs 2002). This mindset has led to a focus on conservation within rural areas, arguably resulting in some of the most critical areas (urban landscapes) being overlooked (Soanes et al. 2018; McKinney 2008; Cavin 2013). Thus, green spaces and remnant vegetated areas persisting within the urban matrix are poorly understood and underexploited in conserving biodiversity.

Without adequately informed urban planning, human infrastructure will continue to progressively break up natural habitat into smaller, disconnected patches, with many being eliminated from the landscape (Kong et al. 2010). Landscape ecologists over the past few decades have developed a wide range of quantitative measures that can be used to estimate connectivity and evaluate the impacts of land use changes on landscape connectivity. Incorporating applicable connectivity measures in adaptive urban planning is therefore essential for enhancing connectivity and biodiversity.

1.3 Questions which connectivity theory needs to answer

Maintaining connectivity in urban environments is a growing and appealing concept for land managers, planners, and politicians (Crooks and Sanjayan 2006, Kool et al. 2012). Attention is moving away from debating the need of connectivity and moving towards understanding how to best apply the theory. The problem of understanding connectivity in conservation is related to multiple topics which can be divided into three overlapping groups: theoretical, empirical, and applied (Figure 1). When interactions between all three groups occur, connectivity will be best employed.

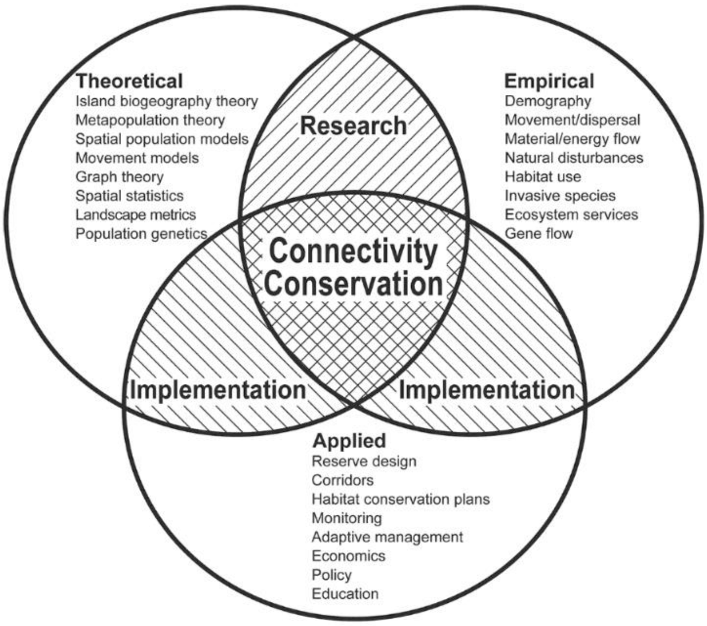

Figure 1. A Venn diagram of theoretical, empirical, and applied concepts which when interact provide the best platform for connectivity conservation. Taken from Crooks and Sanjayan (2006).

Since integration of ecological networks (green spaces and remnant vegetation) in adaptive urban design is necessary to conserve connectivity and biodiversity, information requirements have surfaced within land-use planning, which reflect the impacts of decisions taken by managers within different scenarios (Bergsten and Zetteberg 2013). Three specific questions have been identified when planning for connectivity: where are vulnerable species and habitats situated? (Rubio and Saura 2012); where would modifying the landscape be effective to maintain, protect and enhance connectivity? (McRae et a.l 2012); and after modifying the landscape where would wildlife be distributed? (Foltête et al. 2014). Therefore, it is necessary to understand which theoretical connectivity concept or concepts incorporating empirical information will best answer these questions in a rapidly changing urban environment to produce effective connectivity conservation.

1.4 Structure and Aims of the Literature Review

This literature review examines how the theory of connectivity can best inform adaptive urban planning for a rapidly urbanising landscape. In particular, it will focus on how connectivity theory can answer the question posed by land managers of: where would modifying the landscape be effective to maintain, protect and enhance connectivity? The reason for this approach is because connectivity theory is most helpful in addressing the question and once answered will indirectly help to answer the other two questions posed by land managers (see section 1.3). The literature describes multiple definitions for landscape connectivity and ways in which to quantitatively measure it. This review begins by considering the two fundamental ways in which to describe and measure connectivity (structural and functional). It then compares which metrics are adequate to inform urban design, before evaluating how these metrics are affected by spatial and temporal uncertainties of landscape features. Afterwards it will inspect case studies around the world where connectivity theory using quantitative measures have successfully informed urban management. To conclude, an example will be given of how connectivity theory could be potentially used to inform adaptive urban development within the city of Perth Western Australia.

2. Functional vs structural connectivity concepts

There are two main ways connectivity is defined and measured: structural and functional. Structural connectivity concentrates on the landscape elements which facilitate connectivity, while functional connectivity accounts for the species behaviour towards the landscape (Tischendorf and Fahrig 2000a). Functional connectivity can be broken down further into two subcategories: potential and actual (Calabrese and Fagan 2004; LaPoint et al. 2015). Potential connectivity merges the structural landscape elements with dispersal information about a species and actual connectivity centres around observations of a species movement behaviour (Table 1) (Calabrese and Fagan 2004; Magle et al. 2009; LaPoint et al. 2015).

Table 1: A summary of the different types of connectivity, the information needed to inform the connectivity and sources used to gather the required information (Calabrese and Fagan 2004).

Type of connectivity	**Information needs**	**Common sources**
Structural	Based on the physical traits of the landscape, with no reference to species behaviour	Maps, GIS, remote sensing, field surveys
Potential (functional)	Based on assumptions about species movement behaviour	Expert knowledge, dispersal studies, GIS, remote sensing with dispersal studies
Actual (functional)	based on observed data which reflect species behaviour	Patch occupancy data, radio tracking, genetic data, mark-release- recapture studies

