An Integrated Approach to Enhancing Ecological Connectivity and Accessibility in Urban Areas: a case study of Sheffield, UK

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Abstract

Recently, increasing environmental threats to the functioning of landscape and biodiversity have heightened the need for developing new approaches to nature conservation. Green and ecological networks have been developed as an attempt to maintain the functioning of landscapes, promote the sustainable use and conservation of nature, support the movement of species and increase people's use and enjoyment of the nature (Bennett and Wit, 2001; Bennett and Mulongoy, 2006; Lawton et al., 2010). These can be achieved by the identification and selection of the main features of ecological and green networks based on ecological and / or social functions we intend them to fulfil as well as the determination of objective conservation measures.

The main purpose of this research is to focus on critically examining different ways of defining green and ecological networks and their functionality for biodiversity and people in the case of Sheffield, which were derived from different theoretical and professional perspectives (planning and ecology), and to explore the potential for different approaches to define ecological / green networks. Due to its multidisciplinary nature, this thesis uses a mixed research methodology, based on different methods of data collection and analysis.

This research commences with the analysis of existing green and ecological network approaches, namely the Green Network (Sheffield City Council) and the Living Don (Sheffield and Rotherham Wildlife Trust). In order to analyse these approaches, policy document analysis, semi-structured interviews and ArcGIS spatial analyses were conducted to understand the rationale, aims and the spatial structure of current networks in the case of Sheffield.

For the identification of criteria to develop alternative routes of connectivity, ArcGIS and FRAGSTATS were used. After generating land cover and land use maps at a very fine scale (2m raster resolution) and with different levels of detail, the alternative connectivity routes, for both biodiversity and people, were identified on the basis of two connectivity measures. The first set of spatial analyses took into account structural connectivity of landscape components as the main criteria, to develop potential routes using ArcGIS and FRAGSTATS in combination. On the other hand, based on functional connectivity, the second set of alternative connectivity routes were developed using a least-cost corridor approach in ArcGIS. For the delineation of alternative connectivity routes for biodiversity, 10 species were selected from 3 different taxon groups (birds, mammals and reptiles); and for people, the alternative routes from residential buildings to (a) green and open spaces, (b) public buildings and (c) industrial / commercial units were used considering the effects of physical / legal accessibility and slope. Then, existing approaches and derived alternative routes of connectivity were compared and contrasted to each other in ArcGIS, to analyse the relationship between their structural properties and the urban morphologies in which they occur, with a view to predicting the implications for ecological connectivity and use by members of the public.

The Sheffield City Council and the Sheffield and Rotherham Wildlife Trust aim at maintaining and enhancing ecological connectivity for the benefit of wildlife as well as supporting public enjoyment and movement, and both of their network approaches benefit from the linear connectivity formed around the main rivers, streams and valleys. However, it was found that there are significant differences in the representation, spatial coverage and arrangement of the Green Network and the Living Don based on the methods and the site selection criteria used for developing green and ecological networks.

Regarding the structural connectivity routes for biodiversity and people, significant differences were found in the spatial extent and arrangement of alternative routes. On the other hand, functional connectivity routes for biodiversity showed both similarities and differences in their spatial extents and arrangements according to selected species' habitat requirements and movement behaviours across the landscape. Similarly, functional connectivity routes for people changed as I used different destinations and parameters. The overall results of this research provide further support for the conceptual premise that the definition of green and ecological networks is highly dependent on the methodology, ecological and / or social functions that are considered, and also criteria for the inclusion of different habitats or land uses within the network.

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Acronyms and Glossary

ArcGIS	GIS Software Package
BAP	Biodiversity Action Plan
FRAGSTATS	Spatial Pattern Analysis Software for Categorical Maps
GIS	Geographic Information System
LBAP	Local Biodiversity Action Plan
LCM2007	Land Cover Map (2007)
LNR	Local Nature Reserve
LWS	Local Wildlife Sites
NPPF	National Planning Policy Framework
PLA	Priority Landscape Area
SAC	Special Area of Conservation
SCC	Sheffield City Council
SDF	Sheffield Development Framework
SLOSS	Single Large or Several Small
SLP	Sheffield Local Plan
SNCS	Sheffield Nature Conservation Strategy
SPA	Special Protection Area
SRWT	Sheffield and Rotherham Wildlife Trusts
SSSI	Sites of Special Scientific Interest
UDP	Unitary Development Plan
YHBF	Yorkshire and Humber Biodiversity Forum

Definition of Selected Landscape Metrics

AREA_MN	The arithmetic mean size of the given patch type (ha).
AREA_AM	The area-weighted mean size of the given patch type (ha).
AREA_SD	The patch area standard deviation: Equals the square root of the sum of the squared deviations of each patch metric value from the mean metric value computed for all patches in the landscape, divided by the total number of patches; that is, the root mean squared error (deviation from the mean) in patch area.
AREA_CV	The patch area coefficient of variation: Equals the standard deviation divided by the mean, multiplied by 100 to convert to a percentage, for the patch area.
CA	Total Class Area (ha): The sum of the areas of all patches for the given patch type.
ENN_AM	The area-weighted Euclidean Nearest Neighbour Distance (m): The shortest edge to edge distance between the adjacent patches of the same classes.
GYRATE_AM	The area-weighted Radius of Gyration (m): GYRATE is the mean distance between each cell in a patch and the patch centroid.
PLAND	Percentage of Landscape (%): The proportion of landscape occupied by a particular class type.
PROX_AM	The area-weighted Proximity Index: The degree of isolation and fragmentation within a specified search radius for the given patch type.

Chapter 1 General Introduction

1.1 Study Background

Urban development has significant consequences for the environment, natural resources and biodiversity. The conversion of landscapes into settlements or other intensively used areas has led to the increasing fragmentation and alteration of natural habitats (Saunders et al., 1991; Turner et al., 2001; Hilty et al., 2006; Bennett, 1999 and 2003). Increasing demand for limited resources is considered to be one of main reasons for the reduction in their quality and quantity, for the degradation of ecosystem goods and services and for their increased fragmentation (Farina, 1998; Alberti, 2005).

The increasing degrees of habitat fragmentation and isolation have been regarded as one of the most important threats to nature and wildlife, resulting in the loss of connectivity in landscapes (Harris, 1984; Saunders et al., 1991; Fahrig, 2003; Lindenmayer and Fisher 2006). Therefore, one important aim of landscape ecology and planning has been the maintenance of the quality and quantity of landscape mosaics against the serious threats to biodiversity created by urbanisation and human activities.

In order to reduce the effects of fragmentation and isolation, researchers have emphasised the importance of maintaining and enhancing landscape connectivity for the conservation of nature and biodiversity (Noss, 1991; Collinge and Forman, 1998; Taylor et al., 1993; Farina, 2000; Taylor et al., 2006; Farina, 2006; Noss et al., 2012). In addition to this, the social, economic, health and environmental benefits of urban green and open spaces have been recognised by researchers, planners and decision-makers (Dunnett et al., 2002; Woolley, 2003; ODPM and NAO, 2006; Barbosa et al., 2007).

Growing recognition of the importance of landscape connectivity has been reflected in different approaches to maintain continuity between isolated habitat fragments and conserve biodiversity in urban areas, and integrated into landscape planning strategies and concepts. In addition to this, where it is possible and convenient, those areas serve for human movement and enjoyment. While landscape ecology concepts and principles provide an understanding of many theoretical aspects of landscape structure, function and change (Forman and Godron, 1986; Urban et al., 1987; Turner, 1989; Golley and Bellot, 1991); planned ecological and green networks have an important role to play in enhancing the landscape within the urban environment, in particular as they are aimed at restoring and protecting habitats and biodiversity, and supporting ecological processes and maintaining human well-being (Bennett and Wit, 2001; Jongman and Pungetti, 2004; Bennett and Mulongoy, 2006; Lawton et al., 2010; Forest Research, 2011).

On the other hand, green networks have generally been the outcome of a combination of opportunistic and deliberative planning decisions over time. In many cities, they consist of a collection of heterogeneous green spaces, many of which were not originally intended to deliver biodiversity benefits. These spaces have been combined to form green networks that are said to have biodiversity functions, but how well do they actually function as habitats for a diversity of organisms?

In this context, the introduction of green networks in planning policy has been an attempt to define ecological networks spatially, but little is known about how effectively they function in terms of the diversity of species they actually support; or about the impact of differing land uses both within the networks and in the matrix that surrounds them.

Moreover, one of the most important obstacles to enhancing the functioning of connectivity routes and maintaining biodiversity is the gap between their intended purpose and application. Furthermore, how effectively the ecological and green networks function in terms of the diversity of species they intend to support, or in terms of their contribution to human well-being remain unexplored research areas.

This research is one of the few investigations focusing primarily on critically analysing ecological / green networks in an urban context according to their main aims, functions, spatial components and extents based on existing approaches to defining urban ecological networks in planning and ecology, as well as exploring the potential for alternative approaches. Therefore, this study aims to contribute to this growing area of research on network definition and design, by exploring the efficacy of the ecological / green networks in Sheffield in terms of delivering biodiversity and examining how differing land use morphologies within the wider landscape matrix support or detract from their biodiversity function.

1.2 Study Area

This thesis will examine different ways of defining green and ecological networks and their functioning for biodiversity and people. Within the wider scope of this research, Sheffield has been selected as the case study area. The main reason for choosing Sheffield as the study area is the presence of different approaches to ecological / green network definition and design from the perspective of planners (Sheffield City Council- the Green Network) and conservationists (Sheffield and Rotherham Wildlife Trust- the Living Don ecological network), which will allow me to make comparisons between existing approaches. Also, the availability and accessibility of a variety of data sources provide an important opportunity for developing alternative connectivity routes. The further details of the case study area will be provided in Chapter 3.

1.3 Aim and Objectives of the Research

The main aim of this study is ***to examine different ways of defining green and ecological networks and their functionality for biodiversity and people.*** Such an understanding of different planning and scientific approaches is crucial in both a social and ecological sense, if we intend to maximise the effectiveness of those networks being preserved in, or planned into urban areas. The following objectives have been identified to achieve the main aim of this research:

1. to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes,

2. to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data,
3. to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice.

1.4 Thesis Structure

This chapter has outlined the background of this research. It has also identified the main aim and objectives of this research.

Chapter 2 reviews and discusses the relevant literature. While critically reviewing the literature in a wider perspective, this chapter also reveals how this research can fit in and contribute to the existing literature. After discussing the relevant concepts and revealing the gap in knowledge this chapter also sets research questions.

Chapter 3 is composed of two parts in which the first part introduces detailed information on the study area, data sources and data preparation for analyses. Then, in the second part, it introduces the chosen methods used for this research. The methods include literature review, semi-structured interviews and ArcGIS 10.1 spatial and visual analyses to examine the existing green and ecological network approaches, FRAGSTATS 4.1 landscape metrics and ArcGIS 10.1 least-cost corridor approaches. This chapter also explains their pros and cons and the underlying reasons for the selection of each of these individual methods within the scope of this research.

The thesis reflects four phases of analysis, incorporated in Chapters 4, 5, 6 and 7, and each of these chapters has its own research framework, methodology, results, discussion and conclusions. Chapter 4 is dedicated to critically analysing the existing approaches to defining urban green and ecological networks in Sheffield based on semi-structured interviews with key personnel employed by the relevant organisations and an examination of the spatial plans in ArcGIS 10.1, in order to answer objective 1. Prior to the examination of existing approaches, this chapter also includes the analysis of planning policy documents in order to obtain a deeper understanding of the background and evolution of the Green Network policy in Sheffield. The existing approaches to green / ecological networks: Sheffield City Council’s Green Network and Sheffield and Rotherham Wildlife Trust’s Living Don, were critically analysed on the basis of the results of semi-structured interviews, and an examination of the digital plans of the Green Network and the Living Don ecological network. While maps and associated documents were used to compare the spatial extent and relationships of those approaches, information obtained from interviews was used to reveal the underlying rationale and process of development of the existing approaches in Sheffield.

Having examined Sheffield’s current network approaches, Chapters 5 and 6 deal with objective 2 by exploring alternative ways of defining potential connectivity routes both for biodiversity and people.

Chapter 5 is an exploration of how alternative connectivity and accessibility routes for biodiversity and the public could be developed based on the structural / physical continuity of landscape components using ArcGIS 10 and FRAGSTATS 4.1 landscape metrics. This chapter consists of two parts. The first part explores the potential of FRAGSTATS landscape metrics to describe and characterise the main characteristics of urban landscape structure in Sheffield. The second part attempts to develop alternative routes of connectivity for both wildlife and people on the basis of structural connectivity.

Chapter 6 aims to develop further alternative connectivity and accessibility routes for biodiversity and the public based on animal species and human characteristics, as an indication of functional connectivity. The alternative connectivity and accessibility routes were developed and modelled using a least-cost modelling approach in ArcGIS 10.1.

In order to answer objective 3, Chapter 7 compares and contrasts the alternative connectivity routes - structural and functional - with each other and the existing network approaches, and analyses the relationship between their structural properties / morphologies. This chapter determines the differences and similarities between existing green / ecological networks and the alternative connectivity routes devised in this study in term of their spatial extent, functioning and rationale. It provides an understanding of the relationships between ways of defining ecological and green networks and highlights the spatial and functional differences between each network based on their underlying purposes and spatial extents. This chapter uses ArcGIS 10.1 spatial and visual assessments for comparisons. Moreover, this chapter includes a general discussion of findings and draws together the principal findings from this research.

Chapter 8 concludes this thesis by reflections on the aim, objectives and research questions, and provides a brief overview of the overall research findings. This chapter also reports the main limitations of this research, as well as its potential and implications for planning and designing multifunctional connectivity routes in urban landscapes.

Chapter 2 Literature Review

2.1 Introduction

The previous chapter outlined the general framework of my research and set the main aim and objectives. This chapter reviews and discusses the literature on landscape ecology and its applications in landscape planning, with an emphasis on landscape connectivity and different network approaches. This chapter starts with urbanisation as an issue, then moves on to how it leads to fragmentation. Thereafter, it gives an overview of the models that describe how organisms can be affected by living in fragmented environments, since these models are all based on underlying assumptions about connectivity. After presenting the different methods of measuring connectivity, it then goes on to a brief overview of different ways in which networks have been developed in ecology and planning to mitigate the adverse effects of fragmentation by enhancing landscape connectivity. The last part of this chapter introduces the aim and objectives, and sets out the research questions to be answered in this research.

2.2 Related Concepts

2.2.1 Urbanisation

The Earth's ecosystems provide a range of goods and services to humans. The ecosystem services include provisioning services (e.g. food, timber), regulating services (e.g. climate, water quality), cultural services (e.g. recreational benefits) and supporting services (The Millennium Ecosystem Assessment, 2005). However, in human modified landscapes, the spatial arrangement of ecosystems is altered and fragmented into smaller areas. In particular, increasing human population and the need for meeting the requirements of people have caused a rise in the consumption of natural resources and in the transformation of many parts of natural ecosystems into urban areas.

Spatially, urbanisation can be defined as a process where the land is mainly converted into urban areas, in which people live, and which contains modified land cover / use patches (Niemelä, 1999; Niemelä et al., 2009). Accordingly, the term urban implies how an area (land) is used. In urban areas, the built-up areas, such as settlements, industrial and commercial areas and transportation networks, cover a large proportion of the land surface (Pickett et al., 2001). Therefore, in comparison with rural areas, urban areas are generally assumed to be more disturbed and degraded. However, this assumption contrasts with that of Niemelä (1999), who argued that urbanisation may create both favourable and unfavourable conditions for biodiversity. In one sense, the effects of human activities create and support a variation of species composition in relation to the high variety of habitats in urban areas (Niemelä, 1999).

Moreover, as noted by Gilbert (1989), urban areas provide small scale habitat diversity for a range of animals and plants as a result of several distinct land uses, such as parks, gardens, cemeteries, canals, ponds, reservoirs and water mains. Additionally, Gaston et al (2005) emphasised the importance of domestic gardens in Sheffield as important habitats for biodiversity as well as the provision of ecosystem services by showing that domestic gardens in Sheffield contain a large amount of biodiversity. Hence, it is important to note that urban habitats are not necessarily less biodiverse than disturbed and degraded rural areas. Savard et al. (2000) state that the urban ecosystems may provide benefits to species, people, and the other aspects of biodiversity, such as population structure and genetic diversity. For example, rare plant species can be cultivated in urban areas and this may attract species that are dependent on those plants. Therefore, we should take into account those positive aspects of urban areas when managing, maintaining and enhancing urban biodiversity.

Urbanisation affects the functioning of local and global ecosystems (Alberti, 2005) by the increase of impermeable surfaces and accumulation of wastes and toxic substances. Moreover, in parallel with urbanisation, land use change and fragmentation have become critical environmental problems through their influences on human well-being and the existence of animal and plant species according to the quality and quantity of urban areas, spatial scale and geographic regions.

As an important result of the changes in land uses, many valuable habitats and associated species have been lost (Hilty et al., 2006), or some habitats have lost their characteristics as living environments for native species. In addition to this, fragmentation has affected many species and ecological processes adversely, depending on the degree of disturbance to fragments and the quality of the surrounding habitat (Farina, 1998). Thus, the process of fragmentation and the dynamics of land use change should be investigated with care, especially where urbanisation and human activities threaten the natural environment and biodiversity.

2.2.2 Transformation of Landscapes and Fragmentation

Forman (1995) identified the main spatial stages of the land transformation process as perforation, dissection, fragmentation, shrinkage and attrition (Botequilha-Leitão et al., 2006; Collinge, 2009). All of these spatial transformation stages can give rise to reduction in habitat size or the loss of some habitat patches in landscapes (Figure 1, Adapted from Forman 1995; Botequilha-Leitão et al., 2006).

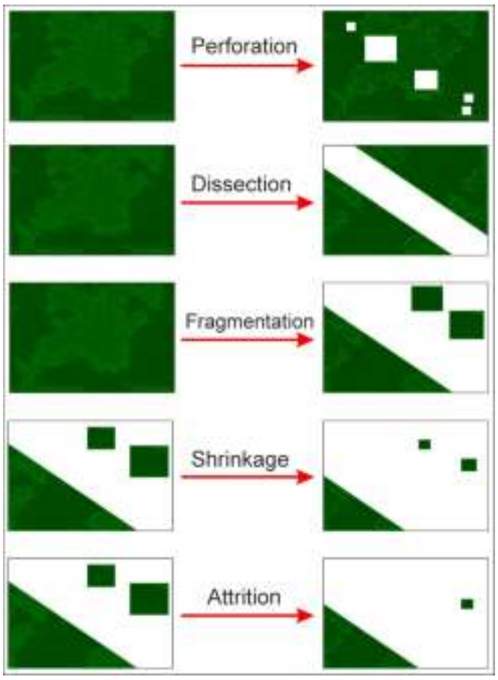


Figure 1: The process of fragmentation

Generally, perforation and dissection are the first stages of the transformation, where habitat patches become subdivided or perforated by linear and nonlinear features, such as roads, railway lines, houses and gardens. However, during these early stages of landscape transformation, habitat loss is the lowest. Furthermore, even though there are holes in the given landscape, the integrity and continuity of habitat patches is not necessarily disturbed. On the other hand, in the course of on-going landscape transformation, habitat patches may split into smaller patches (fragmentation) with a decrease in habitat area and increase in the distance between habitat patches (shrinkage). Finally, as transformation continues, some habitat patches may disappear (attrition).

Botequilha-Leitão et al. (2006) illustrated the dynamic transformation process with an example of a binary landscape that is composed of forest and urban patches, where forest dominates the whole landscape. At the initial stages of urbanisation, while only a few forest patches are transformed into urban area, the landscape matrix is still dominated by forest (Figure 2, Adapted from Winn, 2007).

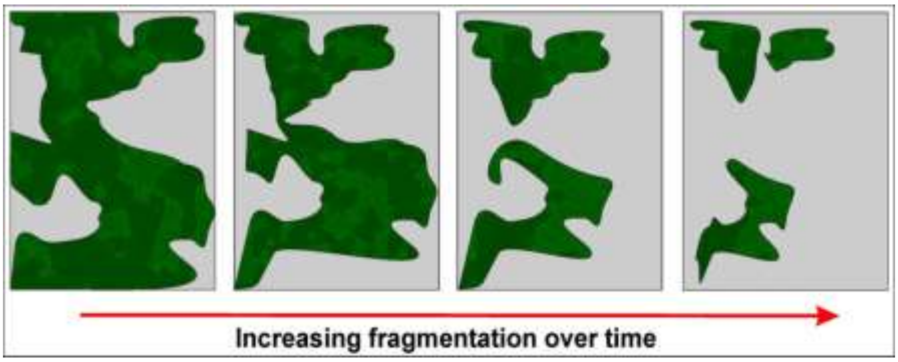


Figure 2: Fragmentation process in a forest

As the conversion of forest patches into urban land continues, we can start to observe separated individual forest patches within the landscape matrix. Inevitably, this stage causes increasing habitat reduction and isolation of forest patches with the dominance of urban patches. Finally, as the transformation process continues, some of the forest patches become lost and urban patches dominate the landscape matrix.

The abovementioned example clearly illustrates the influences of anthropogenic landscape change over time in natural habitats. Within this context, fragmentation is an important driving factor of change in landscape structure and functioning and has therefore received considerable critical attention as an issue of nature conservation and landscape planning.

The term fragmentation reflects a status or process. As a status, fragmentation means the degree of isolation and / or connection of previously connected landscape components at different scales (Franklin et al., 2002; Bennett and Saunders; 2010). As a process, fragmentation refers to a dynamic process of change in the spatial structure and character of a landscape through time, causing a continuous habitat type to split into discrete patches with different sizes, shapes and spatial relationships (Forman, 1995; Fahrig, 2003; Lindenmayer and Fischer, 2006).

Investigating the effects of fragmentation on habitats and species is a continuing concern within landscape ecology. The overall effects of fragmentation are summarised by Bennett (1998, 2003) as the changes in the spatial structure of landscapes and influences on wildlife. In terms of the effects on landscape structure, fragmentation mainly causes changes in habitat patches where the loss and reduction of habitats and increasing isolation can be seen (Bennett 1998, 2003; Hilty et al., 2006).

It is generally accepted that larger habitat patches can support a wide diversity of animal and plant species (Donovan et al., 1995; Fahrig, 2003; Farina, 2006; Debinski and Holt 2000). Therefore, the loss or reduction of habitat patches may also lead to a dramatic reduction in biodiversity, where some species become rare or completely extinct depending on their habitat requirements (Farina, 2006). Additionally, the shape of habitat patches are changed during the process of fragmentation, resulting in changing perimeter-area ratio, patch shape complexity and the creation of edge effects. Here, edge effects refer to the changes in the functioning of ecological processes through habitat boundaries (Pearson, 2002; Hilty et al., 2006). The border areas that are exposed to edge effects are called "ecotones". Farina (2010) defines ecotones as the crossing areas between habitats and the intervening landscape matrix, where the dispersal of animals and plants species as well as the flow of material and energy occur.

As another consequence of fragmentation, some habitat patches may become separated, isolated and surrounded by a hostile matrix. The increasing isolation affects the dispersal of animal and plant species, and the abundance and persistence of species (Bennett 1998, 2003). Therefore, it is essential to understand the changes in landscape structure that emerge from fragmentation. These changes in landscape structure can be identified and measured spatially according to the basic attributes of landscape composition and configuration using landscape metrics, such as the total number of patches, the size of patches, total edge and edge density, perimeter-area ratio and the mean distance and connectedness between patches of the same habitat.

With regard to its effects on wildlife, fragmentation causes the loss of species at local and landscape scale due to the reduction in the size of habitat patches, overall habitat losses and increased isolation between the habitat patches (Bennett, 1999, 2003). However, as mentioned previously, species may respond differently to habitat fragmentation according to their habitat requirements (e.g. home range, availability of sufficient resources) and their sensitivity to disturbances. Bennett (1999, 2003) claims that it is generally hard to associate the loss of species with the overall decrease in the amount of habitat, since there are other human-induced drivers, which may contribute such as hunting, using pesticides and introducing non-native species.

The relationship between the loss of species and the reductions in the size of habitats with increasing isolation is well documented for birds (Johnson, 2001; Courtney et al., 2004; Graf et al., 2007), mammals (Diffendorfer et al., 1995; Bayne and Hobson, 1998), reptiles and amphibians (Vallan, 2000; Cushman, 2006; Nowakowski, 2014) and invertebrates (Zschokke et al., 2000; Braschler, 2005). Here, particularly the removal of natural vegetation in habitat patches results in the loss of species (McKinney, 2002). Finally, Bennett (1998, 2003) claims that habitat specialists and large-bodied species which require larger habitat areas, species found at high levels of the food chain and species with particular food and habitat requirements are generally more sensitive to the adverse effects of landscape fragmentation.

2.2.3 Connectedness and Connectivity

In addition to its effects on habitats and wildlife, increased fragmentation also results in the loss of landscape connectivity (Lindenmayer and Fisher, 2006), which may prevent the dispersal of species and accordingly, induce isolated populations and increase the risk of species extinction (With, 2002). Within this context, the maintenance of landscape connectivity has been recognised as a worldwide concern for nature and biodiversity conservation (Noss, 1991). Landscape connectivity is a fundamental property of landscapes and has been defined as “the degree to which a landscape facilitates or impedes movement of organisms among habitat patches” (Merriam, 1984; Taylor et al., 1993; Tischendorf and Fahrig, 2000). From this viewpoint, connectivity has been evaluated as "a measure of the ability of organisms to move among suitable habitat patches" (With et al., 1997; Hilty et al., 2006).

Stemming from the interactions between the structure and functioning of landscapes, connectivity has been regarded as a key feature of a landscape (Taylor et al., 2006). The concept of connectivity encompasses the structural and functional aspects of a landscape. In the literature, the term structural connectivity tends to be used to refer to the connectedness of the landscape, or, in other words, the degree to which habitat patches are physically / structurally linked to each other (Bennett 1998, 2003; Watts et al., 2008). Functional connectivity, on the other hand, as a measure of species' ability to move between habitat patches, requires functionally connected habitat patches within the landscape depending on the behavioural responses of organisms to the landscape structure (Baudry and Merriam, 1988; Burel and Baudry, 2003). Whereas the measures of structural connectivity are based only on the spatial characteristics of a given landscape without taking into consideration the movement ability of different species, functional connectivity measures are both dependent on the ecological requirements of organisms and landscape structure (Bennett 1998, 2003; Collinge, 2009). Therefore, the same landscape can be evaluated as functionally connected for one species but not for another, based on the spatial composition and configuration of a landscape and the behavioural responses of these species to this landscape (Burel and Baudry, 2003; Taylor et al., 2006; Watts et al., 2008). For example, highly mobile species, such as birds, do not necessarily require spatial links between habitat patches, whereas other species may require permeable landscape matrix structures as functional connections between habitat patches (Bennett 1998, 2003).

As noted by Crooks and Sanjayan (2006), metapopulations ecology and landscape ecology have contributed significantly to our understanding of connectivity. However, the key difference between these approaches in understanding connectivity lies in their spatial scales. Whilst metapopulations ecology regards connectivity as a property of habitat patches, landscape ecology mainly considers connectivity as a feature of the whole landscape (Moilanen and Hanski, 2006).

2.3 Theoretical and Scientific Foundation

2.3.1 Landscape Ecology

Carl Troll (1939), thought to be the first to use the term ‘landscape ecology’, integrated the concepts and approaches of geography (spatial) and ecology (functional) into an interdisciplinary research field (Naveh and Lieberman, 1984; Turner et al., 2001; Turner, 2005). Since then, many definitions have been proposed, in which the most widely used is "the study of structure, function and change in a heterogeneous land area composed of interacting ecosystems" (Forman and Godron, 1986). This definition emphasises three main characteristics of landscapes i.e. structure, function and change. Besides examining the structure and functions of changing landscapes, landscape ecology also helps researchers to understand the origin of changes and the interactions between structure, function and change (Golley and Bellot, 1991). Therefore, the science of landscape ecology and its theoretical foundations provide crucial insights into landscape planning processes.

2.3.2 Landscape Structure, Function and Change

Whilst a variety of definitions of the term ‘landscape’ have been suggested, the appropriateness of each may depend on the scale and context of research being undertaken (Farina, 2000). A generally accepted definition of a landscape is “a heterogeneous area composed of a cluster of interacting ecosystems that are repeated in various sizes, shapes, and spatial relationships throughout the landscape” (Forman and Godron, 1981; 1986). Another description of landscape refers to “an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors” (Council of Europe, 2000). Although landscape has been defined in different ways, all definitions of landscape involve an area of land composed of a mosaic of different components. Considering all this, it is clear that the key point in defining a landscape is the representation of spatial heterogeneity at any scale rather than the size of the landscape. From this viewpoint, the size of a landscape relates to the perception of people, particular organisms or the functioning of the ecological process under consideration (Ahern, 2003).

Here, landscape structure or pattern refers to the mosaic of different geographical / ecological units determined by their composition and configuration (Turner and Gardner, 1991). Landscape composition reflects the occurrence and amount of different patch types without explicit use of any information on the location of these landscape components. On the other hand, landscape configuration corresponds to the spatial distribution and arrangement of those units (McGarigal and Marks, 1995; Selman, 2006).

Composition and configuration together are used to define landscape heterogeneity, and such heterogeneity can be both in space and time (Farina, 2010). Whilst spatial heterogeneity describes the overall complexity and variation in a landscape (Wiens et al., 1995), temporal heterogeneity relates to the changes in the same landscape during a certain time of period (Farina, 2010). As different spatial arrangements of landscape components may create and provide sufficient conditions for the survival and maintenance of a range of species, populations and communities, landscape heterogeneity is generally regarded as a favourable attribute for biodiversity (Selman, 2006; Farina, 2010).

As mentioned above, spatial landscape heterogeneity is a result of landscape structure and the scale at which a given landscape is defined. According to Turner et al. (2001), in landscape ecology, scale refers to “the spatial or temporal dimension of an object or process" and can be defined by grain and extent. Here, grain is the finest spatial resolution of the landscape data and extent is the total area included within the landscape boundary. In practical terms, the importance of scale in landscape ecological studies can be explained as follows. Firstly, a landscape at a certain scale may not be heterogeneous at other scales and, more specifically, a landscape component at a particular scale may be transformed into a different structural component or can completely disappear at other scales (Gosz, 1991; Wiens et al., 1995; Ramalho and Hobbs, 2012). In addition to this, every organism may perceive and utilise the same landscape differently at different scales (Turner et al., 1989; With, 1994; Turner, 2005). This implies that scale must be determined on the basis of the organisms and processes referred to in specific research questions.

2.3.3 Theoretical Models and Principles in Landscape Ecology

Landscape ecology integrates a number of theories and models from different study areas, developed to understand landscape structure and its relationship to landscape function. One of the key elements of landscape ecology is the idea of connectivity. The following models describe how organisms can be affected by living in fragmented environments based on underlying assumptions about connectivity.

Island biogeography was originally developed to describe the relationships between the number of species found on an oceanic island and mainland as a function of the area of islands and the distance of islands to the mainland (MacArthur and Wilson, 1963; Preston, 1962). Later, this theory was applied to terrestrial habitats to understand the relationships between species, related landscape patterns and ecological processes in fragmented landscapes. Island biogeography theory relates species richness on islands to island size and distance from the mainland (resources of species), as a result of the processes of species colonisation and extinction (MacArthur and Wilson, 1967).

According to this theory, the richness of species on an island at a given time is determined by the immigration of species and the extinction of populations based on the area of habitat patches and the distances of this island to the mainland (MacArthur and Wilson, 1967). In this regard, island biogeography theory suggest that the distance between habitat patches, in other words isolation, is the main constraint for the dispersal of species, since dispersal / immigration to the closer habitat patches will be easier and the likelihood of colonisation will be higher in these patches compared to the far away ones. Additionally, this theory predicts that large habitat patches will support more species and diversity of species with higher colonisation and lower extinction rates (Burel and Baudry, 2003; Hilty et al., 2006).

The importance of the island biogeography theory is undeniable, as it was one of the first approaches to describe the relationship between landscape structure and ecological processes. However, in practice, terrestrial habitats do not always contrast sharply with the surrounding landscape matrix. Moreover, the edges of habitat patches and the landscape matrix may provide a gradient of desirable to undesirable habitats to the individuals of different patches, depending on the scale at which species perceive the landscape (Wiens, 1996).

The application of the predictions of this theory to the fragmented habitats for the design of protected areas has raised the question of whether one **S**ingle **L**arge **O**r **S**everal **S**mall habitat patches (nature reserves) would be more favourable for the maintenance of long-term species persistence. This debate denoted by the acronym SLOSS. While some of the early research have concluded that the protection of single large nature reserves is a better strategy (Simberloff and Abele, 1976; Quinn and Harrison, 1988; Honnay et al., 1999); others have claimed that several small nature reserves are better for the design of protected areas (Diamond, 1975; Diamond and May, 1976; Patterson, 1987). However, as noted by many researchers, there is no single answer to the SLOSS debate, since each species perceive, and respond differently to the landscape and landscape structure (Soule´ and Simberloff, 1986; Saunders et al., 1991; Hilty et al., 2006; Laurance, 2010).

Metapopulation theory was originally introduced by Levins (1969) who defined a metapopulation as “a population of populations” or “a system of local populations connected by the movements of individuals (dispersal) among the population units” (Hilty et al., 2006). The metapopulation theory regards the rates of colonisation and extinction as the primary mechanisms to explain population persistence in a landscape. In other words, metapopulation theory explains the relationships between landscape structure and the survival of fragmented populations (sub-populations of populations) based on colonisation rate, movement between habitat patches (dispersal) and local extinction rate. According to Levins (1969), each habitat patch has the same quality as a source for species with the same probability of colonisation / local extinction and successful dispersal. Thus, the survival of a metapopulation depends on the colonisation rate of patches exceeding the extinction rate.

Following the classic metapopulations model, different conceptual models have been developed. Proposed by Boorman and Levitt in 1973, the *Mainland-Island Metapopulation* model includes a large central habitat patch (mainland) and several small habitat patches (islands). This model is based on the presence of a population on a large mainland, which is capable of supporting and sustaining its own population as well as sub-populations in the surrounding island patches. A closely related idea is that of the *Source-Sink* model (Pulliam, 1988). This takes into account the quality of habitat patches. Some patches (sources) are composed of habitats that are abundant in resources to support positive population growth rates in themselves, while others (sinks) have insufficient resources to support positive growth rate themselves, but have populations that are maintained by the immigration of individuals from source patches. Therefore, if the source habitat patches are not protected and well maintained, then the sink habitat patches would go extinct. The difference between mainland-island and source-sink metapopulation models is that the former regards the size of habitat patches as the key factor in determining the source habitats, whereas the latter considers the quality of habitats as the key factor.

Another model, *Patchy Populations* (Harrison, 1991) refers to populations that occur across multiple patches, but in which there is high connectedness so individuals can utilise multiple patches in their lifetimes. In this sense, they are not a true metapopulation. Finally, the *Non-equilibrium Metapopulation* (Harrison, 1991) model refers to the situation where there is very low dispersal and colonisation rate does not exceed extinction rate. In this situation the metapopulation is in decline (more patches go extinct than get recolonized) rather than in equilibrium. This kind of metapopulation is generally seen in areas where the effects of human-induced fragmentation are dominant.

The patch-corridor-matrix model was proposed by Forman and Godron (1981, 1986) as another landscape structural model, where they defined spatial landscape components as part of the whole landscape mosaic. Therefore, their model puts an emphasis on the heterogeneity of a landscape that is composed of a mosaic of discrete spatial components. They defined the matrix as the dominant and connected component of a landscape mosaic that surrounds patches and corridors and plays a crucial role in the functioning of a landscape (Forman, 1995; McGarigal and Marks, 1995; Farina, 2010). As Winn (2007) states, the landscape matrix can be obvious if the other components of the landscape are clearly distinguished. According to this model, while patches constitute the basic spatial components of a landscape, they differ from their surroundings in terms of their physical characteristics i.e. size, shape, vegetation cover or actual use. In other words, patches represent homogeneous areas at different spatial and temporal scales relative to the perception of species or ecological processes under consideration. Because of this, patches in a landscape should be defined by considering the subject of the investigation (McGarigal and Marks, 1995). Corridors, on the other hand, are linear landscape components with characteristics that are distinct from their surroundings. Corridors enable the movement of species between habitat patches (Forman and Godron, 1986; Hilty et al., 2006). According to McGarigal and Marks (1995), researchers have defined and used the term corridors, based on their structural and functional properties. They classified corridors as lines or strips (based on their widths); and stream corridors. In terms of their functionality in a landscape, corridors are classified according to their potential to:

- provide habitats and to enable the movement of species between habitat patches (habitat corridors, facilitated movement corridors),
- disable the movement of species and/or the flow of material / energy (barrier or filter corridors, and
- affect the matrix by changing the flow of material / energy and the movement of species into the surrounding patches (source of abiotic and biotic effects on the surrounding matrix).

To summarise, all of these models stem from the same family, but they just emphasise different elements of the structure of the landscape. Both the theory of island biogeography and metapopulation have provided the basis of theoretical research in order to understand the relationships between species / population dynamics and the structure of fragmented landscapes by putting an emphasis on the colonisation and extinction rates as a result of immigration between discrete habitat patches. However, apart from the source-sink metapopulations model, these models, at least in their original formulations, do not take into account variations in the quality of habitat patches and the properties of the surrounding landscape matrix. Likewise, in its original formulation, the patch-corridor-matrix concept was rather akin to the island type models described earlier, in the sense that the “matrix” was regarded as “non-habitat” (Forman and Godron, 1986; Lindenmayer and Burgman, 2005; Zetterberg, 2011). On the other hand, metapopulation models have become more sophisticated than their initial implementations by incorporating elements such as variation in habitat quality, spatially explicit dispersal, and internal population dynamics within patches, into the models (Theodorou et al., 2009; Taylor and Hall, 2012; Gebauer et al., 2013).

Despite this, in reality we cannot ignore the influences of the surrounding landscape matrix and the quality of patches on the movement of species as well as the rates of colonisation / extinction (Dobson et al., 1999; Lindenmayer and Franklin, 2002; Jules and Shahani, 2003; Franklin and Lindenmayer, 2009). Also, in terms of the conservation of diversity of species and wildlife, we should consider the crucial role of stepping stones (Opdam, 1991; Fischer and Lindenmayer, 2002; Bennett and Mulongoy 2006). The presence of stepping stones between the habitat patches and the surrounding landscape matrix may reduce the effects of isolation and support the persistence of species and populations. This is particularly important due to the fact that different landscape matrices may provide varying conditions for different species and the functioning of landscape processes such as the availability of resources, and the migration, dispersal and movement of animal and plant species as well as material and energy flow (Forman, 1995; Gustafson and Gardner, 1996; Ricketts, 2001; Vandermeer and Carvajal, 2001). In this context, the properties of the landscape matrix should not be ignored when examining and modelling the relationships between landscape structure and the responses of species (McGarigal, 2002; Taylor et al., 2006).

2.4 Methodological Approaches for Assessing Connectivity

Supporting and enhancing connectivity between habitat patches is an important issue for biodiversity conservation in landscape planning. Prior to the processes of planning and implementation of a connectivity conservation strategy, it is crucial to measure and assess the present state of connectivity. Since connectivity is defined both structurally and functionally, the measures of connectivity can be broadly classified as structural and functional connectivity measures.

2.4.1 Structural Connectivity Measures

Structural connectivity measures focus on the spatial composition and configuration of landscapes and do not incorporate any data on the ecology of species. The most common structural connectivity measures are landscape metrics (indices), which can be calculated by various standalone software and extensions of the Geographical Information System (GIS) and Remote Sensing (RS) software.

The main data required for connectivity analysis should be spatially explicit, raster or vector formatted categorical habitat data (or land cover / land use). Landscape metrics can be calculated for all habitat patches for a given type of habitat (class) or for the entire landscape. The main landscape metrics that are used as indicators of structural connectivity are: the number of patches, habitat area, core habitat area (depending on the species of research interest), habitat perimeter (edge), habitat perimeter-area ratio, shape index (the complexity of habitat patches), Euclidean nearest neighbour distance and Proximity index. Here, the number of patches, habitat/core habitat area, habitat perimeter (edge), and habitat perimeter-area ratio indicate the proportional abundance of each habitat type in the landscape as well as giving information on the subdivision of landscape.

Euclidean nearest neighbour distance simply indicates the smallest distance between habitat patches as an indication of isolation and, in turn, connectivity of individual habitat patches. While closer distances reflect strong connectivity, habitat patches further from each other reflect higher isolation. In addition to this, the proximity index indicates both the degree of isolation and fragmentation as a type of buffer metric. It takes into account all habitat patches in a search radius of the focal habitat patch, which should be determined based on the movement abilities of the species of research interest. For this metric, we can take into account all habitat patches within the landscape or only habitat patches occupied by the species of research interest. Here, it is important to note that the Euclidean nearest neighbour distance and the proximity index are able to reflect the potential functional connectivity of a landscape from the perspective of species, if they incorporate some aspects of their habitat requirement (e.g. dispersal distance).

In general, structural connectivity measures do not require very extensive input datasets for their calculation. In most cases, the essential raster or vector dataset can be derived from remote sensing images or are readily available as land cover and land use datasets. The most important features of structural connectivity measures are:

- it is easy to calculate selected landscape metrics for extensive areas,
- they can be calculated at different scales and estimates for structural connectivity can be obtained, and
- the other structural properties of landscapes can be measured and analysed depending on which aspects we are looking for (Botequilha-Leitão et al., 2006; Wiens, 2006).

On the other hand, a number of studies have examined the effects of spatial resolution and the extent of research area (Wiens, 2006), suggesting that the result and interpretation of landscape metrics are highly dependent on the size and spatial resolution of the landscape under investigation. Further to that, several studies have reported that the landscape metrics that incorporate the area of habitat patches into the calculations at the class level give better measures of connectivity, as the contribution of large habitat patches to landscape connectivity is considered to be greater than that of small ones (Bender et al., 2003). Within this framework, FRAGSTATS is capable of computing area-weighted versions of landscape metrics as well as other distribution statistics, such as mean, standard deviation and coefficient of variation. Finally, it is important to note that the properties of the landscape matrix are an important factor for the movement of species, as well as the availability and quality of habitat patches and, as one of the crucial properties of a landscape, it should be assessed at the landscape level (Taylor et al., 2006). However, structural connectivity measures put an emphasis on discrete habitat patches, ignoring the characteristics of the landscape matrix and the responses of species to landscape structure.

2.4.2 Functional Connectivity Measures

In order to reflect the responses of species to landscape structure, the measures of functional connectivity require information on the movement of the species through the landscape. Taylor et al. (2006) identified the information on the movement responses of species used in the assessment of functional connectivity as:

- species' ability to move through the landscape matrix,
- interactions between habitat and non-habitat patches,
- mean dispersal distances, and

- the mortality rates during dispersal.

However, it is generally quite hard to obtain the above mentioned information. Fagan and Calabrese (2006) suggest that there are two broad categories of functional connectivity measures: the potential functional connectivity measures, and the actual functional connectivity measures.

In terms of the potential functional connectivity measures, they mention landscape metrics which involve some aspects of species' movement abilities as well as the relationships between different habitat types (landscape structure). On the other hand, actual functional connectivity measures require empirical data on the movement responses of species to landscape structure and provide an actual estimate of connectivity for the species of research interest (Fagan and Calabrese, 2006). From this point of view, it is clear that potential functional connectivity measures do not require extensive datasets on species and can be applied to large scale landscapes compared to actual functional connectivity measures.

The first set of potential functional connectivity measures are simple Euclidean nearest neighbour distance and buffer radius landscape metrics which incorporate the information on species movement and habitat patch occupancy (Briers, undated). For example, some of the metapopulation ecology studies have measured potential functional connectivity on the basis of spatially explicit habitat patch occupancy and the nearest neighbour distance between the occupied habitat patches (Fagan and Calabrese, 2006). The basic data required for this approach are field surveys, including the habitat patches occupied by the species of research interest and the distances between these habitat patches. Similar to the Euclidean nearest neighbour distance metric, the inter-patch distances of focal habitat patches are assumed to be a measure of isolation and habitat connectivity (Fagan and Calabrese, 2006).

Another potential functional connectivity measure is the Incidence Function Model (IFM), which was developed on the basis of Graph Theory (Moilanen and Hanski, 2001; Moilanen and Nieminen, 2002). The main datasets required are dispersal distance of species and spatially explicit data on occupied and empty habitat patches in the landscape by the species of research interest (Moilenan and Hanski, 2006). Here, with the use of GIS, habitat patches are represented with nodes / vertices, and connections between those habitat patches are represented with edges / links from the perspective of graph theory.

In general terms, the basic IFM measure assesses the contribution of occupied habitat patches to potential functional connectivity by weighting them with the area of habitat patches and the distance between them (Fagan and Calabrese, 2006). Within this model, patch area and the distance between the habitat patches are taken into account as the functions of the population size and the dispersal distance for the species of research interest. However, this basic model ignores the influence of the landscape matrix on connectivity by assuming the matrix as a uniform landscape component and measures connectivity at the level of individual habitat patches. On the other hand, some IFM models are extended to include the quality of the matrix, e.g. by means of the ease of species' movement through the landscape or the effects of habitat edges on the movement of species (Fagan and Calabrese, 2006). Therefore, the extended version of IFM measures is assumed to reflect more accurate estimates for connectivity at a landscape scale (Watts et al., 2008).