Functional connectivity measures provide a more detailed estimate of connectivity than structural measures, as they go beyond structural variables of a landscape (Calabrese and Fagan 2004). However, a major drawback of actual functional connectivity measures is their requirement for large data sets, and the long timescales it takes to collate the data (figure 2) (Hansen and Urban 1992; Hanski 2001; Calabrese and Fagan 2004). For example, Riley et al. (2006) spent over seven years radio tracking, trapping and DNA sampling bobcats and coyotes to determine the effect of a heavily travelled freeway on each species' populations. Whilst the data collected was detailed and direct, the time it took to collect the information is unsuitable when assessing a landscape which is constantly changing. When directly dealing with living organisms the data produced can be limited due to sample size and availability of the species, meaning data can be hard to gather and may be imprecise, affecting the extent to which connectivity can be estimated (Calabrese and Fagan 2004; Taylor et al. 2006). Studies requiring a long timeframe can be expensive and in rapidly changing landscapes data collected on species behaviour may already be incorrect by the time the study is published, as species change their behaviour in response to landcover change (Taylor et al. 2006; Kindlemann and Burel 2008; Zeller et al. 2012). A change in a land cover type can change the way a species navigates other land cover types. For example, Jonsen and Taylor (2000a; 2000b) found that damselflies frequently cross streams and pastures to access resources within a forest but when the forest were removed, they rarely utilised the pastures and streams. In a rapidly urbanising landscape this means linkages can quickly be modified and previously observed linkages become out of date and no longer relevant.

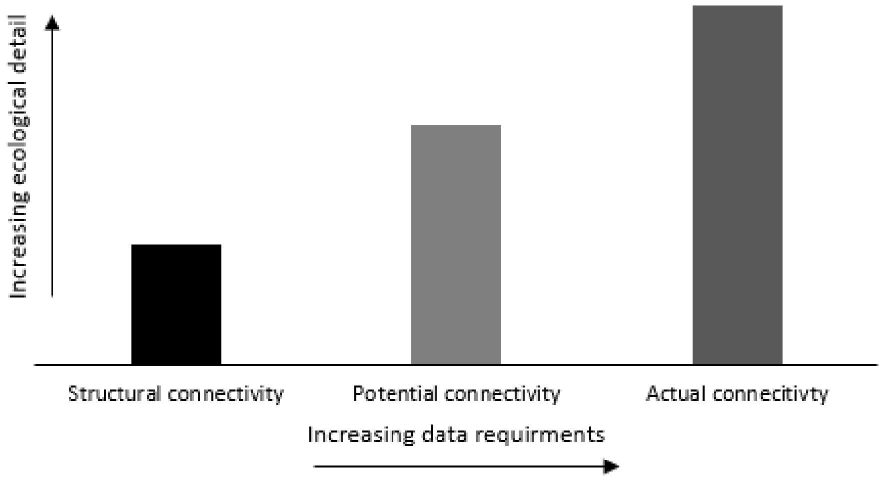

Figure 2: A general interpretation of the trade-off between required data and the amount of ecological detail given by connectivity type (Calabrese and Fagan 2004).

Often potential functional connectivity relies on dispersal estimates from the literature, yet generalisation is not appropriate as this information tends to be site, location, and species specific (Fahrig 2007; Luck et al 2011). There is also little information available on some taxonomic groups and their behaviour in the urban environment, and research is uneven across ecosystems and regions. LaPoint et al. (2015) found that the number of studies which incorporated ecological connectivity in urban environments were primarily based in the northern hemisphere, less than twenty studies had investigated small mammals, arthropods, and plants, and less than ten had investigated reptiles and amphibians. The studies also measured connectivity with a variety of ways and with multiple metrics to choose from (Table 2), so it is hard to compare different connectivity research (Fahrig 2003; Kindlmann and Burel 2008). Understanding of functional connectivity in urban environments is globally inadequate. To be effective, ecological applications within urban environments need to gather their own information on local species to produce accurate estimations of connectivity, a factor that does not align well with the typical timeline of rapid urban planning.

Unlike functional connectivity, structural connectivity is developed from the landscape elements and requires moderate data sets of the location, shape, and size of habitat patches within the landscape. The required landscape information can determine connectivity in a timely manner, due to the limited information demand. However, these connectivity measures do not factor in the dispersal ability of the organism or the relationship between successful dispersal of a species and the spatial pattern of the landscape (Calabrese and Fagan 2004; Taylor et al. 2006). While structural connectivity is therefore easier to measure than actual and potential connectivity, is limited as a concept because connectivity is not an attribute of the landscape alone. The same landscape structure does not have same level of connectivity for different species. Thus, a landscape that is structurally connected might not be functionally connected for certain species (Crooks and Sanjayan 2006).

Potential connectivity is the middle ground of the three connectivity types as it blurs the lines between the strict classifications of structural and actual connectivity. Potential connectivity joins the landscape structure with knowledge of species movement abilities (from published literature or expert judgement) making it a commonly used practice due to its desirable *effort* to *benefit* ratio (Calabrese and Fagan 2004). For example, Serret et al. (2016) examined if green spaces at business sites in France could contribute to the ecological network. To investigate this idea they mapped the size, location and shape of the green spaces within the area, then based the species distance thresholds and their movement ability throughout the urban landscape on expert opinion and scientific literature rather than primary data. This mixing of existing species knowledge and landscape structure provides a robust evaluation of connectivity that did not have to take years to establish. However, the use of scientific literature is good if available, but the researchers need to make sure that generalisations from the literature are representative of the species otherwise the estimation of connectivity will be inaccurate (Fahrig 2007; Luck et al 2011). The incorporation of landscape elements and species behaviour concepts given by potential connectivity provides a good balance between structural and actual connectivity concepts, when evaluating connectivity in rapidly urbanising landscapes.

3. Measures

There are many measures used to estimate functional and structural connectivity (Table 2) and all these metrics are readily available to land managers. The input information used to calculate the metrics will determine if they are informing structural, potential, actual connectivity concepts (Fagan and Calabrese 2006; Rayfield et al. 2011). For example, total number of links will represent structural connectivity unless informed on the species dispersal distance capabilities, then it will inform potential connectivity. The characteristics and behaviour of each metric varies widely, and some are inadequate in a rapidly urbanising landscape. The potential misuse of a metric is obvious when land managers have no guidance to aid in selecting the most appropriate metric to measure connectivity. Therefore, their estimation of connectivity maybe far from the truth.

Table 2: Common connectivity metrics and their measures

Connectivity Metric	Description	Structural level	Theoretical foundation	Binary or Probabilistic	Author
Total number of Links	The amount of links in a landscape, the more links the more connectivity	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Number of components	The number of components in a landscape, more connected landscape has less components	Landscape	Graph theory	Binary	Urban and Keitt 2001
Mean size of the components	Mean area of all the patches within a component, larger the area the more connectivity	Landscape	Graph theory	Binary	Urban and Keitt 2001
Size of the largest component	The area of the patches within the largest component, more connectivity the larger the component	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Betweenness Centrality	The number of shortest paths passing through the focal path, the more paths the higher the connectivity	Patch	Graph theory	Binary	Freeman 1977
Harary index	Shortest connections between patches based on topologically distance (number of links) Patches not connected belong to different components	landscape	Graph theory	Binary	Ricotta et al. 2000
Graph dimeter	The diameter is based on the maximum length of all the shortest paths between any two patches in the graph. It is computed using Euclidean distance rather than number of links. The shorter the diameter the more connected the landscape.	Landscape	Graph theory	Binary	Urban and Keitt 2001
Class Coincidence probability	The chance of two organisms randomly placed within the habitat and will be a part of the same component, the higher the chance the higher the connectivity	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Landscape Coincidence probability	The chance of two organisms randomly placed within the landscape (habitat or non-habitat) will be a part of the same component, the higher the chance the more connected the landscape	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Integral index of connectivity	Increases with improved connectivity, the patch itself is considered a place where connectivity exists as well as the shortest paths between patches	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Delta Integral Index of Connectivity	Ranks patches contribution to connecting the landscape, the higher the connectivity the higher the contribution	Landscape	Graph theory	Binary	Pascual-Hortal and Saura 2006
Probability of Connectivity	The chance that two organisms randomly placed within a landscape fall within habitat that is connected to one another, the higher the chance the more connectivity	Landscape	Graph theory	Probabilistic	Saura and Pascual-Hortal 2007
Delta Probability of Connectivity	Ranks patches contribution to connecting the landscape, the higher the connectivity the higher the contribution	Landscape	Graph theory	Probabilistic	Saura and Pascual-Hortal 2007

The incidence function model	Measures the contribution of each patch towards the focal patch based on their size and distance. The closer and larger the patches the more connectivity	Patch	Meta-populations	Probabilistic	Molianen and Hanski 1998
Flux	Computes the probability of a dispersal flux from one patch to another, landscape version on the incidence functional model. Sums all the incidence functional model values for al patches within the landscape	landscape	Meta-populations	Probabilistic	Bunn et al. 2000
Patch cohesion	Based on the number of pixels in a landscape and if the pixels are isolated or not, the less isolated pixels are the more connectivity in the landscape	landscape	Meta-populations	Binary	Schmaker 1996
Correlation length	When an individual is randomly placed within the landscape, the distance they can travel before reaching a barrier, as the distance increases so does connectivity	Landscape	Graph theory	Binary	Keitt et al. 1997
Buffer	A buffer is set around the focal patch, any other patches within the buffer the patch is connected to, the more patches within the buffer the higher the connectivity	Patch	Meta-populations	Binary	Wiegand et al. 1999
Re-observation after displacement	The distance an organism has travelled when re observation of the organism has taken place	landscape	empirical approach	Binary	Pither and Taylor 1998
Nearest to neighbour	Distance to the nearest patch, the closer the distance the greater the connectivity	Patch	Meta-populations	Binary	Moilanen and Nieminen 2002
Expected cluster size	The average area that an organism can access, when an organism is placed randomly in a habitat. The more habitat they have access to the more connectivity.	Landscape	Graph theory	Binary	O'Brian et al. 2006
Clustering Coefficient	How redundant a patch is within the network; higher values of connectivity indicate greater alternative pathways through the focal patch	Landscape	Graph theory	Binary	Ricotta et al.2000
Dispersal success	A simulation of the total number of first immigration movements of all individuals into all patches. The increased number of dispersal successes the higher connectivity	Landscape	Simulation modelling	Binary	Tischendorf and Fahrig 2000a

Connectivity metrics have been developed by two different disciplines of ecology: metapopulation ecology and landscape ecology. Therefore, some metrics measure connectivity at the patch level (summarise features of specific patches) , while others at a landscape level (summarise whole landscapes and consequently the spatial pattern of individual patches (Tischendorf and Fahrig 2000b; Tischendorf and Fahrig 2001; Moilanen and Hanshi 2001)). Although the focus of this literature review is at the landscape level for urban environments, this section will start by looking at patch level metrics to provide a foundation of the importance of considering structural levels when assessing connectivity, especially in urbanised landscapes.

3.1 Patch metrics

Patch based metrics consist of three main types (Figure 3) (With 2019). The simplest patch connectivity measure are 'Nearest Neighbour' types, as they measure the shortest distance from the focal patch to the nearest patch requiring no information about a species dispersal capability. The metric's disregard for any patch but the closest one means the metric ignores any other habitat which could influence population size or individual movements (Figure 3A) (Hanski 1994; Moilanen and Nieminen 2002; Bender et al. 2003). This is a problem when assessing connectivity in an urbanising landscape as it does not give a holistic viewpoint for the researcher. Knowing the different patches a species is capable of traveling to and from is important in understanding where effective linkages can be placed, and where they can move to if the patch is removed.

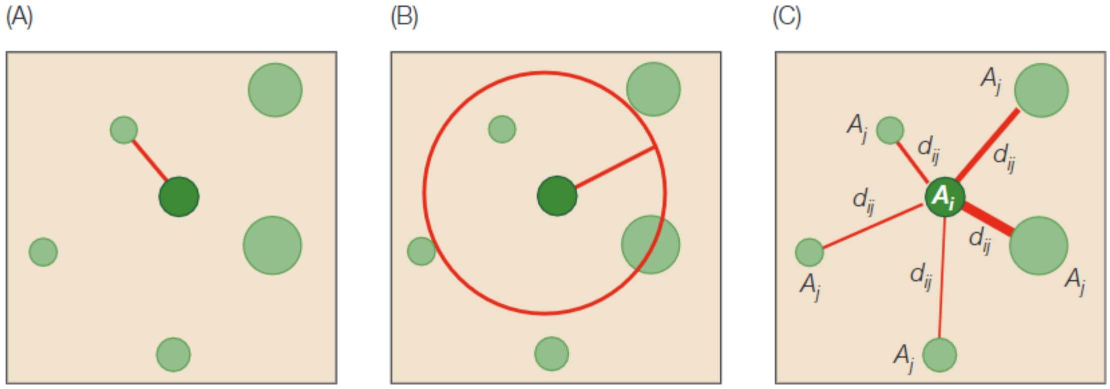

Figure 3: Three patch level measures. A) illustrates the nearest neighbour model, measuring the distance to the nearest patch. B) demonstrating buffer models that measure all patches within a radius of a patch, preferably set at species dispersal threshold. C) Showing the incidence functional model which measures the contribution of each patch based on their distance (dij) and area (Aj) to the focal patch. Hence the closer and larger the patch to the focal patch the increased likelihood of immigrants. Taken from With (2019).