Moreover, some approaches incorporate the individual species movement data in order to obtain more accurate estimates of actual functional connectivity. The required data on the movement patterns of species can be obtained through various methodologies, such as the observation of movement pathways and mark-recapture methods (Fagan and Calabrese, 2006). Even though direct observations of the pathways of organisms may provide the actual movement behaviours of species, this method is restricted to a small portion of a landscape and requires a long term study for its observations. Furthermore, different species may utilise discrete habitat types in a landscape for different purposes in their life histories (Taylor et al., 2006). Therefore, when examining the actual dispersal paths of species, the relationship between their movements and landscape structure should be investigated with care (Gustafson and Gardner, 1996).

On the other hand, the mark-release-recapture method is one of the other most widely used approaches for estimating population size and assessing the dispersal success of focal species through a landscape (Moilanen and Hanski, 2006). With this approach, typically the captured focal species are marked with a unique identifier in the research area and then released to the same habitat. After a lapse of time, the same habitat is revisited and the number of marked and unmarked animals counted by capturing them again. This process can be repeated more than twice if necessary. As a result, from the records history of each visit and capture, one can obtain the estimates of the population size and dispersal movements.

Finally, least-cost modelling was developed on the basis of graph theory, which adopts Dijkstra's Algorithm (Dijkstra, 1959) and computes the least costly paths between edges and nodes. ESRI's ArcGIS 10.1 Spatial Analyst extension provides a set of tools to compute least-cost paths or corridors under the Distance Toolset. Least-cost modelling is also known as cost-distance modelling. Here, the cost (permeability or friction) corresponds to the ease / difficulty of moving through the landscape. The higher cost values indicate the difficulty in moving through the landscape, and lower cost values represent the ease of movement. The cost distance determines the shortest weighted distance from each point / patch to the nearest point / patch under consideration (1995-2012 ESRI Help, for version 10.1). Therefore, apart from finding out the shortest Euclidean distance, the least-cost algorithm also measures the effective distance between the patches of interest. In other words, the cost distance tools in ArcGIS 10.1 modify the Euclidean distance by calculating the distance in cost units, instead of actual geographic units.

The least-cost modelling approach is developed on the notion that the landscape patches in question are surrounded by a mosaic of different land cover / use types, which range from the most hospitable land cover / use patches to the most hostile ones for movement (Ricketts, 2001). The main inputs required for a least-cost analysis consists of a source layer (vector or raster formatted) and a cost / permeability layer (raster formatted). Therefore, in the first place, a source and a cost dataset must be generated. Here, a source layer indicates the origin of movement from which the functional connectivity is calculated. On the other hand, the cost layer identifies the capacity of the intervening land cover / use types to impede or enable movement (1995-2012 ESRI Help, for version 10). The determination of cost values is an essential part of the least-cost modelling approach. In this regard, one of the most common ways to determine cost values is the use of habitat suitability models for one or a group of focal species (Rouget et al., 2006; Wang et al., 2008). In addition, eliciting expert opinion is another way of determining cost values to movement through the landscape, if there is no sufficient data on the species occurrence (Brouwers et al., 2009; Watts et al., 2010; Eycott et al., 2011).

To summarise, the measures of connectivity vary in terms of their data requirements and outputs and, accordingly, they have both strengths and weaknesses. In this context, we can claim that structural connectivity is relatively easier to be measured and mapped, besides its applicability for larger areas compared to functional connectivity. On the other hand, the measures of potential and actual functional connectivity have the capability of estimating the movement of species through landscape. However, the need for direct observation and measurements and the labour-intensive nature of these methods make them applicable to a small scale area only. Therefore, even if it seems possible to measure actual functional connectivity at a landscape scale, the extensive requirements for labour and data constrains the spatial scale at which actual connectivity can be measured.

2.5 Landscape Planning

2.5.1 Landscape Planning and Landscape Ecology

Weddle (1979) defines the landscape planning process as the activity of examining landscape resources, determining and estimating landscape resources to meet the current and future demands which would cause changes in landscapes and then trying to find out solutions for conflicts caused by changes in landscapes. A more up-to-date definition of landscape planning "is the development and application of strategies, policies and plans to create successful environments, in both urban and rural settings, for the benefit of current and future generations" (Landscape Institute, 2012). In this context, landscape planning refers to the formal processes of decision making, technical and spatial planning activities to enhance, restore and / or create landscapes based on the assessment of physical, natural and cultural resources (Council of Europe, 2000; Ahern, 2003; Selman, 2006). Under the influence of urbanisation and changes in land uses, the structure of landscape has been changed. Therefore, an increasing interest in multi-disciplinary and more integrated approaches has become a part of nature conservation and landscape planning (Jongman and Pungetti, 2004).

As mentioned earlier, a major goal of landscape ecology is to understand the relationship between the spatial/temporal structure of landscapes and associated ecological processes. In this context, whilst the landscape planning process incorporates the scientific and technical knowledge to provide the most appropriate options for decision making, landscape ecological concepts and principles have given new opportunities for the basic planning approaches. With regard to this, Weddle (1979) and Boothby (2000) emphasised the substantial contribution of ecology to short and long term planning activities.

While landscape ecology focuses on the functioning of resources, planning activities try to establish the appropriate use of resources (Botequilha-Leitão and Ahern, 2002). In other words, planning attempts to regulate and control the human activities that cause changes in the functioning and structure of resources (Boothby, 2000). By extension, the achievement of short and long term landscape planning activities depends on its capability to deal with the landscape change processes and their driving forces (Boothby, 2000).

The purpose of landscape planning may change case by case, based on the environmental, economic, cultural and social factors in an area. However, Boothby (2000) claims that landscape planning should take into account the following principles to develop a rationalist approach to nature conservation and human requirements. Firstly, landscape planning should take into account the ecological requirements of different species as an essential component of the landscape planning process. Related to this, the scale of planning activity should also be considered carefully, as different species and biological/physical processes operate at different scales. Secondly, the maintenance of ecological processes and their integrity together with the anthropogenic and natural disturbances should also be taken into account. Finally, Boothby (2000) points to the importance of social principles, strict policies and a clear methodology for a landscape planning approach.

2.5.2 Landscape Planning Process

In the general sense, a landscape planning process goes through a set of steps, which are adapted from a conventional planning process. Even though, different studies may define different steps for a planning process, it generally includes: the definition of problems and opportunities, setting the planning aim and objectives, compiling information on the study area, analysis of information, determination of alternative planning scenarios and their evaluation, implementation and monitoring the results.

According to Martinez-Falero and Gonzalez-Alonso (1995) a generic landscape planning process is composed of five main stages, starting with the definition of objectives. At this stage, the most important things to consider are the main aim of the planning activity, determination of techniques for data collection and the methods for processing data sources. The process continues with the selection of important variables from different physical, biological, human and landscape related variables, then, following the information collection, with an inventory and mapping stage. Finally, the planning process ends with the completion of data processing and obtaining the classification of the planning area. On the other hand, Steiner (2008) categorised these stages under eleven steps starting from the identification of problems and opportunities through to the monitoring and evaluation stages of the implemented plans (Figure 3, Adapted from Steiner, 2008).

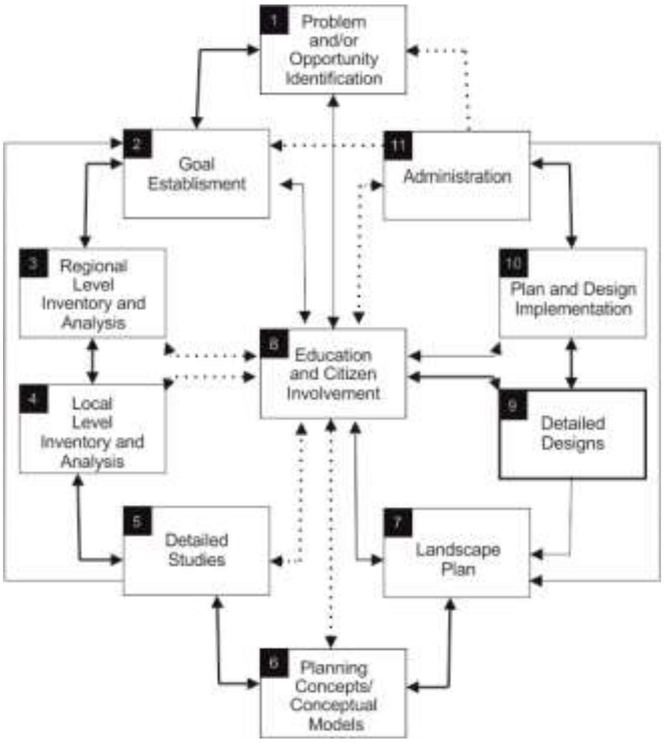


Figure 3: The Landscape planning process

According to Steiner (2008), a landscape planning process starts with the identification of problems and opportunities in a landscape. At this stage the inter-relationship between nature and people should be determined by examining every aspect of the issues and favourable conditions in the landscape. Here, Steiner (2008) particularly highlights issues arising from land-use conflicts. This stage helps researchers or planners to formulate the issues, such as lack of connectivity or the need to protect natural areas.

Then, the goals of planning should be established to address the identified issues or opportunities. Martinez-Falero and Gonzalez-Alonso (1995) claim that, once the aims of a landscape planning activity are determined, planners and researchers can decide on the necessary information sources for the planning. This stage is followed by the analysis of the landscape at regional and local levels using surveys, desktop study, fieldwork and data mapping.

The analysis of the landscape (Figure 3, steps 3 and 4) aims at collecting and evaluating appropriate information on the physical, biological, and social aspects of the given landscape at different levels (Martinez-Falero and Gonzalez-Alonso, 1995; Steiner, 2008). While the regional landscape analysis provides the general information on the landscape, local landscape analysis gives an insight into the specific characteristics of the landscape at a finer scale. Steiner (2008) emphasises the importance of time and cost management for the landscape analysis stage, since they can be restricting factors for many landscape planning processes.

At this stage, all information is blended together. One of the most popular techniques to link all information is called the "overlay technique", proposed by Ian McHarg in 1969 (Malczewski, 2004; Steiner, 2008). This technique puts the layers of inventory information one on top of another, looks at the suitability of different areas to address the goals of planning and tries to identify opportunity areas (Steiner, 2008). An overlay technique can be applied using GIS software, coupled with tools for combining information across layers, such as least-cost modelling (Singleton et al., 2002; Sutcliffe et al., 2003; Nikolakaki, 2004; Lafortezza et al., 2008; LaRue and Nielsen, 2008; Gurrutxaga et al., 2010) or multi-criteria analysis (Jun, 2000; Chakhar and Martel, 2003; Feick and Hall 2004).

The next stage is the development of different planning scenarios. At this stage, alternative planning models are prepared in accordance with the characteristics of the planning area (Martinez-Falero and Gonzalez-Alonso, 1995). Therefore, different planning scenarios are generally represented as different conceptual models according to their capability to tackle the key issues in the planning area. With these conceptual models, planners/researchers can represent the allocation of different land uses or actions and the preferred options can then be brought together and a landscape plan prepared. As pointed out by Steiner (2008), the final landscape plan should include written statements about related policies and strategies accompanying the map. Then, the planners / researchers should ensure public involvement in the development of the landscape plan. This is particularly important to ensure the success of the plan.

After that, Steiner (2008) suggests that each element in the final landscape plan should be designed in a more detailed way. The visualisation of each element in the landscape map can help decision makers to see and represent the consequences of their planning approach in a more comprehensive way. After the implementation of the plan and design on the ground, the final stage of a planning process is the monitoring and evaluation of the landscape plan. This final stage has an important role for the achievement of landscape plans by enabling planners to review the management and decision-making processes.

2.5.3 Landscape Planning in the UK

The landscape planning practices in the UK planning system has evolved from a sectoral to a more comprehensive and integrative approach. Selman (2010) indicates that the scope of early landscape planning practices was limited by the protection of natural beauty and amenity. Accordingly, the early legislations on landscape planning were centred on the concept of natural beauty and amenity (Beer, 1993; Selman and Swanwick, 2010). Additionally, Selman (2010) claims that during this period the landscape planning practice was formed from “a rural tradition which became bureaucratically codified into the selective designation of acclaimed areas of countryside; and an urban tradition of providing and safeguarding civic and neighbourhood amenity”. In this regard, the National Parks and Access to the Countryside Act 1949 and the Town and Country Planning Act 1947 have been regarded as the key pieces of legislation on the designation, protection and management of rural and urban landscapes.

Afterwards, the emergence of the modern environmental movement led to the Environmental Assessment Regulations of 1988 in the UK, in which there was a clear reference to landscape for the first time in UK legislation (Selman, 2010). Moreover, the emerging consensus that all landscape has character resulted in more comprehensive and integrative landscape mapping and evaluation methods, such as the Landscape Character Assessment (Swanwick, 2004; Selman 2006; Selman, 2010).

Selman (2010) suggests that the modern landscape planning in the UK has been started with the National Parks and Access to the Countryside Act 1949. Thereafter, the creation of new national parks has been strengthened through the Areas of Outstanding Natural Beauty (AONB) as a complementary approach to landscape protection. Accordingly, the creation of Boards and the requirement of producing management plans (under the Countryside and Rights of Way Act, 2000) have been regarded as important developments for protecting and managing landscapes (Selman, 2006; Selman 2010).

In the 21st century, the landscape planning practices have started to evolve into a more intellectual practice, in which the landscape sustainability and multifunctionality have been regarded as the key concepts for modern landscape planning practices (Selman, 2010). In this regard, The National Planning Policy Framework (NPPF), the latest planning guidance at a national level, puts a particular emphasis on sustainable development as the main aim of planning (DCLG, 2012). Moreover, the concept of green infrastructure is now recognised as a key approach to deliver multiple functions in landscapes, and reconnecting the natural systems and people (Natural England, 2007 and 2009; Landscape Institute, 2009; CIWEM, 2010; Selman, 2010).

2.5.4 Landscape Planning and Geographic Information Systems (GIS)

The development and application of Geographic Information Systems (GIS) offer an opportunity to link and analyse different data sources in a comprehensive way. In broad terms, GIS is defined as a computer-based tool used for capturing, storing, recalling, analysing and displaying spatial and non-spatial data (Burrough and McDonnell, 1998; Skidmore, 2002).

The development of GIS has given us the opportunity for analysing and managing landscapes through the integration of different datasets, spatial and non-spatial queries, and interpretation and visualisation of these datasets. Therefore, in landscape planning literature there has been a growing use of GIS, and GIS based modelling approaches, to analyse, evaluate and make decisions as an integral part of planning processes and landscape ecological studies (Risser et al., 1984; Burrough, 1986; Han and Kim 1989; Ottens, 1990; Selman, 2006).

The initial idea of GIS emerged from the application of overlay analysis which was proposed by Ian McHarg in 1969 (Brimicombe, 2003). Within his work, he put special emphasis on the ecology and conservation of natural resources as well as the other physical and social aspects of the landscape. Here it is important to note that even though the history of manual overlay analysis methodology dates back earlier, Ian McHarg was the first person to provide a methodological framework in which multiple landscape elements were taken into account (Steinitz et al., 1976 in Brimicombe, 2003).

Overall, GIS technology has been widely used in landscape planning, since it offers opportunities to researchers and landscape planners:

- to conduct suitability analyses for different land use alternatives or planning activities (Malczewski, 2004; Phua and Minowa, 2005),
- to model physical land use / land cover changes and developing alternatives under different conditions (Nagendra et al., 2004; Herold et al., 2005; Wickham et al., 2010),
- to predict the effects of urban development or urban growth on natural resources and biodiversity (Ernoult et al., 2003; Maitima et al., 2004; Theobald, 2005),
- to analyse and model connectivity (Singleton et al., 2002; Marulli and Mallarach, 2005; Watts et al., 2010).

2.6 Landscape Ecology Practices in Planning Associated with Connectivity

The concept of connectivity, as one of the basic notions of landscape ecology, plays a key role in landscape planning. Connectivity is a key characteristic of a landscape, which defines the mobility of organisms among patches (Taylor et al., 1993). The primary motivation of landscape planning has been the maintenance and enhancement of connectivity to conserve the nature and biodiversity as well as maintaining human well-being in an urban environment. The effects of fragmentation could be mitigated by habitat creation or preservation that produces more connected patches (or networks) through the different ways in which networks have been thought about and developed in ecology and planning.

Around the beginning of the 19th century, the growing recognition of the crucial role of connected systems was reflected in strategies such as greenways and greenbelts (Ahern, 2003). Since then, different planning approaches have been developed throughout the world with regard to the connected systems of green spaces in urban areas. As well as greenways and greenbelts, other approaches include: ecological networks, green networks and green infrastructure. While each of these network concepts has been developed in a similar way in terms of their main idea and structural properties, typically they differ from each other in their main aims and functions (Jongman and Pungetti, 2004). As discussed by Ahern (1995) even though there has been a consensus on the benefits of network approaches for people, nature and biodiversity, a generally accepted terminology on network approaches is lacking. Therefore, it is necessary here to clarify exactly what is meant by different network concepts and approaches in the literature.

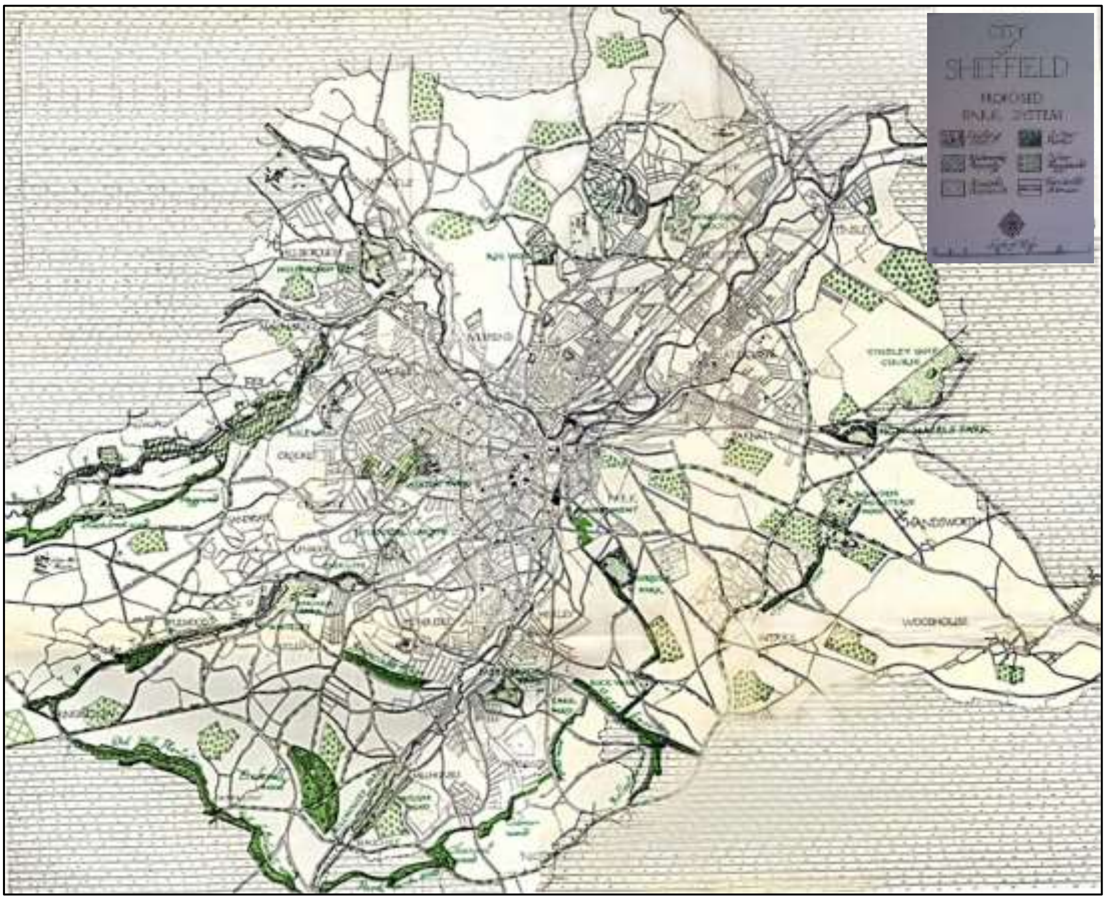
2.6.1 Greenbelts and Linked Park Systems to Greenways

The development of greenways originated from the concept of "parkways" as a system of open spaces in metropolitan areas in the 19th century. The parkways concept was developed by Frederick Law Olmstead, who is regarded as the founder of the profession of landscape architecture in the USA (Makhzoumi and Pungetti, 1999 and 2005). Frederick Law Olmsted proposed two important plans for Brooklyn and Boston in the USA, with the purpose of linking urban parks and the surrounding areas as linear park systems for the benefit and use of people (Jongman, 2004; Fabos, 2004; Jongman and Pungetti, 2004). The Boston Park System, which is also called the "Emerald Necklace", constitutes the first greenway approach in the USA (Ahern, 2002; Fabos, 2004). The crucial role of such a park system was described as the integration of urban and suburban areas to increase the functioning of these areas.

The green belt concept was first introduced by Ebenezer Howard in 1902, in his book Gardens Cities of To-Morrow (Ndubisi, 2002; Amati, 2008). According to Howard, if green spaces were located in a close proximity to residential areas, they would provide positive contributions to residents' physical and psychological health (Howard, 1902). The idea of green belts was developed to separate urban and rural environments from each other as a way of preventing urban sprawl and conserving natural areas beyond the urban areas (Amati, 2008). Hence, the concept of green belts is largely based on the idea of controlling urban growth by surrounding urban areas with a buffer of undeveloped land (Ndubisi, 2002; Jongman and Pungetti, 2004; Thomas and Littlewood, 2010).

In Sheffield, in 1924, the town planner Patrick Abercrombie developed one of the most comprehensive city plans for any city at that time, called the Sheffield Civic Survey and Development Plan. According to Abercrombie, in an urban environment, the success of a systematic provision of open spaces is governed by the extent (area), use and distribution of open spaces.

In his plan, Abercrombie proposed a park system where the individual open spaces are connected to each other with linear features of tree planted avenues (Map 1). In this map, while "*Existing Parks*" are shown with black bushes on light green background, "*New Parks*" are shown with a darker green background and "*New Playgrounds*" are shown with green dots. As seen in Map 1, these features of the Abercrombie's proposed park system are generally distributed in the urban periphery and connected to each other with *"Tree Planted Avenues"* which are shown with green dashed lines. Abercrombie's plan also includes the features of *"Accessible Moorlands"* and *"Waterworks Property"* which are shown with green grids and green forward slashes, respectively.



Map 1: Abercrombie's proposed park system

Within this context, Abercrombie claimed that:

- The extent or area of different open spaces must be proportional to the whole extent of the city,
- The uses and functions of open spaces should be determined by their user groups
- Open spaces must be distributed throughout the city in an appropriate way and where they are required. In this regard, the travel distance to open spaces must be taken into account. Here, while certain types of parks must be placed evenly throughout the city, some of them must be placed in the city centre or distributed irregularly depending on their use (Abercrombie, 1924).