Buffer metrics include patches that are within a set radius of a focal patch which is preferably set at the maximum distance a species can travel (distance threshold) (figure 3B). These metrics provide advantages over ‘Nearest Neighbour’ as they include all the patches that will influence the species population (Bender et al 2003; Cabeza and Moilanen 2003; With 2019). However, the estimated buffer needs to be informed of the species distance threshold, making these metrics sensitive to the radius size (Moilanen and Nieminen 2002). Therefore, if a patch is located outside of this radius then it will not be included in the analysis, thus these patches cannot be colonised by a species within the focal patch, in turn poorly assessing connectivity at larger scales. Patches may border the radius (Figure 3B), a species could colonise this patch and then move to another that was originally outside of the specified radius. The patches within the radius are also assumed to have equal chance of an individual dispersing to them, even though the patches are differing in size and distance (Moilanen and Nieminen 2002; With 2009). Consequently, this metric is weak for estimating connectivity in a rapidly urbanising landscape as it does not provide enough information on how species can move through the whole landscape or give an estimation of which patch they are most likely to travel to. Therefore, not suppling land managers with enough information for them to make informed decisions when planning the landscape structure.

Incidence Functional Models (IFM) assesses the distance and area of a patch to all prospective resource patches. The metrics weigh the likelihood of a patch to be colonised due to their size and distance from the focal patch (Figure 3C) (Hanski 1994). These metrics have greater biological realism as they consider the varying distances and size of the habitat patches as well as the species dispersal capability (Moilanen and Hanski 2001; Verheneyen et al. 2004. Nevertheless, these metrics assume that colonisation and extinction rates are roughly constant and do not change with the age of the patch (Verheneyen et al. 2004). Thus, the metrics do not consider effects of urbanising landscapes on remanent vegetation patches. Ramalho et al. (2014) found that indirect effects of urbanisation negatively impacted species richness and abundance over time. Thereby, species may not interact with the landscape pattern in the future as expected from the model, and connectivity may be less than what is estimated. IFM also considers connectivity at a patch level, therefore species that are good and adaptive colonisers tend to be considered as extinction prone as they move out of the area under investigation, but at a landscape level these are the species that persist into the future as they can adapt faster to a changing landscape (Verheneyen et al. 2004).

3.2 Patch to landscape measures

There are three main reasons why patch measures should not be extrapolated or aggregated to inform connectivity in a rapidly urbanising landscape, even though connectivity is determined using the same process of spatially assessing movement within the landscape structure at both scales (Moilanen and Hanski 2001; With 2019). First, patches within the landscape can cluster in different areas. Hence, patch metrics could measure high connectivity in a landscape that is not very connected (With 2019). Secondly, different species occupy and move between different patches at different times and scales, depending on the size of the habitat and the individual (Peterson et al. 1998). Thus, multiple species may use a habitat patch but experience the area quite differently depending on the species scale (Peterson et al 1998; Crooks and Sanjayan 2006). For example, a patch within an urban environment may be occupied by a turtle and a Carnaby cockatoo, but the way they utilise the patch is different. A turtle may live within the patch its whole life while the cockatoo may move around multiple patches a day at various distances to forage. Lastly, urban landscapes are complex and diverse, complicating the assessment of patch metrics based on distance. Species will potentially behave differently in response to the varying elements within the landscape (Adriaesen et al. 2003; Taylor et al. 2006) and therefore what might be correct at the patch level may not be at the landscape which is problematic.

3.3 Landscape metrics

Landscape metrics use algorithms that estimate connectivity for the whole landscape mosaic. Thus, these metrics provide a holistic perspective of connectivity for the entire landscape. Numerous landscape metrics have been produced, and consequently this section will review metrics that are commonly used and evaluate how well they can inform rapidly urbanising environments.

Dispersal success (the number of individuals who successfully colonise a new habitat) and search time (time it takes for an individual to find a new habitat) are both simulation-based measures of connectivity (Schippers et al. 1996; Doak et al. 1992;

Tischendorf and Fahrig 2000a). Simulating the landscape without large reliable empirical data such as presence and absence, species movement capabilities, and species interaction with the landscape features, will mean the connectivity estimation is random (Tischendorf and Fahrig 2000a). Species are placed randomly in the landscape and can move randomly to different habitats, thus the relationship between real connectivity and the simulated connectivity can be weak. The models both produce a counter intuitive response to connectivity, as connectivity equals zero when the habitat covers the whole landscape (no dispersals or time searching for new habitat (Tischendorf and Fahrig 2000b)). This assessment contradicts the theory that a landscape covered in habitat is more connected than a landscape containing fragmentation. Hence, the use of these metrics could indirectly promote fragmentation to improve connectivity, in turn potentially producing negative consequences for conserving habitats in urban environments. This problem is caused by the measures only accounting for connectivity between patches (inter-patch - the more fragmentation the more habitats the more links) and not movement within the patches (intra-patch) (Tischendorf and Fahrig 2000b; Laitia et al. 2011; Spanowicz and Jaeger 2019).

Pascual-Hortal and Saura (2006), Saura and Pascual-Hortal (2007) have evaluated and discussed including intra-patch connectivity within connectivity metrics and produced new metrics which they compared to several others. Pascual-Hortal and Saura (2006) introduced the integral index of connectivity (IIC) which consider the concept that connectivity exists within a patch and integrates this as ‘intrapatch connectivity’, which is reached through the links to other patches ‘interpatch connectivity’ (Pascual-Hortal and Saura 2006). Connectivity is therefore considered as the amount of habitat available to an organism that comes from either a large habitat patch, the connections available between habitat patches, or a mix of both. Therefore, IIC gives a more holistic view of connectivity. A drawback with IIC is that it is a binary model, which means patches are considered to be completely connected or not depending if they are over or under a threshold distance, therefore there is no variation in the strength of the connection representing feasible dispersal (Moilanen and Nieminen 2002). This limitation means that each linkage is weighted with equal chance of species usage within a set area, restricting its estimation of functional connectivity. However, Pascual-Hortal and Saura (2006) still found that IIC better than multiple other metrics when changes took place within the landscape, an important factor when assessing a rapidly changing urbanising environment.