The underlying principle of Abercrombie’s plan was that green spaces should be located close to the centres of population it serves. This strategic plan has a special importance in the development of Sheffield, since, through an in-depth analysis process, it revealed the actual structure of the city at that time, offered a complete framework for open spaces throughout the city and towards the Peak District National Park, and made clear connections between green spaces and centres of population (Winkler, 2007).

After these pioneering activities, the greenway concept has become a common landscape planning approach throughout the world. Little (1990) defined a greenway as:

- A linear open space established along either a natural corridor, such as a riverfront, stream valley, or ridgeline, or overland along a railroad right-of-way converted to recreational use, a canal, scenic road, or other route,
- Any natural or landscaped course for pedestrian or bicycle passage,
- An open-space connector linking parks, nature reserves, cultural features, or historic sites with each other and with populated areas,
- Locally, certain strip or linear parks designated as parkway or green belt.

On the other hand, Ahern (2003) described greenways as "the connected systems of protected lands that are managed for multiple uses including: nature protection, recreation, agriculture, and cultural landscape protection". According to Ahern (2002) the term greenway is a generic description of various landscape planning approaches, concepts and plans with the aim of ensuring multifunctionality in urban areas. As can be seen from these definitions, the focus of greenways has been moved to a multifunctional network approach from a single purpose planning approach of public use, access and enjoyment.

2.6.2 Ecological Networks

Ahern (2002) points out that while the term ecological networks is more common in European countries, the term greenways is common in the USA. Historically, the term ecological was inserted into the network approach in the Netherlands with the concept of ecological infrastructure (Hailong et al., 2005). Since then, these terms have been used interchangeably.

A variety of definitions of the term ecological networks have been suggested in literature. Ecological networks are defined by Bennett (2004) as “coherent systems of natural or semi-natural landscape elements configured and managed with the objective of maintaining or restoring ecological functions as a means of conserving biodiversity, besides providing appropriate opportunities for the sustainable use of natural resources”. Alternatively, Jongman and Pungetti (2004) defined ecological networks as “systems of nature reserves and their interconnections that make a fragmented natural system coherent, so as to support more biological diversity than in its non-connected form”.

In general terms, the notion of ecological networks is founded on the conservation of natural areas and biodiversity as well as the enhancement of the functioning of ecosystems by providing interconnections amongst them (Jongman et al., 2004; Opdam et al., 2006; Lawton et al., 2010). Therefore, ecological networks have been regarded as the spatial expression of the idea of landscape connectivity (Jongman and Pungetti, 2004).

An ecological network is composed of core areas, buffer zones and ecological corridors (Bischoff and Jongman, 1993). The structure of an ecological network is explained by Figure 4 below (Adapted from Bennett and Mulongoy, 2006). In this figure, the primary concern for core areas is conservation of biodiversity and buffer zones prohibit the damaging effects from external influences.

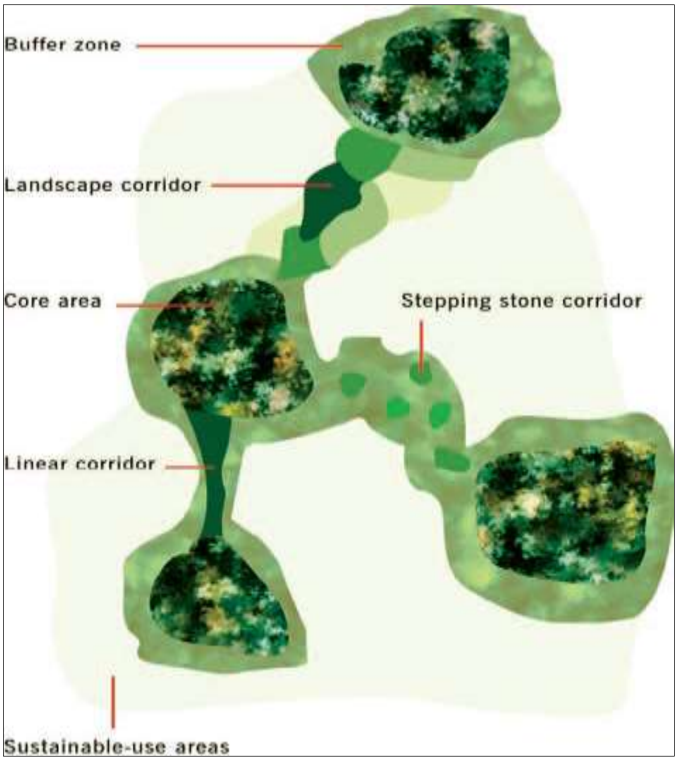


Figure 4: The schematic representation of ecological networks

Corridors are expressed as three types:

- landscape corridors, which can be in various forms of linked landscape matrices,
- linear corridors, such as rivers or forest strips, and
- stepping stone corridors, which are composed of a range of small habitat patches within the landscape matrix.

Ecological networks are important for improving the connectivity between patches in an urban environment since they allow the dispersal and movement of animal and plant species throughout the landscape. Bennett and Wit (2001) suggest that ecological networks share two main goals. The first goal is to maintain the functioning of ecosystems, and the second goal is to promote the sustainable use of natural resources.

From the end of the 19th century, the concept of ecological networks attracted the attention of conservationists and planners in Europe (Jongman and Kristiansen, 2001; Boitani et al., 2007). Within this framework, ecological networks have been considered one of the most important landscape planning approaches to finding solution to the human-induced habitat depletion, since they include both ecological and human aspects of a landscape and the interactions between these aspects. In Europe, many international initiatives and strategies for ecological networks have been developed (Tillman, 2005; Jongman et al., 2004), e.g. the NATURA 2000, Emerald, and PEEN. In urban areas the ecological network concept has been regarded as particularly important for maintaining some level of ecological structure and function. Therefore, an ecological network is thought to provide habitats and ecological connectivity for species and to conserve the wildlife (Jongman and Pungetti, 2004). The emphasis of the wildlife conservation has been a major driver for the development of urban ecological networks.

2.6.3 Green Networks

The green networks concept has been developed on the idea of ecological networks and has been inserted into urban planning practices (Külvik et al., 2008). The concepts of ecological and green networks have been used synonymously. However, the transition from ecological networks to green networks has brought together the spatial planning of nature and human dimensions to deliver benefits both for people and the environment. In other words, the focus of the ecological networks concept was on the conservation of species and habitats, the green network concept has brought the needs of species and human together under the same roof as a multifunctional urban planning approach (Jongman and Pungetti, 2004; Forest Research, 2011).

Moreover, the concept of green networks puts an emphasis on the crucial role of green spaces and the connections between them to support and improve sustainable development as well as enhancing the functioning of urban environments (Forest Research, 2011). The term green networks is defined as "natural, or permanently vegetated, physically connected spaces situated in areas otherwise built up or used for intensive agriculture, industrial purposes or other intrusive human activities", in which both publicly and privately accessible lands are included (Barker, 1997).

In this sense, it is important to note that a green network approach goes beyond the idea of developing individual green spaces in an urban environment just for recreational and visual purposes, and focuses on a functionally and / or structurally connected systems of formal and informal green and open spaces (Barker, 1997; Tzoulas and James, 2010). Forest Research (2011) suggests that the concept of green networks takes into account the different functions offered by green spaces, their interconnections and ability to support the movement of people and biodiversity. Here, we can clearly see that the intended functions of green networks overlap with the main functions of ecological networks, which aims at supporting and enhancing the movement of species. Forest Research (2011) and Moseley et al. (2013) explain the relationships between green spaces and a green network according to their functions and spatial configurations. Whilst green spaces refer to publicly accessible individual green areas in urban environments, green networks reflect a strategically identified and functional system of green spaces, for the benefit of people, habitats and biodiversity.

Barker (1997) claims that the major benefit of green networks is their ability to provide connections between urban and rural landscapes based on their ecological characteristics. On this basis, green networks are said to be able to meet the requirements of wildlife, and ecological processes along with the recreational and visual needs of people. With regard to the needs of people in an urban environment, a recent study by Scotland & Northern Ireland for Environmental Research (SNIFFER) suggests that green networks provide a safe environment for people to travel through and increase the number of people visiting urban green spaces and the countryside (SNIFFER, 2008).

In most of the countries, even though green networks have been primarily developed for their benefits to nature and biodiversity, they serve multiple uses and functions such as addressing the ecological requirements of species, controlling flood and improving water quality and providing recreational facilities to the public (Barker, 1997). For example, Sheffield City Council (SCC, 2013a) explains the underlying reasons for conserving and improving a green network for people and wildlife as follows:

- to increase and support biodiversity in Sheffield and the surrounding areas,
- to allow the dispersal and genetic exchange of species throughout the city,
- to reduce the adverse effects of fragmentation and isolation,
- to control and support a sustainable drainage system,
- to encourage the movement of people by increasing the access to open and green spaces, and countryside,
- to improve the well-being and health of people, and
- to improve the general character of the city as an attractive and healthy place.

In brief, green networks have been inserted into the planning and management processes as a broad concept with the purpose of achieving multifunctionality for biodiversity and people in urban areas.

2.6.4 Green Infrastructure

The green infrastructure is a more recent planning approach, which builds on the previous network approaches within an urban environment for the benefit of biodiversity, nature and people (Benedict and McMahon, 2006). Accordingly, the concept of green infrastructure is not a new idea in the areas of landscape planning and management (Wright, 2011). Hence, we can suggest that the green infrastructure concept is basically grounded on the recognition of the role of green networks in the wider landscape to provide essential services, functions and / or resources like any other form of infrastructure, such as sewer systems, transport infrastructure, access and travel, pollution mitigation and food production.

Benedict and McMahon (2006) defines green infrastructure as "an interconnected network of waterways, wetlands, woodlands, wildlife habitats, and other natural areas; greenways, parks and other conservation lands; working farms, ranches and forests; and wilderness and other open spaces that support native species, maintain natural ecological processes, sustain air and water resources and contribute to the health and quality of life for communities and people". In addition, green infrastructure is defined by Natural England (2007) as "the network of multifunctional open spaces, waterways, trees and woodlands, parklands and open countryside within and between our cities, towns and villages". Furthermore, Natural England (2012) also defines green infrastructure as "a strategically planned and delivered network comprising the broadest range of high quality green spaces and other environmental features".

Taking into consideration the different definitions of green infrastructure, it is clear that they all share the idea of connectivity (in the form of networks), multifunctionality and green components at the heart of this concept (Wright, 2011). However, it is important to note that even though there is an emphasis on the term green, green infrastructure includes river systems, other water features and coastal environments, which are also known as blue infrastructure (Natural England, 2007). Moreover, as understood from different definitions, multifunctionality is the core idea of the green infrastructure concept, since it has been realised that a landscape can deliver multiple benefits and functions at different (and / or the same) temporal and spatial scales for wildlife and people. Natural England (2009) suggests that multifunctionality “refers to the potential for green infrastructure to have a range of functions, to deliver a broad range of ecosystem services. Multifunctionality can apply to individual sites and routes, but it is when the sites and links are taken together that we achieve a fully multifunctional green infrastructure network”. Hence, there is a sharp contrast between landscape planning approaches aiming at landscape multifunctionality or a single objective (Selman, 2006).

Moreover, McDonald et al. (2005) claim that one of the most important features of green infrastructure plans lies in its primary aim, which is the determination of suitable areas for nature conservation, based on the actual and future situation of an urban environment. With regard to this, the Landscape Institute (2009) indicates that a strategically planned and managed green infrastructure approach has a crucial role to play in providing multiple and enhanced functions compared to the sum of individual green and open spaces in an urban area.

Physically or structurally, green infrastructure is composed of natural, semi-natural and man-made ecological systems and altogether these components form a multifunctional network within and around urban areas (Tzoulas et al., 2007). Therefore, the planning and management of a green infrastructure approach should take into account its capacity for delivering multiple ecological services, meeting the requirements of people as well as enhancing the spatial character and quality of landscapes (Natural England, 2007; Natural England, 2012).

Green infrastructure in an urban environment constitutes more than the presence and benefits of formal and informal green and open spaces. The concept of green infrastructure is a comprehensive planning approach, in which a coherent system of urban green and open spaces is developed (Sandström, 2002). So, green infrastructure serves multiple purposes and provides multifunctionality in urban areas. In this respect, it is important to note that multifunctionality in a landscape is characterised by a high level of complexity, where different functions occur at the same time and interact with each other (Selman, 2009).

2.6.5 A Summary of Network Approaches

Broadly speaking, different network approaches have their own planning aims and strategies, particularly in their early stages. However, thereafter they become closer in terms of their general frameworks and common concerns about nature, wildlife and people (Jongman and Pungetti, 2004). As mentioned previously, all network approaches are based on the recognition of the importance of connections / linkages for people and biodiversity in an increasingly fragmented landscape. Within this context, the common characteristics of network approaches are their spatial configuration and focus on connectivity.

Network approaches generally have a linear spatial configuration in which different habitat patches or green and open spaces are included. These habitat patches or green and open spaces are linked to each other structurally or functionally. In a general sense, within a network, whilst the natural or semi-natural habitats are connected for the benefit of wildlife and biodiversity, green and open spaces are linked to each other for the benefit of people. In addition to a linear spatial configuration, sometimes structural and functional connectivity can be reflected in the wider landscape context, such as the various forms of linked landscape components in the surrounding landscape matrix.

As mentioned by Ahern (1995), in an urban environment it is really hard to develop a network which focuses only on the conservation of nature and biodiversity. Also in many cases it is not appropriate to apply such an approach. This is simply because we cannot ignore the requirements of people as well as the interactions between them and nature in urban areas. Hence, there has been a shift from a single purpose planning approaches to more comprehensive and integrative planning approaches with the aim of delivering multifunctionality (Noss et al., 2012). In this regard, it is important to set the priorities and aims of the network according to the landscape context and the requirements of biodiversity and the public.

Moreover, there is evidence for the benefits of different network approaches, such as to facilitate the dispersal, genetic exchange and the variability of many animal and plant species, to increase species' resilience to the environmental changes, predators and human disturbances, to support the essential ecosystem services (e.g. pollination and sustaining natural water filtering systems) (Crooks and Sanjayan, 2006; Taylor et al., 2006) as well as supporting the health and well-being of people and as enhancing community spirit (Dunnett et al., 2002; CABE, 2010; Horwood, 2011). However, a lot of the evidence is missing and our understanding of the underlying science and the ways of planning, designing and managing networks in urban landscapes is still developing. Hence, one of the most important obstacles to enhance the functioning of connectivity, maintaining biodiversity and supporting human well-being through the development of networks has been the gap between their intended aims and actual outcomes in an urban environment.

2.7 Aim, Objectives and Research Questions

The aim of this study is to examine different ways of defining green and ecological networks and their functionality for biodiversity and people. Such an understanding of different planning and scientific approaches is crucial in both the social and ecological sense if we intend to maximise the effectiveness of those networks being preserved or planned in urban areas. Within this framework the following main research questions will be addressed under each of the objectives of the proposed research study:

Objective 1. to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes,

1.1. How are ecological and green networks defined in Sheffield at present?

1.2. How are the spatial components of the actual green and ecological networks identified?

1.3. What are the differences (if any) between the ways of defining the objectives and spatial coverage of these networks?

Objective 2. to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data,

2.1. Can criteria be derived to identify the potential routes of connectivity?

2.2. What forms do the potential routes of connectivity constructed using these criteria take?

Objective 3. to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice.

3.1. Do the derived routes of potential connectivity and accessibility coincide with each other and the actual green and ecological networks?

3.2. How does the landscape matrix complement or detract from the potential routes of connectivity and what are the best possibilities for improving the functionality of connectivity in urban areas considering potential habitat use by organisms and/or accessibility to the public?

3.3. Considering the space limitations in urban landscapes, are some types of land uses and morphologies more compatible with the potential routes of connectivity. If so, how can we measure their compatibility?

Chapter 3 General Research Methodology, Study Area and Data Sources

3.1 Introduction

As described in Chapter 1, this study aims to examine different ways of defining green and ecological networks and their functionality for biodiversity and people. In order to achieve the main aim of this project, a variety of methodological techniques will be employed. This chapter consists of two main parts: the first part introduces the methods used by describing the chosen methods and the process of modelling alternative networks for biodiversity and people and explaining the underlying reasons for their selection. The second part describes the study area and various datasets used in the analyses, which form the basis of Chapters 4 to 7.

Part 1 Research Design and General Methodology

3.2 Methodological Framework of the Research

In order to achieve the main aim of this research, a single case study approach was adopted as the overall research strategy, in which a mixed methods research design was employed. In this context a six-phase methodological framework has been developed (Figure 5), where the literature review and the case study area selection constitute the first and second phases for the basis of this research.

Literature study was used to understand the relevant theoretical and scientific background of green and ecological networks in landscape ecology and planning, relevant policy and legislative context of green and ecological networks and their implementation in the case of Sheffield. After defining the boundaries of the case study area, the main data sources were determined and all the necessary datasets for the spatial analysis were prepared. I generated three levels of land cover and land use maps using Geographical Information Systems (GIS) for the resulting spatial analysis.

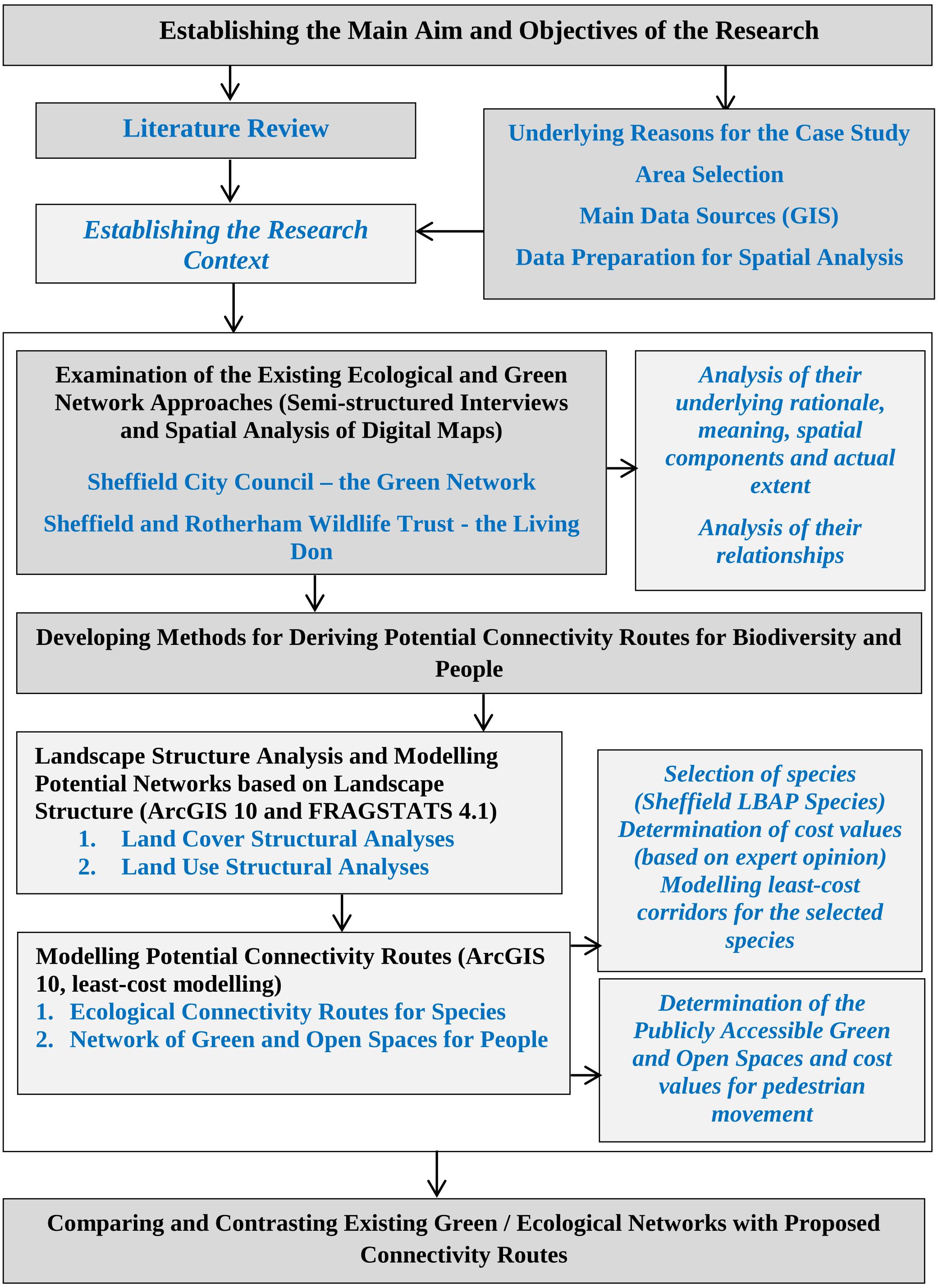


Figure 5: Research framework

In the third phase, I used a combination of a qualitative and quantitative approach in which semi-structured interviews and ArcGIS spatial analyses to examine the existing green and ecological network approaches in terms of their intended purposes, spatial coverage and structural components in Sheffield. Accordingly, I conducted 2 semi-structured interviews altogether with the officers of the Sheffield City Council (SCC) Ecology Unit and the Sheffield and Rotherham Wildlife Trust (SRWT), and analysed their green / ecological network maps in ArcGIS 10.1. The results provided the network definition and design from the perspective of planners and conservationists in the case of Sheffield.

The main role of green and ecological networks is to prevent the combined threats of fragmentation and isolation of natural areas (Jongman and Pungetti, 2004; Lawton et al., 2010). Therefore, the key concept on which the green / ecological networks are grounded is landscape connectivity. Since, landscape connectivity can be defined both structurally and functionally, I developed two different methods to derive networks for biodiversity and people, based on the previously generated land cover and land use maps. The first method was an exploration of how alternative connectivity and accessibility routes for biodiversity and the public could be developed based on structural / physical continuity of landscape components using ArcGIS 10.1 and FRAGSTATS 4.1 landscape metrics. The second method employed the least-cost modelling approach in ArcGIS 10.1 to develop alternative connectivity and accessibility routes for biodiversity and the public based on functional connectivity.

In terms of biodiversity the suitability of different land cover types as habitat for 10 selected species and their likely dispersal characteristics in each type of habitat was used as an indication of functional connectivity. On the other hand, regarding the accessibility routes for the public, I used physical / legal accessibility and the effects of slope on the movement of people as an indication of functional connectivity. At this stage, I modelled different networks as the routes of ecological connectivity for 10 species. These species were selected from Local Biodiversity Action Plans (LBAPs) based on their habitat requirements. I also modelled a network of green and open spaces for people on the basis of all publicly accessible green and open spaces in the urban part of Sheffield to derive routes of connectivity for people. Finally, by comparing and contrasting the existing networks with my derived routes of connectivity, I tried to determine the similarities and differences between their main purposes, the criteria on which they were based, as well as their spatial components.