Saura and Pascual-Hortal (2007) later introduced the probability of connectivity (PC) which is the same as IIC but counter acts the binary model drawback, as instead it calculates the probability of a species moving between patches, providing a more credible evaluation of species movement. Still, if the chance of a species dispersal is incorrectly measured or assumed then the results will be skewed. Gathering suitable data to predict dispersal probability may be difficult and time consuming as the information that could be used to predict probability includes habitat quality, the amount of individuals a patch can sustain, habitat suitability, and colonisation-death ratio (Saura and Pascual-Hortal 2007). However, when compared to other metrics PC was the only one to produce a desirable outcome for every element considered to be relevant for a measuring connectivity (Saura and Pascual-Hortal 2007), making it superior for estimating connectivity in an urban landscape.

Saura and Rubio 2010 partitioned IIC and PC into three fractions: intra, flux, and connector. Intra represents a patch's contribution to connectivity based on its area (connectivity that exists within the patch). Flux resembles the dispersal through a patch due to its connections with other patches within the landscape, based on the patch being the beginning or the finish point of the dispersal flux. Therefore, flux measures how well connected the patch is to the rest of the habitat within the landscape. Connector computes the importance of a patch to the connectivity of the landscape, calculating whether it is vital stepping stone (a patch that is used as a refuge for individuals crossing the landscape to other habitats) which upholds connections. The three fractions are measured using the same units, allowing them to be directly compared to each other. Now the estimates not only calculate a patch's contribution to connectivity and how well connected the patch is, but also the importance of that patch to maintain connectivity. These estimates are becoming increasingly used in ecological applications because of their integration within a logical and consistent multi-layered framework and the information it provides not incorporated within pre-existing connectivity measures (Gurrutxaga et al. 2011; Rippa et al. 2011; Baranyi et al. 2011). Still, the connector fraction gives larger patches more importance over multiple smaller ones (Saura and Rubio 2010), which may not be ecologically correct, especially if the larger patch is facing more disturbances than the smaller patches. Additionally, the IIC binary model has been found to produce a bigger variation than PC in patch importance, as small changes to the distance threshold may remove or add multiple patches in the analysis (Ziółkowska et al. 2014). The equivalent change for PC would produce a comparatively smaller variation, as it would just change the dispersal probabilities providing a more ecological evaluation (Bodin and Saura 2010; Ziółkowska et al. 2014). Therefore, if land managers have access to the empirical information needed to use PC it would give them a reliable estimation of connectivity and an understanding of where best to modify the landscape to enhance connectivity.

3.4 Distance parameters

The majority of connectivity measures are underpinned by empirical distance parameters. For example, distance to the nearest patch or distance a species can travel. Initially Euclidean (shortest straight line) distance was used to determine the distance a species travels between patches (Figure 4A). However, the assumption that a species travels in a straight-line from one habitat to another is too simplistic when measuring connectivity in a rapidly urbanising landscape. Urban environments are diverse and complex generating multiple barriers that species have to avoid or overcome.

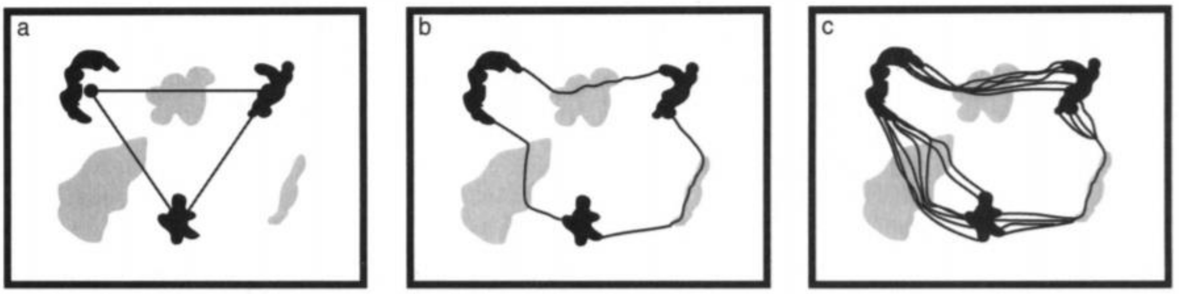

Figure 4: Demonstration of connectivity linkages based on the amount of empirical information incorporated into a metric and the distance parameter used. Habitat patches are the black polygons and are connected with links (black lines) through inhospitable (white) and hospitable (grey polygons) land. A) Linking habitat patches with Euclidean distances, requiring no empirical information. B) Least cost paths connecting patches based on the pathway which inflicts the least cost to an organism, incorporating information about the landscape in between patches. C) Multiple paths created from circuit theory, incorporating further information on the landscape. Taken from Rayfield et al (2011).

Least cost path (LCP) modelling has since been developed and calculates the path which will have the least stress inflicted on an organism (Figure 4B, Figure 5). LCP needs two map layers, the source layer consisting of the habitat patches, and the resistance layer which specifies the difficulty of moving through each mapping unit based on the landscape features it contains (Adriaensen et al. 2003). However, LCP relies on the idea that the organism will take the optimal path and that they have knowledge of the entire landscape pattern (Adriaensen et al. 2003). When building a resistance map for LCP modelling there are a few important factors that can make or break the validity of the results: the size of the map (extent) needs to be greater than the species dispersal capabilities, the resistance values recognised in the map should correspond to the way the species views the landscape, and the distance thresholds that determine if the species can reach another patch need to be ecologically informed (Schadt et al. 2002; Ferreras 2001; Adriaensen et al. 2003). If these factors are not considered appropriately, then the estimation of connectivity will be weakened. While LCP modelling likely does not provide the actual path taken by an organism, it is still more realistic and comprehensive than Euclidean distance. For example, Driezen and colleagues (2007) found that paths taken by hedgehogs (*Erinaceus europaeus*) were not random and that they preferred paths with significantly lower costs than the general landscape, but their trajectories and predicted least cost paths did not perfectly align.