3.2.1 Literature Review

Reviewing relevant literature constitutes one of the most important parts of a research study. Literature study is particularly valuable for establishing the context of the proposed research project by relating theory to its application, discovering what has been done and what needs to be done in the related research area; finding out the widely used methodologies and their advantages and disadvantages and finally revealing the importance of the proposed research project by relating it to the previous research and to its real-world context (Hart, 1998; Bell, 2005). Additionally, Hart (1998) emphasises the crucial role of a literature review in achieving a deeper understanding of the proposed research topic and the emerging key issues when conducting a study in the related research area.

In the context of this research, I reviewed the theoretical and scientific background of landscape ecology and green / ecological networks, approaches to planning green / ecological networks and the most common methodologies and techniques used to measure structural and functional connectivity.

3.2.2 Case Study Area Selection

Case studies have been widely used in landscape research to present detailed analysis of the relationships between theory, policy and application to a real life situation, with the intention of bridging the gap between science and practice. Since case studies provide practical information on the potential solutions to difficult spatial problems, they have been particularly useful in analysing and investigating the efficiency or suitability of different landscape approaches (Francis, 1999 and 2001). As explained previously, the main purpose of this research is to examine different ways of defining green and ecological networks and their functionality for biodiversity and people in an urban context. Therefore, in this research a single case study approach was used, in which both qualitative and quantitative research methods were employed. Sheffield has been selected as the case study area for the following reasons:

- Sheffield is one of the largest and greenest municipalities in the UK with a wide variety of habitats,

- It has different approaches to ecological / green network definition and design from the perspective of planners (SCC-the Green Network) and conservationists (SRWT-the Living Don), and
- It has a variety of accessible data sources.

3.2.3 Data Sources and Preparation of the Datasets for Analyses

After the selection and definition of the case study area, I identified the potential data sources which were available to use for the preparation of the datasets required in connection with the selected methods (Table 1). The available data sources, in a digital format, were collected online or in CD format from public websites or local government departments, after obtaining all relevant permissions.

Table 1: List of available data sources

Available Data Sources	**Source of Dataset**	**Description**
Ordnance Survey MasterMap Topography Layer	Digimap via the University of Sheffield	Base Map for the delineation of land cover and land use maps (vector formatted)
Ordnance Survey AddressBase Plus	By request from Ordnance Survey Research- Research Project Coordinator	Provides detailed information on current properties and addresses in which the Royal Mail's Postcode Address File (PAF) and Local Authorities data are combined (vector formatted)
Centre for Ecology and Hydrology- Land Cover Map 2007 (LCM2007)	By request from Centre for Ecology & Hydrology- Data Licensing Administrator	Represents 23 land cover classes, which combine to map 17 terrestrial Broad Habitats (vector formatted)
Forestry Commission National Inventory Woodland and Trees	From the website of Forestry Commission Spatial Data	Represents all areas of woodland over 2 ha and their interpreted forest type (IFT), small woodlands and trees covering an area of less than 2 ha (the groups of trees, belts of trees and individual trees) (vector formatted)
Sheffield City Council- Green and Open Spaces	By request from Sheffield City Council Parks & Countryside- GIS Officer	Represents all of open spaces, sport and recreation sites in Sheffield (vector formatted)

Ordnance Survey-1:10 000 Scale Colour Raster	Digimap via the University of Sheffield	Backdrop map (raster formatted)
MIMAS-Landmap-Cities Revealed & UK Map Datasets-Modern Aerial Photography	MIMAS (Manchester Information & Associated Services) Landmap Collection	Backdrop map- high resolution aerial photography (raster formatted)

Once I obtained all the available data sources, I used them to generate a three level hierarchical classification for use in land cover and land use maps. The first step of the manipulation of the data sources was developing a classification scheme for both land cover and land use maps. I developed a three level classification scheme based on the National Land Use Database (NLUD-Version 4.4) classification scheme and the suitability of available data sources for a detailed mapping process. Whilst the land cover classification scheme includes 34 land cover categories at the most detailed level (level 3), the land use classifications scheme is composed of 49 land use categories.

3.2.4 Research Ethics

Prior to commencing this research project, ethical clearance was obtained from the University of Sheffield via the Department of Landscape’s devolved ethics procedure. The University of Sheffield Research Ethics Policy set outs the key principles, statements and guidelines for researchers to follow, if the research project involves human participants, personal data and human tissue. As this research involves human participants and personal data, it has been through the Department of Landscape's ethical approval procedure. It was approved by the Department’s Ethics panel as follows:

- On 14/05/2012: to conduct interviews with the officers of Sheffield City Council (SCC) and Sheffield and Rotherham Wildlife Trust (SRWT), who are concerned with planning and supporting biodiversity in Sheffield, in order to analyse current approaches to defining green and ecological networks in the research area,
- On 09/12/2013: to gather expert opinion in order to determine the habitat suitability of different land cover types for a group of selected species and the

cost values for landscape permeability. The information gathered from experts was used in the parameterisation of connectivity models using the least-cost modelling analytical tool in ArcGIS 10.1.

Neither of these methods involves the participants in any foreseeable risk or discomfort. All participants were supplied with information sheets and consent forms to allow them to be involved in this study knowingly and voluntarily. As well as explaining the aim of the research to all of the potential participants contacted, I also provided information to all potential participants on:

- the justification for requesting their opinion,
- the anticipated duration of semi-structured interviews and expert opinion processes,
- the methods that would be used to handle information obtained from them,
- the duration of data use and storage, and
- the explanation for the different ways of the data usage.

On the basis of all information they had been supplied with, participants were free to decide whether they wished to participate or not. Also, if they were interested in participating in this research and wished for more information, they were given the chance to contact me and my supervisors by e-mail.

All data obtained during these procedures were protected under the Data Protection Act 1998. The raw data gathered during these procedures were kept in my laptop and external hard disks. Furthermore, the hard copies of the consent forms gathered from interviewees were kept in locked drawers in my office.

3.2.6 Examination of Current Ecological and Green Network Approaches

The first analyses include critically examining existing approaches to defining urban green and ecological networks in planning and ecology in the research area. As the first step, I analysed planning policy documents related to the Green Network. The analysis and comparison of these documents provided a deeper understanding of the details of the context and evolution of planning policies on green networks in

Sheffield. Afterwards, the second analysis included semi-structured interviews with the officers of Sheffield City Council and the Sheffield and Rotherham Wildlife Trust, as well as analysing the spatial extent and the relationships between these networks based on their digital maps.

Objective 1. to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes. I aimed to achieve the first objective of this research by addressing the following research questions:

1.1. How are ecological and green networks defined in Sheffield at present?

1.2. How are the spatial components of the actual green and ecological networks identified?

1.3. What are the differences (if any) between the ways of defining the objectives and spatial coverage of these networks?

3.2.6.1 Planning Policy Document Analysis

Document analysis of planning policy document was carried out. For this, the Sheffield Nature Conservation Strategy (1991), the Sheffield Unitary Development Plan (1998) and the Sheffield Local Plan (2013, previously called as the Sheffield Development Framework in 2009) were analysed by I comparing and contrasting the Green Network policy, other related policies and also their Proposals Maps for the Green Network.

3.2.6.2 Semi-structured Interviews

An interview has been described as a conversation, in an attempt to reveal information on a particular subject (Moser and Kalton, 1971; Kvale and Brinkmann, 2009). Interviews can be structured, semi-structured or unstructured. Brinkmann (2013) claims that it is not possible to conduct an interview in a way that is completely structured or unstructured. Even though, when conducting an unstructured interview, we direct the conversation towards the main subject and overall aim of the interview; or when conducting a structured interview, we may raise more specific questions related to the subject of the interview.

Structured interviews are generally conducted in the form of questionnaires based on specialised questions. While, structured interviews are useful as ways of gathering information that has been specified in advance, they may not be able to catch additional information from conversations - as the interviewer cannot add or remove questions during the interview process (Berg and Lune, 2012; Brinkmann, 2013). On the other hand, unstructured interviews are more flexible in nature and the interviewer may catch some other important information that may come out spontaneously during the conversation. However, they may take longer than structured interviews and the interviewer needs to be more focused in order to keep the conversation in the right direction (Brinkmann, 2013). Semi-structured interviews include previously prepared questions and / or topics to talk about in a flexible manner, whereby the interviewer can add or remove some questions, or can go into detail where it is required (Berg, 1989). Therefore, a semi-structured approach was chosen to achieve in-depth analysis of the existing green and ecological network approaches in the case of Sheffield, as they allow focused but flexible two-way conversations on the topic of interest. As stated above, ethical clearance was obtained from the University of Sheffield on 14/05/2012 prior to carrying out the semi-structured interviews. The aim of the semi-structured interviews was to reveal the intended aims, spatial coverage and components of the green / ecological network approaches in Sheffield.

Preparation of the Interview Questions

The interview questions were prepared to reveal a better understanding of defining green and ecological networks in use in Sheffield, based on two different approaches. The schedule of themes and questions were prepared in an iterative manner in consultation with my supervisors. After preparing the initial questions and themes, these were progressively developed and refined to make them clear, unambiguous and relevant to the project, and to capture all necessary information. Interviewees were asked 10 questions regarding the following main themes:

- Introduction to the interview by asking the interviewees to outline their role in green / ecological network preparation,
- The policy background and aims of the green / ecological networks in Sheffield, and
- Site selection and the main features of the green / ecological networks in Sheffield.

Identification of Prospective Participants

The prospective participants were identified by taking into account whether they were concerned with planning and supporting biodiversity and / or have been involved in the process of planning green/ecological networks in Sheffield. The prospective participants were divided into two groups based on their involvement in different green and ecological network approaches. I conducted three semi-structured interviews altogether with the officers of the Sheffield City Council (SCC) Ecology Unit, SCC Forward and Area Planning Team and the Sheffield and Rotherham Wildlife Trusts (SRWT).

Approaching and Recruiting Participants

After the initial contact by e-mail, we arranged suitable times and places for interviews. All prospective participants were sent a digital copy of the interview questions, consent form and an information sheet, and asked for their availability. Each of the interviewees preferred to have their interviews in their workplaces, i.e. in the office of SCC Ecology Unit and in SRWT. The semi-structured interviews were conducted on a one-to-one basis. Each interview took approximately an hour to complete and each was recorded on a digital audio recorder with the consent of the interviewees. Then, all audio records were firstly transcribed by using an on-line transcription tool (***Transcribe-*** which is available on https://transcribe.wreally.com/) and then analysed to gain a deeper understanding of the underlying rationale for existing green and ecological network approaches in Sheffield (Figure 6). The general analysis approach was deductive, looking for specific material that would throw light on the research themes and questions.

Mike: So, how did you get started with

Transcribe audio without alternating between an audio player and a text editor.

Looking for more features? Try out Transcribe Pro!

Esc: pause/resume
F1: slow down
F2: speed up
F3: rewind 2 seconds
F4: forward 2 seconds

Figure 6: A Screenshot from *Transcribe*

3.2.6.3 Analysing the Digital Maps

Once the interview process was completed, participants were kindly requested to send me the digitally formatted Green Network map, developed by Sheffield City Council and the Sheffield and Rotherham Wildlife Trusts. After their agreement, I received the digital map (compatible with ArcGIS form SCC and SRWT) by e-mail. Then, using ArcGIS 10.1, the digital maps and documents associated with each approach were examined in terms of their components, spatial extent and representation, as well as the relationships between those approaches, to support the information obtained from the interviews and to examine how the green / ecological networks were represented graphically on the plans. Overall, the semi-structured interviews combined with the examination of their maps allowed me:

- to explore and evaluate the meaning, components and actual extent of individual network approaches,
- to reveal the similarities and differences between those approaches by analysing the responses of interviewees, and
- to reveal the similarities and differences between the Sheffield City Council and Sheffield and Rotherham Wildlife Trusts' plans.

3.2.7 Landscape Structural Analyses

After analysing the current network approaches in Sheffield, the next step was to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data

(Objective 2). Therefore, it was intended to investigate the potential for landscape metrics to describe the main characteristics of landscape structure, to derive the potential routes of connectivity. The main research question to be answered was:

1. Can criteria be derived to identify the potential routes of connectivity?
2. What forms do the potential routes of connectivity constructed using these criteria take?

I used FRAGSTATS 4.1 landscape metrics to describe, quantify and evaluate the structural properties of the whole landscape and the inherent characteristics of the landscape components. The main reasons behind the selection of the FRAGSTATS software are that it is compatible with ArcGIS, includes a variety of landscape metrics and it is freely available on the web with its user guide. FRAGSTATS accepts raster datasets in a variety of formats. Therefore, as the first step in the landscape structural analysis, I used ArcGIS 10.1 in order to convert the vector formatted land cover and land use datasets into raster format.

In order to determine the most appropriate raster size for my analyses, after converting vector layers into 1m, 2m and 5m raster sizes, I checked the capability of each of them to represent landscape features accurately. Although the most realistic and accurate representation of landscape components was obtained with the 1m raster size, due to problems related to the digital memory size for loading and processing the datasets, I chose 2m. I then selected the landscape metrics considering their capability to measure the structure and character of the landscape and structural landscape connectivity as well as their widespread use and easy interpretation. Landscape metrics can be calculated at a multilevel structure i.e. patch, class and landscape levels (McGarigal and Marks, 1995; McGarigal, K., 2002).

Taking into account the main aim of this part of the research, I calculated the landscape metrics at class level as they broadly characterise the fragmentation of a particular land cover / use type and provide a more in-depth analysis of landscape structure. In order to interpret and evaluate the outputs of FRAGSTATS landscape structure analyses, I converted comma-delimited ASCII formatted files into excel format.

3.2.7.1 Land Cover Structural Analysis-Ecological Aspects

The sub research questions intended to be answered in the first part of the landscape structural analyses are:

1. Taking into account the structural characteristics, what are the most favourable land cover types to support structural landscape connectivity?
2. What forms do the potential routes of connectivity take and how does the structural connectivity change by aggregating less connected land cover types of a broad land cover category to the most connected ones?

As previously mentioned, land cover types in the research area were determined based on a three-level hierarchical classification system in which each land cover type is defined in progressively more detail at each level. So, I conducted landscape structure analyses at multiple levels to enable ecological connectivity analysis by aggregating the sub-classes of the same land cover types at a higher level. Such an approach also enabled me to control the consistency between the results of analyses at different levels.

For the second part of the land cover analysis, I used ArcGIS and FRAGSTATS in combination. ArcGIS 10.1 was used to aggregate the sub-land cover classes of the same land cover types at a higher level to find out the form of alternative connectivity networks. Then, using FRAGSTATS 4.1, I attempted to measure the change in structural connectivity of alternative networks as I added the patches of different land cover types based on their physical continuity.

3.2.7.2 Land Use Structural Analysis-Social Aspects

The main purpose of this part is to identify and prioritise land use types which would contribute to the potential routes of accessibility for people by providing the strongest structural connectivity. As land use is related to how people utilise the landscape through different activities and the arrangements of certain land cover type(s) in order to set out the relationships between the use of landscape and people, I decided to conduct all the analyses associated with people using only the land use maps.

Land use structural analyses were conducted based on a three-level hierarchical land use dataset using a similar approach to the one I did in the land cover structural analyses. Furthermore, all of the results obtained from the land use structural analyses were evaluated in the same way as the land cover structural analyses by addressing the following sub research questions:

1. To what extent are different land use types more connected inherently considering their structural properties?
2. How differently do the structural landscape connectivity patterns appear for public accessibility when we add less connected land use patches to the most connected ones?

3.2.8 Modelling Ecological Connectivity Routes for Biodiversity and Networks of Green and Open Spaces for People

In the previous landscape structural analyses and the proposed networks for biodiversity and people, the matrix was assumed to be homogenous without considering the potential contribution of different land cover / use types to the potential connectivity routes. However, the discrete land cover / use types in the surrounding landscape matrix may behave in a different way (hospitable or inhospitable) to different species (Wiens, 1996) and also to people. Therefore, at this stage, I attempted to model potential connectivity routes in different way taking into account the landscape matrix and its influences on the movement of selected species and people.

Modelling Approach-Use of Geographical Information Systems (GIS)

The least-cost modelling approach is one of the most widely used GIS methods in order to analyse and model potential connectivity routes for biodiversity and people. There are three main reasons why this approach has become an attractive method to determine the potential routes of connectivity for a range of species. Firstly, it incorporates data on the ease of movement through the landscape into the landscape structure. Hence, it provides the potential for estimating functional landscape connectivity and removes the limitations of modelling approaches which are only based on structural connectivity. Secondly, it is able to incorporate simple or complex environmental variables on the habitat requirements of organisms. Finally, it enables researchers to analyse and model the potential routes of connectivity over large areas. Therefore, as an alternative way of modelling potential connectivity routes for different species and people, I used the least-cost corridor approach tool in ArcGIS 10.1.

The least-cost modelling approach is grounded on graph theory and basically finds out the shortest distance between habitat patches (or green and open spaces) to another through a cost / permeability surface. Here, the term “cost” or alternatively "permeability" indicates the capacity of different land cover / use types to impede or enable the movement.

A least-cost corridor model requires two input layers. These are composed of two different cost distance layers as an indication of the accumulated cost (or the ease) of movement across non-habitat between habitat patches. The cost distance layers were created on the base of source and cost layers. Therefore, prior to creating the required cost distance layers for the least-cost corridor models, source and cost layers should be created. Here, a source layer is a raster or vector formatted dataset which determines the starting point of movement, and a cost layer is a raster dataset, which identifies the ease of movement throughout the landscape mosaic. The source layers can directly be extracted from land cover / use maps.

On the other hand, in order to obtain a cost layer, each of the land cover / use categories needs to be assigned to a cost value (in other words a permeability value) as an indication of how landscape components hinder or facilitate the movement of organisms. If a land cover / use type enables the movement of organisms, the cost of movement will be low, whereas a land cover / use type that impede the movement will have a high cost of movement.

Once, the source and cost layers are obtained, the required cost distance layers were prepared in ArcGIS 10.1. Then, for each of the selected species and people, I modelled the least-cost corridors. In a least-cost corridor model, the lowest cost values represent the easiest movement routes through the landscape matrix between the defined sources (for example between suitable and potential habitat patches), rather than the shortest Euclidean distance. Further details of the least-cost modelling approach and the parameterisation of each model for species and people have been provided in the following sections.

3.2.8.1 Modelling Ecological Connectivity

This part of the research design was intended to define the potential connectivity routes based on the ease of movement of species to traverse across non-habitat between habitat patches. The least-cost modelling approach was used to model potential connectivity routes for a group of species. The following research question was answered under the overall objective of *developing methods for deriving the potential routes of connectivity for both wildlife and people*: Can criteria be derived to identify the potential routes of ecological connectivity and what forms do the potential routes of connectivity constructed using these criteria take?

A. Species Selection

Since ecological connectivity is a species-dependant attribute of a landscape, the first step of this modelling approach is the selection of focal species for the analyses. Applying the criteria below, I aimed to obtain a list of local species to reflect the differences between the potential ecological connectivity routes based on their habitat requirements. The criteria applied for the selection of species and the selected species are defined below. The detailed explanation of the species selection process can be found in Chapter 6, Part 1 (pages from 172 to 176).

List of local candidate species: First of all I assembled a list of local species of conservation concern and other associated species. I referred to the Sheffield Local Biodiversity Plan (LBAP) Priority Species listed in the Local Species Action Plans (29 species) and the associated species (21 species).

Association with landscape cover types: The focus of this criterion is to identify local species that would be broadly distributed within a land cover type(s). Initially, I intended to use the Recorder 6 database to associate species distributions with land cover types in my research area. The Recorder 6 is a tool to enter, collate and exchange the records of species and habitats and its outputs can be linked to the Geographic Information Systems (GIS). Therefore, I digitised a large amount of species records on paper into the Sheffield Biological Records Centre copy of

Recorder 6. In Recorder 6, the detail of the species records are indicated by different sized grid squares, such as 1 km squares (SE3502) or 100 km squares (SK39). There are also some records with the detail of 100m squares, but most of the dataset are recorded at lower level of details. On the other hand, the land cover map that I prepared was based on OS MasterMap Topography Layer with a high level of detail. Therefore, when I overlapped the species distribution maps and the land cover map, individual species seemed to be associated with most of land the cover types. In other words, the level of detail for the distribution of species in my research area (extracted from the Recorder 6 species database, Sheffield City Council, Ecology Unit) did not match with the prepared land cover maps. As a consequence, I attempted to associate each of those species to one or more land cover types using related reports and literature. At this stage, any species that were not associated with identified land cover types were excluded (42 species were left).

The Level of Threats: Each of the remaining species were characterised for their population's vulnerability to major threats identified using related reports and literature. Also, any species not associated with identified major threats were excluded. Thus, special consideration is given to the most vulnerable species that are particularly sensitive to habitat fragmentation and other changes in their habitats.18 species were left including 8 bird species, 6 mammal species and 4 herptiles.

Final Selection: In terms of birds, the Song thrush and Skylark were selected as focal species due to their habitat requirements, which were also representative of the other candidate species. The Greenfinch and Blackbird (associated species with urban birds) were added to the bird target species group as they favour a variety of different habitats. Additionally, the Pipistrelle bat, Leisler's bat and Brown long-eared bat were selected for their wide range of habitat preferences. Regarding reptiles, the Common lizard, Grass snake and Slow-worm were selected, for the differences in their preferred habitats as well as their different movement behaviours.

B. Gathering Expert Opinion

The next step was to obtain information on species habitat requirements for the parameterisation of the model, derived from empirical data or expert opinion. Where the empirical data on species does not exist or is insufficient, an "Expert Opinion

Technique" can be used to gather the opinions of a group of experts on the required information for the parameterisation of least-cost models (Brouwers et al., 2009; Zeller et al., 2012).

For this research, I wanted to get expert opinion on the suitability of different land cover types as habitats for the selected species, the minimum required habitat area for each of them and their likely dispersal characteristics in each type of habitat. Initially, I intend to gather expert opinion via the "Delphi Method", which aims to build a consensus on a given issue by gathering the opinions of a group of experts. During the Delphi process, each expert is asked to answer some questions themselves and also to review other experts' responses for 2 or 3 iterative rounds. After the initial round, the responses of all experts are summarised, then a summary will be sent to them to submit a revised response and reasoning in the light of all the other experts' opinions. This process would continue until a consensus is achieved or three Delphi rounds have been completed.

Originally, I was planning to deliver / post questions about habitat suitability and species' likely dispersal characteristics in different land cover types on a printed copy with a stamped and addressed envelope to return it. Afterwards, my supervisors and I agreed on using an online survey tool to save time and make the process easier for experts considering the following issues. The response of each expert would take quite a long time as I was intending to achieve at least three rounds for each expert. There were also potential risks to lose the documents in the post, and if this happened, then participants would not want to do it again and their participation would decline for the further stages of the Delphi process.

As a result, I used an online survey software package (Survey Gizmo) to prepare the questions that I wanted to be answered by experts. In this way, I intended to ensure an easy and quick way to conduct Delphi Technique for myself and potential participants. Also, I prepared a supporting information document which gives an outline of the concept of connectivity, expert process, questions to be answered and the explanations of land cover types present in my research area. Prior to start the Delphi process, I conducted a pilot study for one of my selected species with former PhD students in the Department of Animal and Plant Sciences, University of Sheffield, who have some expertise on the species and their habitat requirements, and also are able answer or consider the questions in a real manner. This stage was especially important as I wanted to find out if the online surveys were clear enough to be understood in the same way by all experts and the approximate time to complete surveys. The pilot study confirmed that each Delphi stage would take approximately an hour to complete. Also, I made some amendments on questions as well as in some parts of the supporting information for connectivity ranking exercises.

Afterwards, I identified 60 experts on the basis of their expertise in the ecology and behaviour of selected species and contacted them with an initial e-mail by explaining the aim of my research, the Delphi process, selected species that they were expected to take into account, and an explanation of the questions to obtain estimations of habitat suitability and species dispersal. If experts wished to participate in my research they were contacted again with an e-mail with a link to an electronic questionnaire for each species they were considering. At this stage I aimed at receiving at least 3 responses for each species. Then, each of them was sent to an electronic survey link accompanied by a supporting information sheet about the connectivity ranking exercise. However, over a period of three months I received only 5 responses in total for all of the selected species. Then, I decided to use a single expert opinion process instead of a Delphi Technique considering the time limitations and lack of expert participation. As a result, I obtained 5 expert responses which were composed of only one response for each of 4 bird species, only one response for each of 3 bat species and 3 responses for each of 3 reptile species.

C. Model Parameterisation-Creating the source, cost and cost distance layers

As mentioned earlier a least-cost corridor requires two cost distance layers which are generated on the basis of two source layers and a cost layer. The previously generated land cover map was used to create the required inputs of the least-cost modelling approach (the raster formatted source and cost input layers). There are 34 land cover categories within the land cover dataset. To prevent unnecessary time consumption and to maximise the participation of experts, the most detailed sub classes of the most detailed land cover dataset were aggregated to a broader category according to their relevance to each other at level 2. For example, the land cover categories of *Broadleaved Woodland, Mixed Woodland, Felled Trees, Young Trees* and *Orchards* were aggregated under the broader land cover category of *Woodland*. The final land cover map consists of 14 broad categories: *Woodland, Coniferous Woodland, Shrub, Mixed Vegetation 1 (roadside and railway vegetation), Mixed Vegetation 2 (private gardens and other landscaped areas), Improved Grassland, Amenity Grassland, Unimproved Grassland, Heathland, Arable Land, Standing Water, Running Water, Wetland, and Buildings/Structures and Constructed Surfaces.*

Using this land cover map with 14 broad land cover categories, I created 20 source layers in which 10 suitable and 10 potential habitat patch(s) were shown for each of the selected species. The suitable and potential habitat patches were determined on the basis of habitat suitability and minimum habitat requirement estimations made by experts. The habitat suitability estimations were made in a probabilistic way, on a scale of 1 to 100, where 1 represents habitat in which individuals would struggle to survive for any period and would never breed successfully and 100 is habitat in which mortality is low and most breeding attempts are successful. Based on this scale, higher scores reflect higher probability of land cover categories to be the habitat for the selected species.

After determining the land covers with higher scores, I extracted these land cover categories as separate layers from the existing land cover map. Then, I examined these land cover layers in terms of meeting the required minimum habitat area estimations for each of the selected species. Then, I split these into two categories as core and least suitable habitat layers where the core habitats layer was the representative of the first source layer for each species and composed of land cover categories with an area of greater than or equal to minimum habitat area requirement. On the other hand, the least suitable habitat was the representative of second source layer for each species and included the remaining land cover patches with a smaller area than the minimum habitat area requirement.

Similar to habitat suitability scores, these cost values were estimated by experts in a probabilistic way, on a scale of 1 to 100. However, on this scale, the value 1 represents the habitat in which the species would normally reside/breed and movement is not restricted, and 100 indicates habitat that is either a complete physical barrier to movement, or one in which there is a high likelihood of mortality in crossing the habitat for any distance. Applying the cost value estimates of experts on the cost values to the land cover dataset, I generated 10 cost surfaces in which the capacity of intervening land cover patches to impede or enable the movement of each species across habitat and non-habitat patches was shown. The cost layers were created using the *Spatial Analyst, Reclass Tools* and *Reclassify Tool* in ArcGIS10.1.

Afterwards, for each species I created two cost distance layers as the inputs of the least-cost modelling approach. The first cost distance layers were created using the first source layers showing all core habitat patches and the cost layer. The second cost distance layers were based on the second source layers representing the least suitable habitat patches and the same cost layer for each species. Here, while the first cost distance layer represents the accumulative cost of movement through the landscape starting from core habitat patches, the second cost distance layer shows the accumulative cost of movement through the landscape starting from the least suitable habitat patches.

D. Modelling least-cost corridors and determining the corridor width

The least-cost corridors were generated using *Spatial Analyst, Distance Tools* and *Corridor Tool* in ArcGIS 10.1 on the base of two cost distance layers. The output least-cost corridors represent the accumulative cost of movement for each of the selected species when they traverse across the landscape between suitable and potential habitat patches. The output least-cost corridor layer is a continuous raster surface, where the lower cost values characterise the most permeable areas for the movement of species as parts of the ecological connectivity routes. In accordance with the nature of continuous raster datasets, the representation and the width of the least-cost corridor changed when I used different classification methods with different number of classes. Therefore, it is important to identify the best classification method and the threshold to determine an optimum corridor width for the least-cost corridors.

Firstly, I classified each of the least-cost corridor models using different classification methods and after my initial examinations I decided to use the geometrical interval classification method with 5 classes. The most important features of the geometrical interval classification method are (1) it provides a comprehensive representation of least-cost corridors and (2) it works well with heavily skewed and not normally distributed data by balancing the differences between the middle and extreme values. Then using the classes break values, I attempted to create binary maps from least-cost corridor models. Because the cost values of resulting least-cost corridors were highly skewed, I used the first three break values as the thresholds to create binary maps. Afterwards, I examined each of these binary corridor maps to determine the optimum width of least-cost corridors. For this purpose, I calculated (1) the percentage of the corridor which is made up by all habitats (core and least suitable), (2) percentage of all habitats that are covered by the corridor and (3) the percentage of the corridor which is made up by all core habitats. When determining the width of corridors, I aimed to include at least all core habitat patches to meet the minimum habitat requirements of the selected species.

After these stages, the width of least-cost corridors for selected species was determined, excluding the binary least-cost corridors for Brown-long eared bat and Leisler's bat. Therefore, for these species I forced the binary least-cost corridors to include the remaining patches of suitable habitats by adding them to the corridor. The details of these procedures can be seen in Chapter 6, page 182.

E. Validation of Parameters Gathered from Experts

The functional connectivity routes for the chosen species are based on very limited input from experts on their habitat requirements and the cost values for their likely movement characteristics. Hence, within the availability of data on each species, I attempted to validate the expert opinions and the output least-cost corridors using the following approaches.

- With regard to the 3 different expert opinions on the habitat requirements of selected 3 reptile species, I assessed the internal consistency of expert estimates by the use of the Cronbach’s alpha analysis in SPSS. The Cronbach’s alpha analysis was conducted in SPSS using the tools of *Analyse, Scale and Reliability Analysis*.
- In order to evaluate and highlight the extent of variations in the least-cost corridor modelling outputs, I varied the original expert opinion values on the habitat suitability and the difficulty of the targeted species’ movement across

different land cover types (cost values) as the input parameters of least-cost corridors. Using an example from each taxon (Skylark, Leisler's bat, Common lizard), I varied the original expert estimations by ±5% and ±20% and used these values as the input parameters of the least-cost corridors. Then, I analysed the change in the least-cost corridor as an indication of the sensitivity of expert opinion values by comparing these models with the original least-cost corridor models for each species.

- The next approach was overlaying the species occurrence data onto my least-cost corridors to validate expert opinions on the habitat requirements of the selected species. Within the availability of the species occurrence datasets which were obtained from the Sheffield City Council Ecology Unit, Recorder 6 species database, I had sufficient grid sized (1 km and smaller) data for Song thrushes, Skylarks and Pipistrelle bats. For each of these species I overlaid their occurrence data and the least-cost corridors in ArcGIS 10.1 and calculated the spatial overlap between the occurrence records and the corridors. In this way, I tested the validity of expert estimations by exploring the affinity of least-cost corridors and real data on the occurrence of these species.
- The final approach was validating the expert estimates on the habitat suitability of different land cover types as the inputs of the least-cost models for the selected bird species. For this purpose, I compared those habitats which I identified on the basis of expert estimates with the published data on relative population densities in different habitats from the British Trust for Ornithology (BTO).

3.2.8.2 Modelling the Networks of Green and Open Spaces for People

This part of the analysis is aimed at modelling functionally connected networks of green and open spaces for people in an urban environment, which would contribute to the movement of people across existing green and open spaces and the surrounding landscape. The main objective here is *to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data* (Objective 2), by addressing the following research question:

1. Can criteria be derived to identify green and open spaces for inclusion in the potential routes of connectivity?
2. What forms do the potential routes of connectivity constructed using these criteria take?

A case study was undertaken within the boundaries of Sheffield, excluding the Peak District National Park. The underlying reasons for the exclusion of the Peak District National Park were (a) to focus on the urban part of Sheffield in order to obtain a functional network of green and open spaces, which contributes to the movement of people by walking, and (b) to avoid the bias and influence of the Peak District Park in the modelling process, as it covers a large area (almost 30% of the whole study area). In order to develop a different approach to model the potential routes of connectivity for people, I used the least-cost corridor modelling approach in which physical / legal accessibility was considered as the main factor in obtaining the functional networks of green and open spaces. I also took into consideration the effects of slope on the movement of people by walking. Since people may use green and open spaces to access different destinations, the following potential routes were modelled to provide functional movement routes for people by walking from residential buildings to (1) publicly accessible green and open spaces, (2) industrial / commercial units and (3) public buildings. As a result, for each of these potential routes I obtained two different least-cost corridor models, where the first ones developed on physical / legal accessibility, and the second ones developed on the basis of both physical / legal accessibility and the effects of slope on the movement of people. In this way, I attempted to explore the potential for alternative ways of defining functionally connected networks of green and open spaces for people as well as highlighting the differences and similarities between the structural components of these networks.

The following sections explain the procedure of the least-cost corridor approach that was applied to delineation of the networks of green and open spaces for the movement of people.

A. ***Preparation of Study Area and Land Use Map Manipulation***

As mentioned earlier, the previously created land use map, which includes 49 land use classes, was used as the main dataset for the analysis. However, as it covers the whole of Sheffield, I cut out the areas included in the Peak District National Park. Then, I proposed the potential components of the green and open spaces network including the following land use categories: *Allotments, Cemeteries and Churchyards, Parks and Gardens, Provision for Children and Young People, Amenity Green Spaces, Natural and Semi-natural Greenspaces, Outdoor Sport Facilities, Roadside Vegetation, Railway Vegetation* and *Inland Water*. Then, I attempted to identify the publicly accessible green and open spaces within these land uses based on the Sheffield City Council (SCC) accessible green and open spaces layer. After determining physically / legally accessible green and open spaces, I aggregated the remaining land use classes into a broader land use category to reduce unnecessary time consumption for the modelling process. The final land use map is composed of 30 land uses, in which all green and open spaces that are definitely accessible were identified.

B. ***Preparation of Source, Cost and Cost Distance Layers***

As mentioned in the previous sections, a least-cost corridor requires two cost distance layers which are developed on the basis of two source layers and a cost layer. The source layers were directly extracted from the final land use map to model the connectivity routes between abovementioned destinations including: *Residential Buildings*, *Publicly Accessible Green and Open Spaces*, *Industrial and Commercial Units*, and *Public Buildings*. Here, it is important to note that the layer of *Residential Buildings*, as the starting point of people's movement, was used as the first source layer for each of the potential connectivity routes.

Within the scope of this research, I generated two cost layers using the final land use map. For the first cost layer, I took into account the effect of each land use type in terms of their public accessibility to support the movement of people. For the second cost layer, besides the effects of each land use type to support public accessibility, I also combined the effects of slope. In order to generate the first cost layer, I determined cost values based on a set of rules for each land use type in terms of their permeability to support the movement of people between *Publicly Accessible Green and Open Spaces*. For this purpose, I assigned a score to each land use type where lower cost values correspond to higher permeability (or accessibility) for the movement of people by walking and developed the land use cost layer.

On the other hand, for the second cost layer I created the slope map for the urban part of Sheffield using Ordnance Survey Terrain 50m dataset. Then, I determined the effects of slope on the ease movement of people by walking based on the "Inclusive Mobility" document (Department for Transport, 2005). Accordingly, I reclassified the slope map into 4 classes and assigned a cost value for each of the slope classes to generate the slope cost layer. The final stage of generating the second cost layer was combining the land use and slope cost layers into a single layer by weighting them according to their influence on the movement. The primary concern of the present analysis was the effects of public access to green and open spaces on the movement. Therefore, I combined the land use cost layer and slope cost layer by giving an influence weight of 66% and 34%, respectively (see details in Chapter 6, page 232). Once source and cost layers were created, I generated 12 cost distance layers to model 6 least-cost corridors, as the potential connectivity routes for people. Within these, the first two cost distance layers were used for the delineation of the first least-cost corridors only considering the effects of the public accessibility of each land use type, whereas the third and fourth cost distance layers were used for the delineation of second alternative least-cost corridors in which both the public accessibility and the effects of slope were taken into account.

Between *Residential Buildings* (Source Layer 1) and *Urban Green and Open Spaces* (Source Layer 2):

- The first and second cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 1 (land use cost layer).
- The third and fourth cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 2 (land use and slope cost layer).

Between *Residential Buildings* (Source Layer 1) and *Industrial / Commercial Units* (Source Layer 2):

- The first and second cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 1 (land use cost layer).
- The third and fourth cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 2 (land use and slope cost layer).

Between *Residential Buildings* (Source Layer 1) and *Public Buildings* (Source Layer 2):

- The first and second cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 1 (land use cost layer
- The third and fourth cost distance layers: from Source Layer 1 to Source Layer 2 and from Source Layer 2 to Source Layer 1 over the Cost Layer 2 (land use and slope cost layer).

C. *Modelling least-cost corridors and determining the optimum corridor width*

As mentioned, I created 6 different least-cost corridors for the movement of people using different parameters. Afterwards, I attempted to determine the optimum thresholds and the width of each corridor. Using a similar method as I used for the potential routes of connectivity for species, I reclassified each least-cost corridor based on the geometrical interval classification method with 5 classes. Then, I examined each of the green and open spaces networks in terms of their strength to provide sufficient connections between the intended starting points and destinations, spatial coverage and the feasibility of created networks in an urban context. Overall, the least-cost corridor analyses allowed me to develop different potential connectivity routes for selected species and people based on a functional perspective compared to the previous landscape structural analyses. The outputs of the least-cost corridor analyses highlighted the differences and similarities in the spatial structure of different networks by the use of different parameters. The output maps also revealed the importance of some types of land uses in terms of their potential contribution to a multifunctional network by providing functional connections for both species and people, such as *Roadside Vegetation*.

3.2.9 Comparing and Contrasting Existing Green / Ecological Networks with Proposed Connectivity

The final analysis part had the aim of finding out the differences and similarities of different ways of defining / planning connectivity routes for people, and investigating the possibilities for improving the connectivity in urban areas considering potential habitat use by organisms and / or accessibility to the public. The main objective of this part was to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice (Objective 3).

1. Do the derived routes of potential connectivity and accessibility coincide with each other and the actual green and ecological networks?

2. How does the landscape matrix complement or detract from the potential routes of connectivity and what are the best possibilities for improving the functionality of connectivity in urban areas considering potential habitat use by organisms and / or accessibility to the public?

3. Considering the space limitations in urban landscapes, are some types of land uses and morphologies more compatible with the potential routes of connectivity. If so, how can we measure their compatibility?

Part 2 Study Area, Data Sources and Data Preparation for Analyses

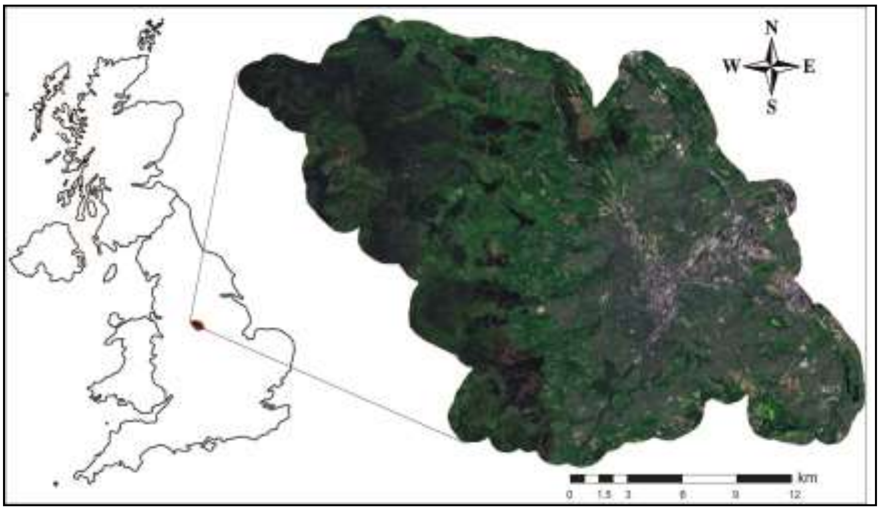
The second part of this chapter describes the study area, data sources and the preparation of the datasets used in this research. As stated, the main purpose of this thesis is to examine different ways of defining green and ecological networks and their functionality for biodiversity and people in an urban context and the relative strengths and weaknesses of the various approaches. Accordingly, a case study approach was used:

1. to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes (Objective 1),
2. to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data (Objective 2),
3. to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice (Objective 3).

The broad use of the term case study is sometimes equated with an empirical inquiry (Yin, 1994). In a broad landscape architecture context, a further definition has been given by Francis (2001), who describes a case study as "*a well-documented and systematic examination of the process, decision-making and outcomes of a project, which is undertaken for the purpose of informing future practice, policy, theory, and/or education*". Case studies have been widely used in landscape research in order to inform underlying theory and practice through detailed analysis of real life situations. Yin (1994) underlines the value of case studies to identify the characteristics of real life situations in an integrated and meaningful way. In the general sense, case studies can adopt various research methods, either single or multi method approaches (Francis, 2001). In the context of this research, I adopted a single case approach to critically analyse and understand the relationships between ways of defining green and ecological networks and their functioning for biodiversity and people in a specific urban context.

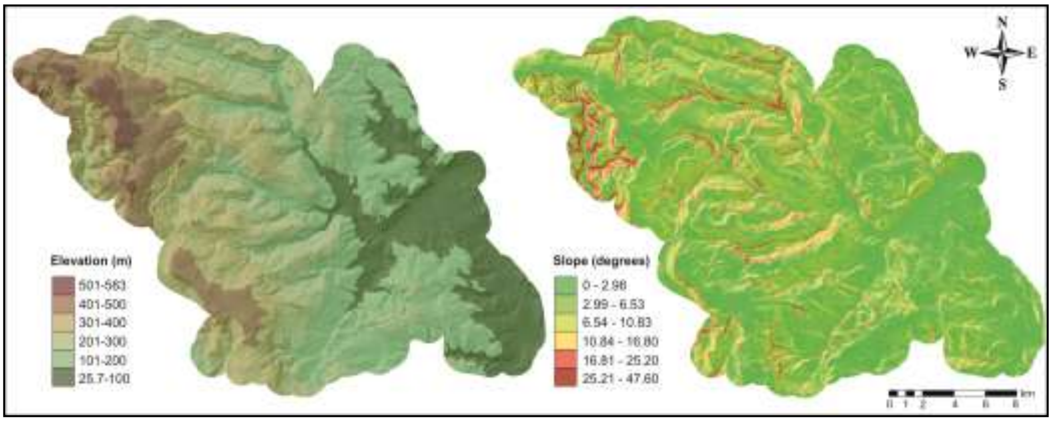
3.3 Description of the Study Area

Sheffield, the case study area, is located in the county of South Yorkshire (53°23´N, 1°28´W) with an area of 36,794 ha. However, the results of landscape metrics are affected by the boundaries of the study area. If the selected boundaries split a land cover / use type into pieces or if the same land cover / use categories are not included within boundaries, then the area and connectivity metric may not reflect the actual structural characteristics for these land cover / use categories. Also, the results of the least-cost corridor analyses can be affected by the relationships between neighbouring habitat patches. Therefore, in order to obtain more accurate results for structural connectivity analyses, I extended the administrative boundaries of Sheffield by 1km (Map 2).



Map 2: Study area

In this way, the case study area included the proportions of the same land cover / use types along the administrative boundaries beside the other neighbouring land cover / use types. By extending the case study area by 1km, I obtained a total area of 48,527 ha. Sheffield is the third largest municipality in the UK with an estimated population of 560,085 people in mid-2013 (ONS, 2013). As being geographically diverse and one of the greenest cities in the UK, Sheffield is composed of a wide variety of habitats (SCC, 2014a). Sheffield is situated in a natural basin surrounded by seven hills (Winkler, 2007) and within the valleys of the rivers Don, Loxley, Porter Brook, Rivelin and Sheaf. The urban area of Sheffield is generally surrounded by agricultural areas, and natural and semi-natural lands. The urban settlement is mainly concentrated in the south east part of the study area, particularly alongside the main rivers where the altitude is the lowest (25.7m-100m). The agricultural activities are broadly distributed between the altitudes of 100m-300m. Examination of the steepness of those areas reveals that, apart from riverbeds, the slope lies between 0 and 10.83 degrees. On the other hand, the west part of the study area, where a portion of the Peak District National Park is included, has the highest altitude and the steepest slopes (Map 3).



Map 3: Elevation and slope in the study area

3.4 Land Cover / Land Use Classification Schemes and Data Sources

The main data used in this research, as environmental variables were land cover and land use datasets. Therefore, the first step of this research is concentrated on the design of a three level, flexible land cover and land use classification systems. Land cover and land use reflects different aspects of the landscape. However, in practice it is generally conflated, resulting in ambiguous classifications (McConnell and Moran, 2001). Therefore, it is fundamental to make a clear distinction between these. Land cover refers to the directly observable biological and physical (biophysical) land surface, whereas land use indicates the purposes for which the land is used by people (FAO, 2000; Jansen and Gregorio, 2002; Fisher et al., 2005; Lambin et al., 2006; Haines-Young, 2009; Verburg et al., 2009). Some land cover types may have a single use, but most have multiple uses. Similarly, some land use types may appear in a single land cover type, whereas some may be part of multiple land cover types. For example, the broadleaved woodland land cover could be managed for recreation or for both recreation and wood production.

3.4.1 Development of Land Cover and Land Use Classification Schemes

Land cover and land use classifications should be suitable for the purpose and requirements of the research. There are many classification systems and most of these existing systems are a combination of land cover and use information. However, because land cover and use reflect different aspects of an area, they should be evaluated individually - especially where we focus on the ability of a landscape to deliver different benefits for biodiversity and the public.