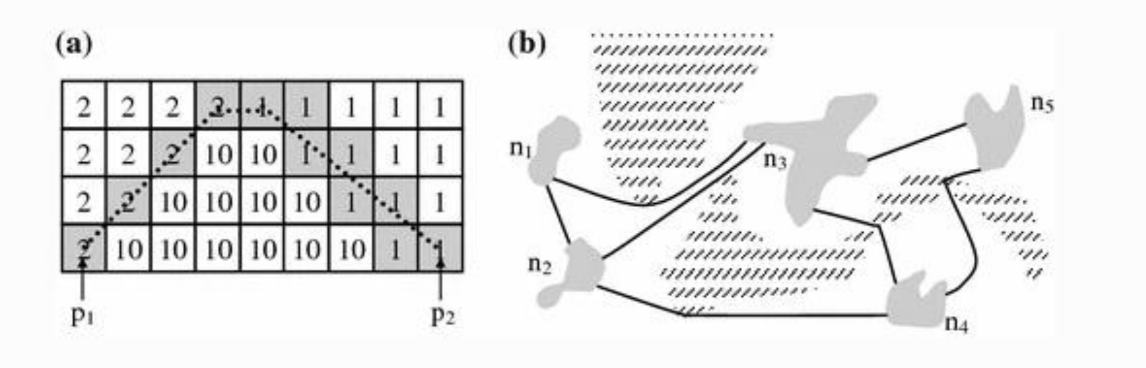

Figure 5: A) represents a resistant layer in least cost path (LCP) modelling. The values within the grid cells correspond to the difficulty a species has moving through a land cover type, with lower numbers the greater permeability to a species. The dashed line links patch one (P1) and patch two (P2) through the least cost path, the cumulative cost for the LCP is 13 where the cumulative cost for straight-line path is 64. B) demonstrates how the land cover and their associated ‘cost’ influences the path taken by an organism (landcover with high cost barriers are crossed-hatched), and that these paths may not be shortest straight line between patches. Taken from Fall et al (2007).

An alternative to LCP modelling is circuit theory, which links species movement or gene flow on a grid representing the landscape features and connectivity moves between the cells (Figure 6). One of the main issues with circuit theory is estimating the resistance values of the landscape, the same as LCP. These resistant values tend to come from prespecified values within the literature that have been hypothesized to impact connectivity (Cushman et al 2006; Cushman et al. 2009). These values however can be species and site specific, and there is no way to assess if values from the literature are accurate for the site and species in question. Incorrect values can result in inaccuracy of the relationship between the connectivity estimation and actual connectivity (Fahrig 2007; Huck et al 2011; Theobald et al. 2011; Hanks and Hooten 2013). For example, LaPoint et al. (2013) found linkages and under-road passages maintained functional connectivity for *Martes pennant* (Fishers) in Albany, New York. Camera traps were used to compare whether the species used the predicted corridors produced by circuit theory, least cost path and their own model. The authors found that their model worked the best, but it includes capturing and monitoring animals, in turn requiring greater effort. Circuit theory predicted 5 out of the 23 linkages and least-cost 1 out of the 23 linkages. Cost-based models therefore can be an inaccurate estimation of connectivity if interactions between species and landscape features are ignored. A distance threshold cannot be added to circuit theory, therefore it assumes that a species can travel at any distance, limiting its relationship with real connectivity. Circuit theory has been found to provide better estimates of gene flow through the landscape than LCP (McRae and Beier 2007). For example, McRae and Beier (2007) used genetic information based off other studies of two different wolverine populations and examined the path that would be taken between the populations. They compared LCP and circuit theory and found that circuit theory gave a better estimation due to its ability to produce multiple pathways (Figure 4C). Knowing different pathways an individual can take to find other populations means when changes in the landscape take place the researcher can assess which pathways will be affected and how it will affect connectivity. Circuit theory therefore provides a useful model in predicting population change due to changes within a rapidly urbanising landscape (Hanks and Hooten 2013).

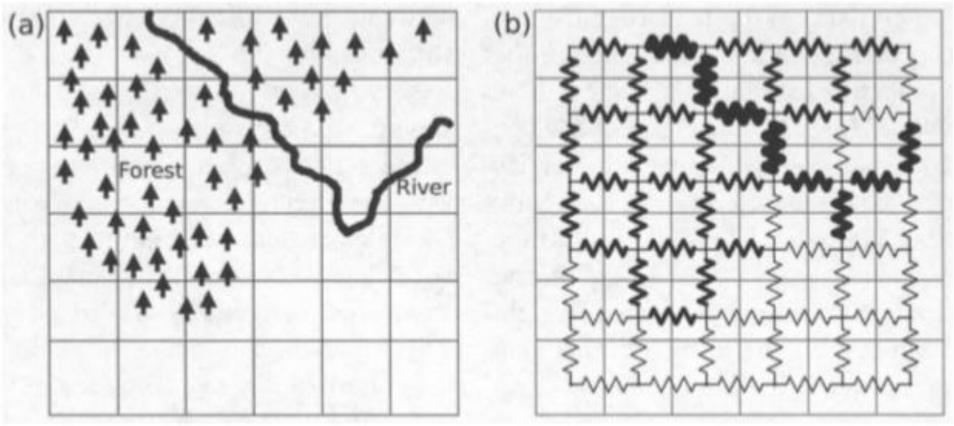

Figure 6. Demonstrating circuit theory as a model for connectivity. A) represents the landscape on a raster grid where the forest and the river are seen to inhibit connectivity. B) Connectivity is observed between the adjacent cells as the cells represent nodes that are connected to different land cover (resistors). The thicker the line between the cells represents higher resistance and therefore the less connections between nodes. Taken from Hanks and Hooten (2013)

4 Spatial and temporal impacts

4.1 Spatial impacts

High spatial and temporal heterogeneity in urban environments is due to the rapidly changing structure of the landscape. The pressures imposed by human activities on remnant vegetation, wetlands and the connections between patches varies over time and space (Graham et al. 2018; Martin et al. 2018). The literature however mainly focusses on the spatial perspective of connectivity such as finding linkages that aid dispersal pathways to maintain species populations, or where to restore areas to re-establish connections (Ribeiro et al. 2011; Kool et al. 2013; Lencher et al. 2017; Perry and Lee 2019). Several studies have therefore investigated the impacts of spatial uncertainties produced by connectivity measures, primarily around resistance surfaces, in static landscapes (Verheyen et al. 2004; Kautz et al. 2006; Pascual-Hortal Saura 2006; Saura and Pascual-Hortal 2007; Beier et al. 2009; Simpkins et al. 2017). Spatial ambiguities arise from errors in the underlying variables used to inform the metric. For example, mis-estimation of resistance values, errors in the spatial pattern data and errors estimating species behaviour, as well as the metric's response to changes within the landscape structure (Saura and Pascual-Hortal 2007).