In this study the land cover and use classes and their definitions were initially based on National Land Use Database (NLUD-Version 4.4) classification schemes, and then developed and detailed according to available data sources. Based on the main aim of this research, a three-level hierarchical classification typology was generated and applied to both land use and cover, in which each level represents different land cover and land use categories including information ranging from general to the more detailed.

The land cover classification scheme represents 4, 10 and 34 classes at level 1, 2, and 3, respectively (Table 2, see Appendix 1 for the explanations and Appendix 2 for land cover maps). On the other hand, the land use classification scheme demonstrates 4, 11 and 49 land use classes at level 1, 2, and 3, respectively (Table 3, see Appendix 3 for the explanations and Appendix 4 for land use maps).

Table 2: Land cover classification scheme

Land Cover Classes			
Level 1	**Level 2**	**Level 3**	
LC100 Vegetation	LC110 Woodland and Shrub	LC111	Conifer Woodland
		LC112	Broadleaved Woodland
		LC113	Mixed Woodland
		LC114	Shrub
		LC115	Felled
		LC116	Young Trees
	LC120 Mixed Vegetation	LC121	Roadside Vegetation
		LC122	Railway Vegetation
		LC123	Private Gardens
		LC124	Other Landscaped Areas
	LC130 Grasslands	LC131	Improved Grassland
		LC132	Unimproved Acid Grassland
		LC133	Unimproved Neutral Grassland
		LC134	Amenity Grassland
		LC135	Rough Grassland
	LC140 Heathlands	LC141	Heather
		LC142	Heather Grassland
	LC150 Cultivated Land	LC151	Arable
		LC152	Orchard
LC200 Surfaces	LC210 Bare Surfaces	LC211	Derelict Vacant Unused Land
		LC212	Inland Rock
	LC220 Constructed Surfaces	LC221	Metalled Roads
		LC222	Paths and Pavement
		LC223	Tracks
		LC224	Railway
		LC225	Paved Surfaces
LC300 Water and Wetlands	LC310 Water	LC311	Standing Water
		LC312	Running Water
	LC320 Wetlands	LC321	Heath Dominated Bog
		LC322	Grass Dominated Bog
		LC323	Marsh Reeds and Saltmarsh
LC400 Buildings and Structures	LC410 Residential and Non- Residential	LC411	Single Structures
		LC412	Connected Structures
		LC413	Mixed Structures

Table 3: Land use classification scheme

Land Use Classes			
Level 1	**Level 2**	**Level 3**	
LU100 Artificial	LU110 Residential Buildings	LU111	Dwellings
		LU112	Institutional Accommodation
		LU113	Communal Accommodation
	LU120 Public Buildings	LU122	Institutional Buildings
		LU123	Educational Buildings
		LU124	Religious Buildings
		LU125	Leisure and Recreational Buildings
		LU126	Medical Buildings
		LU127	Community Buildings
	LU130 Industrial and Commercial Units	LU131	Retailing
		LU132	Offices
		LU133	Industry
		LU134	Storage and Warehouse
	LU140 Other Buildings and Structures	LU141	Mixed Use Buildings
		LU142	Other Buildings
		LU143	Derelict Vacant Unused Buildings
	LU150 Sealed Surfaces	LU151	Residential Sealed Surfaces
		LU152	Public Buildings Sealed Surfaces
		LU153	Industrial Units Sealed Surfaces
		LU154	Other Buildings and Structures Sealed Surfaces
	LU160 Transportation and Utilities	LU161	Highways and Road Transport
		LU162	Pavement
		LU163	Railways
		LU164	Paths
		LU165	Tracks
		LU166	Airports
		LU167	Transport Terminals and Interchanges
		LU168	Open Car Parks
		LU169	Utilities
LU200 Natural and Semi-natural Land	LU210 Recreation and Leisure	LU211	Allotments
		LU212	Amenity Greenspaces
		LU213	Cemeteries and Churchyards
		LU214	Outdoor Sport Facilities
		LU215	Parks and Gardens
		LU216	Natural and Semi-natural Greenspaces
		LU217	Provision for Children and Young People
		LU218	Countryside / Urban Fringe
	LU220 Mixed Vegetation	LU221	Roadside Vegetation
		LU222	Railway Vegetation
		LU223	Private Gardens
LU300 Agriculture and Open Lands	LU310 Agriculture	LU311	Agricultural Land
	LU320 Open Land	LU321	Refuse Disposal
		LU322	Mineral Workings and Quarries
		LU323	Derelict Vacant Unused Land
LU400 Water	LU410 Inland Water	LU411	Lakes and Ponds
		LU412	Reservoirs
		LU413	Canals
		LU414	Rivers and Brooks
		LU415	Dams

The generated land cover and use maps have cross references to each other, where the land cover map includes some land use types and vice versa. For example, in the land cover classification scheme, *Mixed Vegetation* and its sub-classes, excluding *Other Landscaped Areas*, corresponds to the land use classes of the same name.

3.4.2 Data Sources

Identification of land cover and use classes, and mapping of these and the extent of the whole landscape, was carried out in Sheffield, with the aim of defining boundaries and the landscape structure in the research area. The baseline data source for land cover and land use mapping processes was the Ordnance Survey MasterMap Topography Layer. Whilst the MasterMap Topography layer polygons were used to define each land cover / use polygon, other data sources were used to assign relevant land cover / use information to each polygon.

3.4.2.1 Ordnance Survey MasterMap Topography Layer

Within the Ordnance Survey (OS) MasterMap Topography layer, real world features are represented as points, lines and polygons. In order to define each land cover and land use map polygon, Master Map Topography area polygons were used. Polygon features are represented as "Topographic area", in which each MasterMap polygon is described by a number of attributes, including theme, descriptive group, descriptive term and make (Table 4).

Table 4: An example of the attributes table for a polygon record in MasterMap Topography layer

Legend	Theme	Descriptive Group	Descriptive Term	Make
0321 Archway	Buildings	Building	Archway	Man-made
0321 Building	Buildings	Building	--------	Man-made
0000 Track	Roads Tracks and Paths	Road or Track	Track	Natural

- Theme: Represents feature- referencing attributes, where one or more of the following features can be found: Administrative boundaries, Buildings, Heritage and antiquities, Land, Rail, Roads, Tracks and Paths, Structures, Terrain and height, and Water.

- Descriptive Group: As the primary classification of a feature, it represents the descriptive attribute of a polygon, such as Road or Track, Building, Structure or General Surface.
- Descriptive Term: If present, it is the further classification of a feature after the descriptive group. Whilst most of the features have one or no descriptive term, some features are assigned to multiple descriptive terms.
- Make: This attribute represents whether a polygon is "Man-made" or "Natural".

These attributes were used as the baseline information in land cover and use mapping processes for the initial classifications. Then, each polygon was assigned to an appropriate land cover / use type, using the information obtained from the following data sources.

3.4.2.2 Ordnance Survey AddressBase Plus

The OS AddressBase Plus Point dataset provides detailed information on current properties and addresses in which the Royal Mail's Postcode Address File (PAF) and Local Authorities data are combined. Within the OS AddressBase Plus dataset, whilst the PAF includes postal addresses for delivery points, the Local Authority data is composed of addresses that are not contained in PAF addresses.

The OS AddressBase Plus allows users to get a more detailed classification of each property (e.g. dwelling, retail, industry etc), as well as enabling the cross reference to the OS MasterMap features through their topographic identifiers (TOIDs: a unique 16 digit reference identifier). Therefore, the OS AddressBase Plus dataset is used in the land use mapping process to associate MasterMap buildings/structures and some of the land polygons with an appropriate use type by examining the information presented within the OS AddressBase Plus Point fields.

3.4.2.3 Centre for Ecology and Hydrology- Land Cover Map 2007

The Land Cover Map 2007 (LCM2007) is a satellite imagery-derived, vector-based land cover map. The dataset is provided as polygons, where each polygon has a list of attributes attached to it comprising: parcel ID, broad habitat (BH), broad habitats sub-classes (BHSub), Field Code, area, source images and processing details.

The land cover classes in the LCM2007 dataset were obtained by aggregating the broad habitat sub-classes. Within the LCM2007, the minimum mappable area is larger than 0.5ha. The LCM2007 includes 23 land cover classes based on the UK's terrestrial Broad Habitats (Jackson et al., 2000 in CEH, 2011). In order to assign the relevant land cover type, broad habitat and broad habitat subclass attributes were used.

I used the LCM2007 land cover classes and broad habitat subclasses together in order to determine their composition in MasterMap polygons, which could not be classified using only MasterMap data at the initial classification stage. LCM2007 is mainly composed of 13 land cover classes, which are further split into 23 broad habitat sub-classes within the boundaries of Sheffield (Table 5).

Table 5: LCM2007 classes and broad habitat subclasses for LCM2007 (in the boundaries of Sheffield)

LCM2007 class	**LCM2007 broad habitat sub-classes**
Broadleaved Woodland	Deciduous Mixed Scrub
Coniferous Woodland	Conifer Conifer Felled Arable Bare
Arable and Horticulture	Arable Unknown Orchard
Improved Grassland	Improved Grassland
Rough Grassland	Rough / Unmanaged Grassland
Neutral Grassland	Neutral Grassland
Acid Grassland	Acid
Heather	Burnt Heather Heather and Dwarf Shrub
Heather Grassland	Heather Grass
Bog	Bog-Grass Dominated Bog-Heather Dominated
Inland Rock	Despoiled Land
Freshwater	Water Lake Water River
Urban	Bare Urban Urban Industrial

3.4.2.4 Forestry Commission National Inventory Woodland and Trees Layer

The Forestry Commission National Inventory consists of two different parts: the survey of woodlands of 2ha or more, and the survey of small woodlands and trees covering an area of less than 2ha (the groups of trees, belts of trees and individual trees). The main attributes found in this dataset are Reference Date, Interpreted Forest Type (IFT) and Tile Name.

IFT is composed of Broadleaved Woodland, Coniferous Woodland, Mixed Woodland, Shrub, Young Trees and Felled Trees. Therefore, the IFT attribute was used in the determination of Woodland and Trees land cover sub-classes as well as assigning some land use sub-classes of *Natural and Semi- natural Land*.

3.4.2.5 Sheffield City Council Green and Open Spaces

This dataset was obtained from the Sheffield City Council, Parks and Countryside Service- audit of Open Space, Sport and Recreational facilities (PPG17, 2008). The vector-formatted dataset is composed of open spaces, sport and recreation sites across Sheffield.

The attributes attached to this layer are: Site ID, Site name, Typology, Typology0, area and perimeter. Under the Typology attribute, the following open space, sport and recreational facilities are included: *Parks and Gardens, Natural and semi-natural Greenspaces, Outdoor sports facilities, Amenity Greenspaces, Provision for Children and Young People*, *Allotments, Cemeteries and Churchyards* (PPG17, 2008). These were assigned to MasterMap Topography Layer polygons to derive associated Recreation and Leisure facilities.

3.4.2.6 Other Datasets

The following data sources are mainly used for providing additional information for land cover / use mapping and for the validation of these maps. The first additional layer was the Ordnance Survey, 1:10 000 scale colour raster dataset. This layer is used to check and compare layers where there is little or no information in

MasterMap layers for land cover / use mapping processes (e.g. Unknown / Unclassified).

The second layer was the Cities Revealed & UK Map Datasets-Modern Aerial Photography (2009) which was obtained from LandMap. Modern Aerial Photography is a tiff formatted high resolution aerial photography with 0.125X0.125 cell size. The Modern Aerial Photography (2009) was used as the control dataset for the validation of generated land cover and land use maps.

3.5 Land Cover Dataset Preparation

3.5.1 Land Cover Classification Procedure

The land cover classification scheme developed for this research is designed to include as many categories with the highest detail of information and reasonable accuracy as possible, within the availability and quality of source datasets. Hence, after the initial classification of MasterMap (24 categories), I used Land Cover Map 2007 (LCM2007) and National Inventory Woodland and Trees (NIWT) data sources in an attempt to classify the unclassified polygons or, if further detail was required, for the delineation of land cover classes at level 3.

The ArcGIS10 Intersect Tool was used to determine the composition of the different categories of LCM2007 and NIWT layers in MasterMap polygons. Initially, each unclassified MasterMap polygon was assigned an attribute that comes from the intersection with LCM2007. In this way, I obtained most of the land cover categories at level 3. Then, to delineate the subclasses of *Woodland and Shrub* at Level 2, I used the National Inventory Woodland Trees vector dataset. The *Woodland and Shrub* at Level 2 broad land cover class was further reclassified by splitting it into subclasses at Level 3, using the attributes from the National Inventory Woodland Trees vector dataset.

After intersecting MasterMap polygons with LCM2007 and National Inventory Woodland Trees datasets, there were still some of polygons that were not classified. So, after building a mosaic dataset from Modern Aerial Photography (0.125x0.125m cell size), I clipped and classified the remaining polygons. For this purpose, I used

ArcGIS 10.1, the *Image Classification* and *Maximum Likelihood Classification Tool*. Initially, all remaining polygons clipped from the imagery were classified into 2 classes according to their reflection value of pixels (as vegetation and no vegetation). Then, running the *Zonal Statistics* tool, I found the majority of cover within the remaining unclassified polygons. All areas with a vegetation cover were classified under “Other Landscaped Areas”, since they are generally located around buildings and structures and have different characteristics from private gardens and other mixed vegetation areas. On the other hand, polygons with no vegetation were classified under the “Paved Surfaces” land cover category.

3.5.2 Land Cover Map Validation

I utilised an accuracy assessment for the generated land cover map by comparing reference points and the categories of the land cover map. Initially, I created 2.5 x 2.5 km sized grids using *Fishnet Tool* in ArcGIS 10.1. Following this, the *Sampling Design Tool* for ArcGIS is used to generate randomly stratified points for the assessments. While the random stratification process creates randomly placed points within the sub-areas of a landscape (representing each land cover class), it prevents biases in the sample and facilitates the generalisation of findings to a wider population.

Each land cover class is identified by choosing "Description_3" attribute at level 3 in the sample frame and, in this way, all polygons with the same Description_3 attribute are classified under the same strata. For the allocation of points among each class/strata, the total number of points is set proportional to the area of each stratum. Here, larger classes got more points in comparison with smaller classes.

Additionally, each stratum is set to include a minimum of 3 randomly allocated points to make sure that each class is represented in the sample. In total, 770 points were allocated in the land cover map. Here, I used Modern Aerial Photography-2009 as the control dataset for the validation process. Each point within created grids were checked by eye on the aerial photography and recorded on an excel spread sheet plot by plot to avoid confusion.

Then, developing an error matrix, I calculated the accuracy of the whole land cover map. In addition to overall (total) accuracy, the accuracy of each individual class was calculated in terms of user's and producer's accuracy. The user's accuracy refers to the probability of a point classified into a given land cover/use class actually representing the same land cover / use class on the ground. On the other hand, the producer's accuracy indicates the probability that a land cover (or use) category is correctly mapped.

Accuracy assessment is a crucial part of land cover / use mapping processes, as it provides the evaluation of the quality and reliability of produced maps. The land cover classification and typology are validated on an error matrix, which is generated by random stratified sampling points within the test object areas. The error matrix demonstrates the comparison of the same sites in the ground and acquired land cover/land use class on the map. While the accuracy for different land cover classes varied, the results showed that the overall classification accuracy for the land cover was 94.81%.

3.5.3 Final Land Cover Map

The most important challenge during the land cover mapping process was the differences in the structure and level of detail of data sources, which caused some spatial errors in the reclassified land cover map. For example, as a result of intersection analysis, some polygons became fragmented. However, after the classification process, these polygons were corrected on the basis of the spatial composition of the classified polygons and their relationships with neighbouring polygons.

The final land cover map includes 4 main classes at level 1, 10 subclasses at level 2, and 34 land cover subclasses at level 3 (see Appendix 2). The most significant benefit of this new land cover map is being able to represent smaller areas of land and borders between different land cover types more accurately than the existing LCM2007. Also, the three level hierarchical structure of the generated land cover map enables ecological connectivity analysis at different levels of detail.

3.6 Land Use Dataset Preparation

3.6.1 Land Use Classification Procedure

The first step of the land use mapping procedure is the initial classification of the MasterMap Topography layer. Then, each polygon associated with different land use categories were defined by the intersections of multiple data sources. I obtained most of the land use information from the MasterMap Address Base Plus layer, especially for the uses of buildings and structures. The relationship between OS MasterMap Topography and Address Base Plus layers are set by their unique reference identifiers (TOIDs). In order to delineate the sub-classes of *Recreation and Leisure* at level 3, the Sheffield City Council Green and Open Spaces layer was used. This layer only represents publicly accessible green and open spaces, and so does not includes *Amenity Greenspaces* and *Natural* and *Semi-natural Greenspaces* in private ownership. Hence, some additional areas of *Amenity Greenspaces* and *Natural* and *Semi-natural Greenspaces* in were identified using OS 1:10000 scale colour raster dataset and the land cover map. Then, the additional areas of *Amenity Greenspaces* and *Natural* and *Semi-natural Greenspaces* were added to the corresponding land use types. The OS 1:10000 scale colour raster dataset and the developed land cover map were also used to help assign land use sub-types of *Agriculture*, *Open Land*, and *Inland Water* categories.

3.6.2 Land Use Map Validation

In order to determine the accuracy of the land use map, the same process was applied as in the land cover validation. I generated 991 randomly stratified points for the accuracy assessment. For the validation of the land use map, I mainly used Modern Aerial Photography and OS 1:10000 scale colour raster datasets. The land use map was found to have an overall accuracy of 94.95%.

3.6.3 Final Land Use Map

During the land use mapping process, the inconsistency in data sources, both in resolution and accuracy, raised the problem of spatial errors of the type that occurred during the land cover mapping. Additionally, some of the AddressBase Plus points are not positioned precisely and most of the polygons in MasterMap Topography layer are split into adjacent features (e.g. roof overhang, steps). Therefore, as a first step, polygons containing address points were selected and classified. Then using the *Select by Location* tool, remaining polygons (ie. those do not contain AddressBase Plus points), were assigned to the nearest land use class. In this way, all polygons were classified under an appropriate land use category. The final hierarchical land use map includes 4 broad land use categories at level 1, each includes one or more detailed land use category. These 4 land use categories split into a further 11 and 49 land use sub-types at level 2 and level 3, respectively (see Appendix 4). The main advantage of this land use map is providing detailed land use categories at a fine spatial scale with the flexibility of representing landscape heterogeneity at different levels.

3.7 Summary

This chapter has outlined the overall research strategy, research methods and the justification for their use in the context of this research project. Also it provided the details of the case study area, main data sources and their use in the creation of the necessary land cover and land use maps for the spatial analyses. The next chapter provides an in-depth analysis of the "Green Network" planning policy background prior to the examination of current green and ecological network approaches in Sheffield.

Chapter 4 Examination of Current Green and Ecological Network Approaches

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4.1 Introduction

In the previous chapter, I introduced the general methods used for this research and described the study area and various datasets used in the analyses. This chapter now focuses on the examination of existing green and ecological network approaches in Sheffield. The main objective of this chapter is "*to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes"*. In line with this objective this chapter aims to address the following questions:

1. How are ecological and green networks defined in Sheffield at present?
2. How are the spatial components of the actual green and ecological networks identified?
3. What are the differences (if any) between the ways of defining the objectives and spatial coverage of these networks?

4.2 Methods

The green and ecological network approaches in Sheffield have been developed and supported both by governmental bodies and non-governmental organisations. There are two main network approaches in Sheffield: the Green Network developed by Sheffield City Council (SCC) and the Living Don ecological network developed by the Sheffield and Rotherham Wildlife Trust (SRWT).

Prior to examination of the existing green and ecological network approaches, I analysed the prevailing planning policy documents to obtain a clear understanding of the evolution of the Sheffield Green Network. These planning policy documents are the Sheffield Nature Conservation Strategy (SNCS- 1991), the Sheffield Unitary Development Plan (UDP- 1998) and the Sheffield Local Plan (SLP- 2013).

The SRWT's Living Don ecological network project and associated map was originally developed on the basis of the original area of the Living Don, which was identified within the *Regional Biodiversity Opportunity Areas Map* by the Yorkshire and Humber Biodiversity Forum in 2009 (YHBF, 2009 in Rivers, 2013a).

In order to obtain a deeper understanding of the underlying rationale for these network approaches, I held semi-structured interviews with two officers in the SCC Ecology Unit and Forward and Area Planning Team and one officer in the SRWT respectively. Additionally, I analysed the planning policy documents in order to understand the evolution of the Green Network in Sheffield. The semi-structured interviews were conducted around the main themes set out below:

- policy background, and aims of the green and ecological networks in Sheffield,
- application of the Green Network policy, and
- site selection criteria and the main features of green and ecological networks (see Appendix 8 for the interview questions).

The prospective participants in this research project were identified based on whether they are concerned with planning and supporting biodiversity in Sheffield, and whether they have been involved in the process of planning green/ecological networks in Sheffield. In terms of the semi-structured interviews, I had a predefined series of questions to which I was seeking the answers and I took those answers at their face value. The semi-structured interviews were recorded on a digital audio recorder with the consent of the interviewees and transcribed. The transcript of the interviews were analysed deductively and the pre-determined research themes were extracted, organised and examined. In addition, using their digital maps and associated documents, I examined the spatial components and extent of the proposed networks to reveal the relationships between these network approaches.

4.3 Policy Document Analysis

4.3.1 Sheffield Nature Conservation Strategy (SNCS-1991)

Regarded as one of the greenest cities in the UK, Sheffield has always been a remarkable case, in the sense that it was ahead of its time, both because of the Abercrombie's plan and the early Nature Conservation Strategy. Sheffield was one of the only local authorities that had a variety of planning policies for green networks and a green network plan in the 1990s (Punter and Carmona, 1997).

The Sheffield Nature Conservation Strategy (SNCS) was published in 1991, as a local response to the growing concern for the quality of the natural environment, in which a green network approach has been developed as a comprehensive strategic framework. The Strategy made land use policies for the City of Sheffield excluding the area of the Peak District National Park, since it was under the responsibility of the Peak Park Joint Planning Board.

The aim of the Nature Conservation Strategy was "*to protect and enhance Sheffield's natural heritage and promote its enjoyment by the public*" (Bownes et al., 1991). Within the scope of the strategy, one of the objectives explicitly references a network approach by stating "*to establish a network of green spaces and wildlife corridors throughout the city*" (Bownes et al., 1991). Therefore, the original Green Network policy and the development of Sheffield's Green Network is grounded on the Nature Conservation Strategy.

The Green Network policy of the SNCS, NCS 13 (P), is located under Chapter 5 (Problems and Opportunities- the Council's Policies for Nature Conservation) and the section entitled "Enhancing the Green Network". The components of the Green Network are Green Corridors, Green Links and Desired Green Links (Box 1). The Green Network policy of the SNCS can be seen in Box 2.