It is not feasible to remove all uncertainties incorporated within a connectivity model, hence the importance of understanding how they impact the analysis and how they interact with each other. Simpkins and colleagues (2017) found that errors within the spatial pattern data had greater impact on estimating connectivity than mis-estimating resistance values. However, resistance values build on the spatial pattern layer as they are informed by the landscape elements, thereby amplifying any spatial inaccuracy. Multiple studies have found that the selection of resistance values will alter the connectivity estimate, but if the ranking of cost values stays the same it has little impact on the results (Beier et al. 2009; Rayfield et al 2010; Simpkins et al. 2017). The number of land classes within an analysis can affect the connectivity estimation. Incorporating or removing classes impacts the configuration of the landscape (Zeller et al. 2012; Simpkins; 2017), influencing the placement of the most effective linkages between patches. Errors in the spatial pattern data are now less likely than historically, due to increased use of satellite data. However, errors in the data will change the estimation of connectivity (Simpkins et al. 2017). For example, if the data presents a habitat patch where there is not one, the overall connectivity of the landscape will increase. In a rapidly urbanizing landscape where clearing is happening constantly, it is important to have up to date spatial data. This is especially a problem if this patch is calculated to be important for maintaining connectivity and therefore recommendations for land managers might incorporate a patch that does not exist. If the species dispersal data influencing the patches and linkages are incorrect then the emphasis on protecting and conserving certain areas may also be incorrect (Fahrig 2007; Merrec et al 2020).

Different metrics respond to spatial changes better than others. Pascual-Hortal and Saura (2006) and Saura and Pascual (2007) found that many connectivity metrics responded inconsistently and unfavourably when changes in the landscape occurred. Making many metrics inadequate to determine any spatial changes in the landscape and therefore inadequate for assessing connectivity in a rapidly urbanising landscape.

4.2 Temporal impacts

Less attention has been placed on temporal aspects of connectivity, even though it has been argued that temporal uncertainties outweigh spatial uncertainties when assessing connectivity (Fahrig 1992; Zeller et al. 2012; Zeigler and Fagan 2014; Bishop-Taylor et al. 2018; Perry and Lee 2019). Connectivity changes over time and in some cases relatively fast (Ramalho et al. 2014; Perry and Lee 2019). For example, wetland habitats can be intermittent depending on the dynamics of the water cycle, therefore potentially disconnecting, and connecting habitat patches (Calhoun et al. 2017; Datry et al 2017). Temporal variation also influences terrestrial systems over a range of time scales: For example, Dalattre and colleagues (2013) found that in more fragmented landscapes *Maniola jurtina* (butterflies) are temperature sensitive when moving between habitats. Similarly, Martin et al (2018) found *Capreolus capreolus* (Roe deer) movements are dependent on their proximity to habitat and human presence, thus dispersing at greater distances at night. Brotons et al. (2012) found that disturbances such as fire, shift the landscape mosaic, thereby altering species distribution and connectivity. Rapidly urbanising environments have been found to disturb patch composition, negatively affecting habitat quality over time, and increasing species extinction risk (Ramalbo et al. 2014; Zeigler and Fagan 2014). Negative time -lagged responses to fragmentation is particularly pronounced for trees and species who have low dispersal ability, while species who have a good dispersal capability respond better to connectivity measures (Metzger et al.2009). The size of patches maintaining species populations therefore need to be large enough to sustain them into the future. Connectivity needs to be classed as temporally shifting to be able to understand how temporal uncertainties will influence species populations over time.

Many metrics produce static outputs presenting connectivity as a snapshot in time, limiting its usefulness for decision making in planning, especially in rapidly urbanising landscapes (Bergsten and Zetterberg 2013; Whitten et al. 2011; McHugh and Thompson 2011). Temporal uncertainties can shift dramatically, as linkages open and close to species depending on structural alterations within the landscape (Lencher et al. 2015). It is therefore crucial for assessments to be flexible in design and ready to be modified with updates in response to management decisions, species characteristic, and spatial data.

A scenario approach which considers the impacts imposed by different land use and seasonal changes is useful for applying to planning exercises in a rapidly changing urban landscape. Stakeholder interest can be represented in multiple scenarios by modifying different data inputs (Figure 7) (Lechner et al. 2015). Changes in land use can be shown to have a positive or negative impact on connectivity by changing the size of the patches, adding or removing landscape features, changing dispersal costs and thresholds due to the changing landscape. This will allow land managers to qualitatively visualise the impacts as well as quantitatively analyse them through the metric (Clauzel et al. 2013; Foltête et al. 2014). In many circumstances however there is little ability to simulate different scenarios or update existing maps, thus where land use scenario mapping already exists it may not be quantified (Bergsten and Zetteberg 2013; Whitten et al. 2011). A regular tactic to overcome static mapping is to overlay the land use changes with the connectivity network (Lechner et al. 2015). This approach can be suitable for simplistic impacts that disturb one patch or link. When impacts are more complex, affecting multiple areas of the connectivity network, the approach may be inadequately assessing the changes in connectivity. Assessing spatial and temporal impacts on landscape connectivity requires a systematic approach where changes can be demonstrated to assess their effects on connectivity (Lechner et al. 2015).

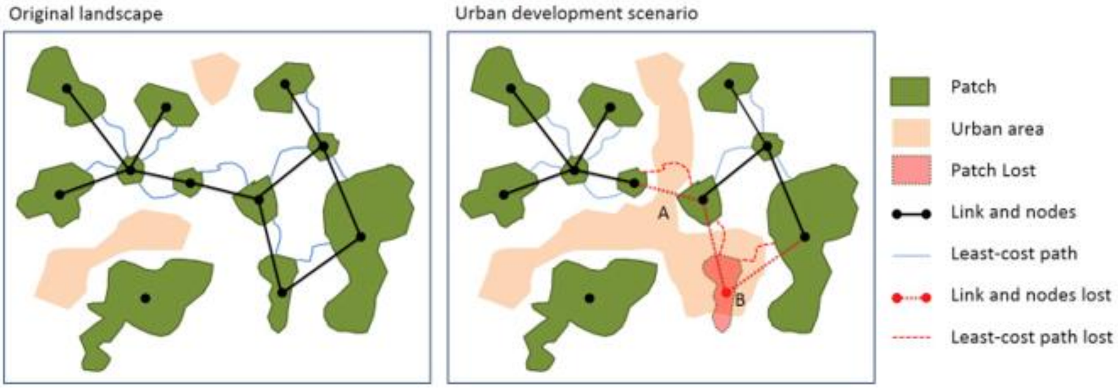

Figure 7. Illustrating a development scenario where effects of an increased complexity in the urban matrix are assessed using graph theory. The graph represents patches as nodes and connection between patches as links. Graph metrics can be used to quantitatively assess a patches contribution to the overall landscape connectivity, and the effect of the urban growth can also be qualitatively expressed through the loss of patches and links within the graph. Taken from Lencher et al (2015)

5 Case studies

This section represents case studies of research that have informed urban planning or improved land planners and mangers awareness of how to enhance connectivity in urban landscapes. These studies indicate how the theoretical concepts of connectivity can be applied in urbanising landscapes. Each one will be assessed to determine how they could be improved.

Caryl and colleagues (2013) found in Melbourne that connectivity for *Petaurus breviceps* (Sugar Gliders) could be aided by lowering highly divergent land-cover edges between residential areas and conservation reserves. The authors suggest that management of the urban matrix is important in limiting disturbance induced by humans. Incorporating policy such as pet control and housing density, plus maintaining and restoring trees along streets and back yards will enhance connectivity for gliders. Animal capture, radio tracking, spatial data were used to analyse species behaviours, however the sample size collected was too small to determine which variables were being influenced, so data had to be pooled. Having a small sample size could mean that the results are not necessarily true of the entire population. Small sample size is a common limitation in fauna capture studies, but it does provide a context of functional connectivity. Requesting policy changes although important for changing and adapting ecological urban designs could take a long time to be put into practice, therefore supplying applications that can be introduced at present, increases the practical application of this study.

Jha and Kremen (2013a; 2013b) found in California impervious surfaces are major barriers for *Bombus vosnesenskii* (Bumble Bee) and reducing these surfaces by improving floral diversity within urban gardens and suburban areas will improve foraging and potentially further extend pollination. The authors used genetic information to predict actual connectivity, then measured distance using resistant values based on previous studies and Euclidean distance. The study could be improved by weighting the patches by species occupancy, to further inform land managers of where the species is concentrated. The study does however give land managers and planners a greater awareness on how to modify the urban landscape to aid pollination. Planting diverse flora throughout a rapidly urban environment is something that land managers could incorporate in adaptive urban planning relatively easily, however land managers should be mindful about what species they are planting to not incorporate invasive species.

Horta et al. (2018) found potential functional connectivity linkages within the region of Belo Horizonte for *Ramphstos toco* (Toco Toucan). Using IIC and least cost models the authors identified permanent food supply resources for the species that was allowing them to persist in the city, and critical patches that allowed the birds to move between habitats. Part of these fundamental routes are licensed for construction yet have remained preserved due to social engagement. The study however uses a large 3000 m distance threshold, many other species would not be able to travel this far, limiting the usefulness of the research in indirectly aiding other species. This study and others such as de Castro Pena et al. (2017) have pushed for the better ecological planning in Belo Horizonte and have improved awareness for land planners and managers.

The above connectivity studies in urban environments demonstrate that connectivity research requires ecological information to inform practical applications for urban planning. Structural connectivity helps to facilitate functional connectivity in application design, as land managers can promote linkage features such as verge gardens and green spaces, as well as reduce barriers through the creations of covenants and underpasses. The studies do not incorporate a scenario approach, if they did, they would further inform land managers on how their actions will affect connectivity.

6 Conclusion

Adaptive urban planning needs to be informed by theoretical connectivity concepts which are underpinned by a framework which incorporates suitable metrics, empirical data, and scenario planning. Land managers and planners need a toolbox that is dynamic and flexible to evaluate connectivity, which is also not overly complex, time consuming or difficult. Numerous studies either emphasize the structural importance of the landscape or the ecological processes influencing species behaviour, far less assess the importance of combining both functional and structural aspects. Merging both structural and functional connectivity concepts increases the ability to inform land managers and planners in rapidly urbanizing environments on the most effective way to enhance connectivity and improve the city's ecological design through modification of the landscape.

A greater understanding of the relationship between connectivity metrics needs to be gained, as different metrics will give different results, and many have not undergone examination. It is still relatively unknown how sensitive they can be to different types of empirical data and changes in the landscape. At present, habitat availability metrics such as IIC and PC have proved to be effective for landscape planning, as they handle spatial changes in the landscape appropriately, identify crucial habitats, and incorporate a good balance between data demands and effort. PC is suggested to use over IIC unless data is scarce then IIC should be applied. Distance parameters of circuit theory or least cost modelling should be used over Euclidean distance, to gain a more realistic interpretation of path taken by a species.

More than one measurement of connectivity needs to be applied. The researcher needs to explore different scenarios that will impact connectivity based on decisions taken by land managers. Removing and adding patches will aid in determining potential changes in connectivity over time. IIC and PC will also be able to rank which patches are important for maintaining connectivity and therefore land managers will be able to quantitatively and qualitatively assess how decisions will impact connectivity. Habitat patches should be given a minimum size threshold, to enable population preservation. Patches that are smaller in size should be considered as stepping stones maintaining connectivity to habitat patches. Using a flexible scenario approach will give land managers and planners a holistic view of their impacts on connectivity from modifying the landscape.

Future research on species behaviour interactions within the landscape structure is needed to continue to further understand functional connectivity and to incorporate better empirical data into connectivity metrics. This will not just make the models more realistic in terms of species movement behaviour in response to the landscape structure and their associated costs, but also in determining what structural level (landscape or patch) is appropriate for assessing a species. Testing of connectivity assessments to validate the performance of the ecological network in rapidly urbanising environments is important to ensure the networks are enhancing connectivity. This is especially valuable when data and time to perform the assessment is limited, the connectivity framework being applied based on the measurement of connectivity should not be the final stage of the analysis. Ideally the framework will evolve over time as more theoretical and empirical information is produced.

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