Box 1. The associated terminology for the Green Network

Green Corridors form a strategic network linking up important habitats in the countryside and in the built up areas. They are significant wildlife areas in their own right as well as facilitating migration and movement between important sites. Green corridors coincide with the main rivers in Sheffield and open spaces between large green areas.

Green Links are narrower than green corridors, often appearing as thin linear features on the ground. They include railway embankments, road verges along main roads such as the Parkway and important paths in the city. They are often important routes for the movement of people as well as wildlife.

Desired Green Links indicated areas where wildlife and recreation would be enhanced by the creation, as opportunities arise, of a physical link between existing green space.

Box 1: The associated terminology for the Green Network

Box 2. The Green Network policy in the SNCS

NCS 13 (P) The network of Green Corridors and Green Links (shown on the proposal map) will generally be:

(A) Protected from development which would detract from their predominantly green and open character;

(B) Enhanced by encouraging development and land management changes which increase their wildlife value; and

(C) Extended by seeking to create new green space in the areas of Desired Green Links.

Box 2: The Green Network policy in the SNCS

In general terms, we can suggest that the SNCS has an integrated approach to the Chapter 4 Green Network as one of the first pieces of nature conservation policy that recognised the value of urban nature, as opposed to remnant bits of habitat or ex urban nature. However, the use of term "generally" in the introductory sentence of the policy NCS 13 (P) reflects uncertainty for multiple land use planning practices and poses a very serious threat to nature conservation.

4.3.2 Sheffield Unitary Development Plan (1998)

The SNCS was replaced by the Unitary Development Plan (UDP) in 1998, and the Green Network policy was then incorporated into the UDP under the Chapter of

"Green Environment Policies and Proposals", and the section of "Greening the City" (SCC, 1998).

The purpose of the Green Environment chapter was to accommodate development alongside nature conservation. In the general sense, the definitions of Green Corridors, Green Links and Desired Green Links in the UDP are very similar to the SNCS with a few differences in their wording and emphasises. For example, Green Belt was particularly mentioned as part of Green Corridors in the UDP, whereas in the SNCS the main rivers in Sheffield were referred. Box 3 represents the GE10 Green Network policy in the UDP.

Compared to the SNCS, we can claim that the Green Network policy in the UDP was strengthened and clarified both in terms of its wording and structure. The removal of the word "generally" from the introductory sentence in the Green Network policy of the UDP makes this statement stronger and clearer compared to SNCS by eliminating the subtle ambiguity in this expression (Lee, 2007).

Box 3. The Green Network Policy in the UDP

GE1O GREEN NETWORK

A Network of Green Corridors and Green Links will be:

(a) protected from development which would detract from their mainly green and open character or which would cause serious ecological damage; and

(b) enhanced by encouraging development which increases their value f or wildlife and recreation; and

(c) extended by creating new open space in areas of Desired Green Links.

Box 3: The Green Network Policy in the UDP

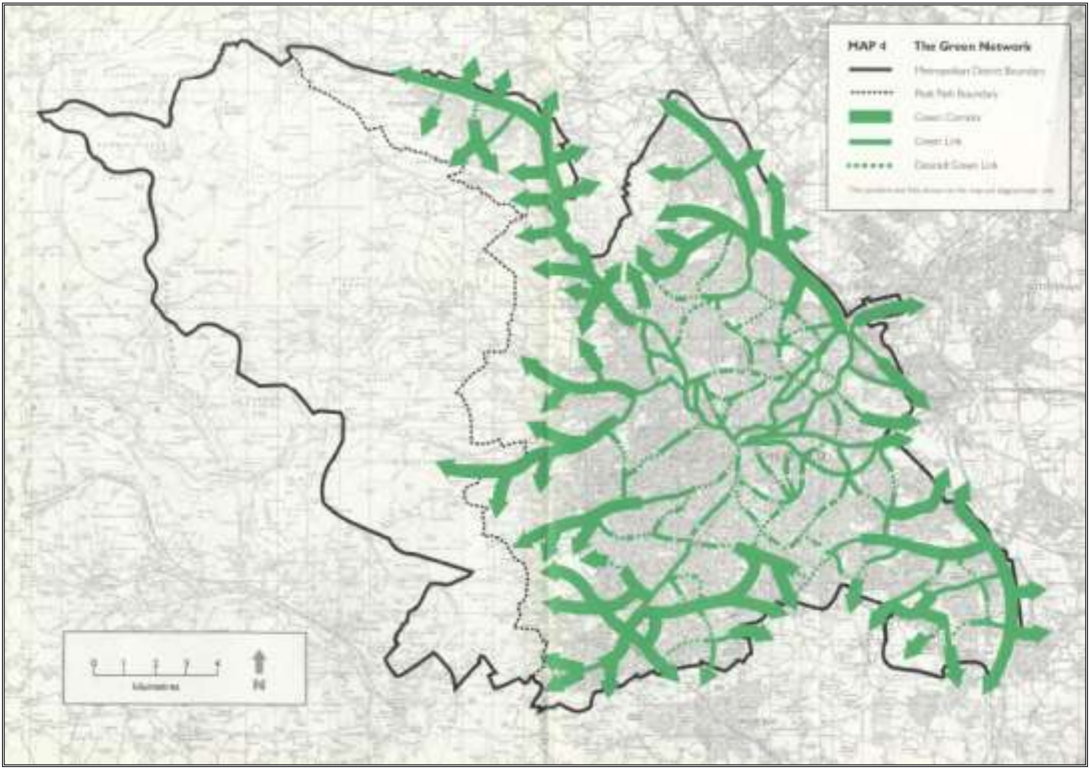
The specific changes in the Green Network policy of the UDP can clearly be seen in its sub clauses. In the sub clause (a) of the UDP, the insertion of the expression "which would cause serious ecological damage" extends the scope of nature conservation against development applications that would affect open and green spaces and decrease their value for wildlife and recreation. Moreover, the use of "recreation" in the sub clause (b) of the UDP emphasises the importance of multifunctionality for the Green Network. In addition to this, although the expression "land management changes" was removed from this sub clause, it was mentioned under how this policy will be put into practice by stating that "Encouraging developments and land management changes which enhance the ecological, recreational and amenity value of open space and the countryside". Finally, the word "seeking" in the sub clause (C) of the SNCS causes vagueness about the creation of new open spaces by raising the question of what happens if we cannot find any opportunity to create new open spaces. Herein, the removal of this word from the sub clause (c) of the UDP makes this statement clearer and stronger compared to the SNCN (Lee, 2007).

There are some other policies related to the Green Network in the SNCS. The key policies on Sheffield's Green Network in the SNCS, relating to its development, creation and functioning, are mentioned under the section entitled "the Importance of Rivers as Green Corridors" with policies NCS 14 (P), NCS 15 (P) and NCS 16 (E/P). The crucial role of rivers, streams, and the canal as wildlife habitats and potential areas of public access and enjoyment was underlined in NCS 14 (P) for the development of the Green Network. The contribution of lakes, ponds and reservoirs in forming "stepping stones for wildlife" within the network was also emphasised with NCS 15 (P). Additionally, woodlands constitute a large amount of land cover in Sheffield, with a high value for wildlife and public. Therefore, a particular emphasis has been put on the creation of woodlands (tree planting) to enhance Sheffield's Green Network with NCS 16 (E/P).

Similar to SNCS, the UDP included additional policies related to the Green Network policy. Those policies emphasised the importance and contribution of Trees and Woodland (GE15), Lakes, Ponds and Dams (GE16), Rivers and Streams (GE17) and The Canal (GE18) for the development and creation of the Green Network in Sheffield. Furthermore, policies GE15, GE16 and GE17 of the UDP clearly spelt out the importance and relevance of standing and running water in the creation and development of the Green Network for the benefit of wildlife, public access and recreation, considering their value as wildlife habitats, linkages and visual and historical features.

As indicated previously, the Green Network of the SNCS is composed of Green Corridors, Green Links and Desired Green Links which are shown on the Proposals

Map diagrammatically. The Proposals Map of the SNCS had been directly incorporated into the Proposals Map of the UDP as it was in the SNCS (Map 4). In this map, green wide lines represent Green Corridors and narrower lines show Green Links. The Desired Green Links are shown in green dashed lines where there is a current break in the Green Network.



Map 4: The Proposals Map of the SNCS and the UDP

4.3.3 Sheffield Local Plan (2013)

The Sheffield Local Plan-SLP (SCC, 2013b) is the latest statutory development plan for Sheffield which was formerly known as Sheffield Development Framework -SDF (SCC, 2009). The SLP includes the current Core Strategy (March, 2009), the saved policies and Proposals Map of the UDP, the pre-submission version of City Policies and Sites, and the Proposals Map (SCC, 2013b). The Sheffield City Council will use all of these documents and the Proposals Maps in development management decisions until the new Local Plan is adopted.

As the primary document of the SLP, the Core Strategy states the vision and objectives for the whole Local Plan for Sheffield with the aim of regulating planning activities at a strategic level. It is composed of two main parts in which the first part explains the context, vision, objectives and the overall spatial strategy for the whole of Sheffield city, and the second part sets out the spatial policies and the issues of strategic importance. While the Sheffield Green Network is defined in the Core Strategy in accordance with the policies stated in the national framework, it is represented on the draft Proposals Map. The Core Strategy outlines the importance of green networks with Policy CS73 The Strategic Green Network, under "Chapter 12 Prizing, Protecting and Enhancing Sheffield’s Natural Environment and Distinctive Urban Heritage" (Box 4).

Policy CS 73 clearly puts emphasis on the importance of the main rivers, streams, valleys, and the links alongside these as well as their influences on the development of the whole city. Therefore, while the policies of the UDP with regard to rivers and valleys are transferred into the new Local Plan, rivers and valleys are designated as the most important part of the strategic green network in the Core Strategy at a strategic level.

Box 4. Policy CS 73 - The Strategic Green Network

Within and close to the urban areas, a Strategic Green Network will be maintained and where possible enhanced, which will follow the rivers and streams of the main valleys:

a. Upper Don
b. Loxley
c. Rivelin
d. Porter
e. Sheaf
f. Rother
g. Lower Don/Canal;

and include other strategic corridors through:

h. Oakes Park to the Limb Valley
i. Gleadless Valley
j. Ochre Dike Valley
k. Shire Brook Valley
l. Shirtcliffe Brook Valley
m. Blackburn Brook Valley and its tributaries
n. Birley Edge.

These Green Corridors will be complemented by a network of more local Green Links and Desired Green Links.

Box 4: Policy CS 73 - The Strategic Green Network

With the introduction of the Strategic Green Network approach, main river corridors and valleys in Sheffield are defined as Green Corridors. According to the policy CS 73, these Green Corridors provide various benefits for both wildlife and people as they connect built-up environments with the countryside. Whilst the policy states that local Green Links and Desired Green Links will be the supplementary components of Green Corridors, it also identifies the main areas of the Strategic Green Network. Here, it is worth noting that the Policy CS 73 incorporates a shift to seeing the Green Network at more of a landscape scale. Additionally, policy CS 73 indicates that the Green Network will be secured by protecting and enhancing existing open spaces from development as well as creating new ones when opportunities rises as a part of new development activities.

On the other hand, the City Policies and Sites Document comprise city-wide policies (development management policies), city-wide policy areas (with their preferred and acceptable land uses), site allocations and the Proposals Map. As a part of this document, under the section entitled "Green Environment", policy G2 the Green Network completes the remaining requirements of the Strategic Green Network (Box 5).

Box 5. The Green Network in the Sheffield Local Plan (Policy G2)

Any development within the Green Network will be expected to:

a. maintain or increase its continuity and green and open character;
b. not damage its value for wildlife and, wherever possible, increase it by including new areas of habitat particularly for species identified as being of national, regional or local importance;
c. create open space and footpath links in areas of Desired Green Links;
d. provide access to any public footpaths close to the site.

Where space permits, and providing it would not harm its wildlife value, the Green Network will also be used to extend opportunities for informal recreation, including walking and wheelchair use, and, where appropriate, cycling and horse-riding away from the road network.

Box 5: The Green Network in the Sheffield Local Plan (Policy G2)

There are a number of significant changes in the green network policy of the Sheffield Local Plan (City Policies and Sites, G2) when compared to the policy GE

10 in the UDP. Although, it is still expected to promote values for both wildlife and recreation within the network, compared to GE10 in the UDP, a more wildlife oriented approach is now more dominant. In addition to a sub clause, also new phrases have been added to the policy, to express the importance of its value for wildlife.

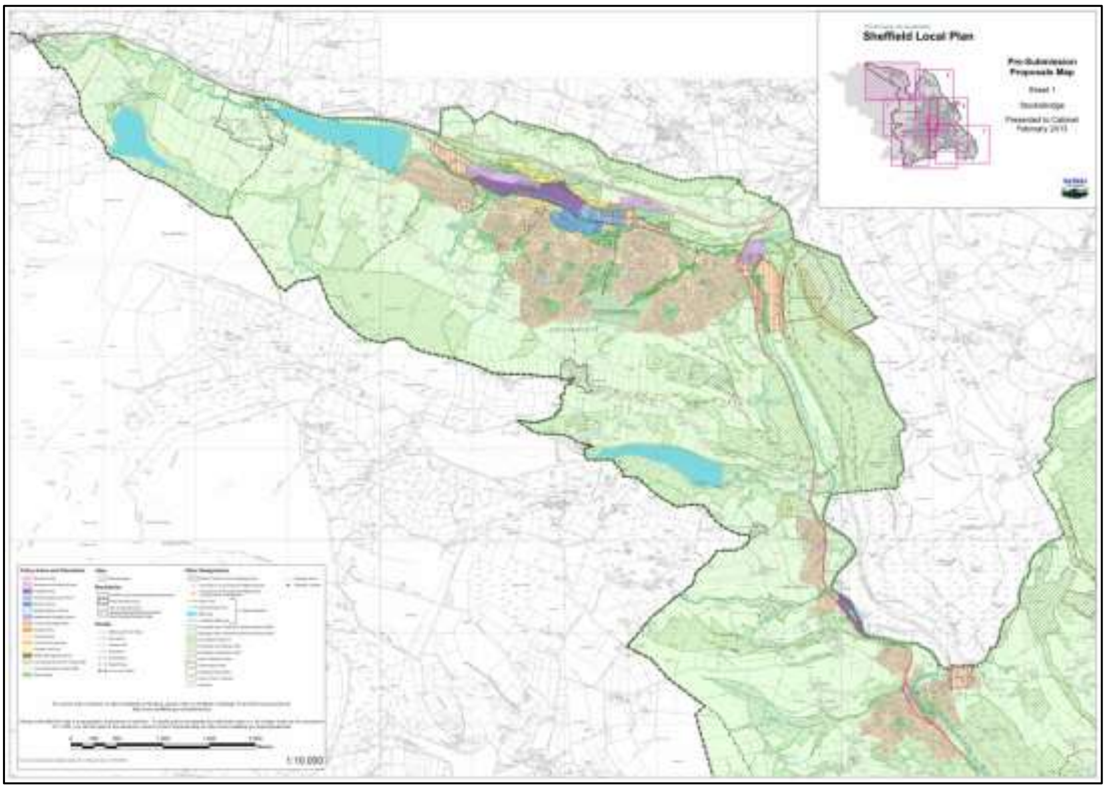
The expression of "maintain or increase its continuity and green and open character" is explicitly mentioned for the first time in the Green Network policy with the sub clause (a) of the SLP. However, the measures of continuity and its application to the ground have not been explained in detail (whether structural or functional). In the previous planning policy documents the importance of the continuity of the Green Network was mentioned as background information but was not reflected into the Green Network policies. The sub clause (b) includes more rigorous measures to protect and enhance the Green Network as well as increasing its wildlife value and included habitats, particularly by referring to the species of national, regional or local importance. In this way, species oriented objectives have been inserted into the Green Network policy for the first time.

Moreover, for the sub clauses (c) and (d), a more focused objective has been inserted into the policy for the public use of the Green Network, by mentioning the public right of way links and their access to adjoining areas. Further to that, as it was pointed out in policy G2, formal and informal recreation are still regarded as important values of the Green Network, however, the emphasis has been placed on its wildlife value.

Similar to the SNCS and the UDP, the policies related to the G2 Green Network policy in the City Policies and Sites have been strengthened for the benefit of the network by adding new objectives or rewording their context (such as the policies of G3 Trees, Woodland and the South Yorkshire Forest, G4 Water in the Landscape).

4.3.3 Summary

Overall, it is obvious that the Sheffield's Green Network has been regarded as an important part of the strategic legislation, because of its potential effects on development and other land use policies. The Green Network policy in the SLP has been strengthened both in structure and wording where wildlife has taken the top priority. Additionally, when examining the Proposals Map, the Green Network in the UDP has been represented with different line thicknesses, as an indication of the areal extent of the network (Map 5). In spite of that, when the Green Network was transferred into the SLP, the lines have become uniform and there is no clue for their extent. The effectiveness and success of Sheffield's Green Network may be adversely affected due to the representation of the network in the SLP, since it is not clearly defined in the Proposals Map. This may particularly be an issue, if there is a demand for the development in and around the Green Network.



Map 5: Sheffield Local Plan Proposals Map (Map 1 - North Stocksbridge) (see Appendix 5)

4.4 Examination of the Green Network and the Living Don

4.4.1 The Semi-structured Interviews

I conducted two semi-structured interviews with an ecologist in the Sheffield City Council (SCC) Ecology Unit and with a planning officer in the Forward and Area Planning Team. The interviewee in Ecology Unit had been working as a volunteer and then became a member of staff at the Council in the late 1980s as well as being involved in the development of the Sheffield Nature Conservation Strategy. As part of her job she was responsible for identifying local wildlife sites and was involved in the planning process of the Green Network for the city. The main role of the interviewee in Forward and Area Planning Team was to write and implement planning policy on a range of issues, including the Green Network. The third interviewee was the landscape development manager at the Sheffield and Rotherham Wildlife Trust relating to the Living Don ecological network project, and had been involved in the planning of ecological networks since 2008 / 2009.

As pointed out in the previous section, the Green Network policy in Sheffield has been developed on the basis of the Sheffield Nature Conservation Strategy and then incorporated into the UDP and SLP with some updates and changes to strengthen the Green Network policy as an integrated approach to nature conservation. The results of the policy document analysis revealed that the structure and wording of the Green Network has been strengthened since the 1991 Nature Conservation Strategy. For example, the importance of maintaining or increasing the continuity of the Green Network is explicitly mentioned for the first time in the SLP under policy G2. Also, from the SNCS to the SLP, wildlife has taken a higher priority by the insertion of more rigorous measures into the Green Network policy for species of national, regional or local importance. Within this framework, when asked if the Green Network policy in Sheffield had been strengthened since the 1991 Nature Conservation Strategy, the first interviewee believed that it had in the SLP but also needed to be taken into consideration in planning applications:

> R1: "Yes, because it was actually in policies. I think the Nature Conservation Strategy had a few bullet points, whereas it’s now much stronger. It has to be taken into consideration in the planning."

The respondent of SRWT, on the other hand, thought that the planning policy had been changed but still does not reflect a comprehensive network approach by saying:

> R3: "Well, some of it has been tweaked and updated but not sort of comprehensively I would not say it is or has not been recorded exactly what people done, they have just sort of updated and tweaked, you know."

Throughout the evolution of the Green Network policy in Sheffield, the representation of the Green Network has also been changed since the SNCS (1991). With regard to this, the first respondent in SCC thought that:

> R1: ".....the Green Network was then sort of incorporated into the new Sheffield Plan, I suppose what was called the Sheffield Development Framework and is now called the Sheffield Plan, and I feel that it was detrimental to it. I think there are still policies that protect it but it is not defined as a particular width, it just shows it as a linear line on a map, rather than actually showing width which is what the original one did."

In particular, the representation of the Green Network has become more uniform, for example, there is now no indication of the extent of the Green Links and Desired Green Links. The explanation of the logic behind this is "to allow each link to be considered on its own merits and to avoid the concept of a minimum width" (SCC, 2013a). Although the policy CS 73 in the SLP indicates that the Green Network will be secured by protecting and enhancing existing open spaces from development as well as creating new ones when opportunities arise, the first respondent from SCC drew attention to the fact that the Green Network may now be challenged because of its representation in the SLP:

> R1: "..... it is just sort of arrows, just a line with an arrow pointing towards.....parks and things.......but without having an indicative width to them, and there is not one published either, there is not a defined width to what a Green Corridor, Green Link should be. So, I think it is weakened the policy to some extent by just having them drawn as links, which disappoints me greatly really, because we worked so hard to get them done. They are still there, and they still have a definition, they are still covered by policies, but it is very difficult to then argue when in fact that should be that wide and someone says "*well, it does not say that it should be*", whereas I think on the original maps they were far better defined. They showed up. I think there was a dilution really of the strength of the policies..... if you have not got something clearly defined it makes it far more difficult to argue in planning that you are actually taking part of a green link when you look at this and somebody says "*well, it does not actually go through my site*", but it would have done originally, so I think that has weakened it. Well, not weakened it but makes it more difficult, I suppose, to argue for."

The respondent in SRWT thought that the Green Network was almost the same as it was in the SNCS with a few updates, but similar to the first respondent in SCC, complained about the uniform format of the new Green Network in the SLP:

> R3: "The base is same, so in terms of this policy background, my understanding is the Green Network, which is in the Sheffield Local Plan is the same one in 1991 before GIS, with some amendments over time by the ecology unit, and other's plan is probably just tweaked and updated it, but in an ad-hoc kind of way, rather than, it has not been properly reviewed in the light of GIS information......in the development of the Sheffield Local Plan, these lines got changed to thin green lines, and we (called the) unit we were not very happy about that.....Because not all the networks are uniform width but planning said they could not change it that have to be like that apparently."

By contrast, the second interviewee in SCC (a member of the Forward and Area Planning Team) does not think that the representation of the Green Network would create challenges by stating that:

> R2: *"Green corridors are given a wider arrow to show their strategic importance. The width of the arrows does not necessarily reflect the width of the network, this is determined on a more local basis depending on the nature / function of that part of the network. So there is no 'minimum' width. Future revisions of the map may show the network extending out of the city."*

The purposes of protecting and enhancing the Green Network are identified in the SLP (SCC, 2013b) and also in the Green Environment Policy Background Report (SCC, 2013a). This includes promoting wildlife and recreational activities within the network. Accordingly, the first interviewee in SCC claimed that the main aim of the Sheffield Green Network is to try to connect and create continuous green links mainly for wildlife but also for people, such as cycle paths and pathways. However, the first respondent in SCC also added that there should be some protected areas just for the benefit of wildlife, in which development is not permitted:

> R1: "To try and link, to create continuous green links for all sorts of things really, but mainly from our purpose this is for wildlife. And those are the main, as I say from our perspective, that is main thing, but I do not have any objections for cycle paths, pathways and things in with those as well, but then there is also issues with

> lighting and things like that, and use and things. But otherwise, at the moment, I think we are moving more towards that, but I think we still feel there should be Green Links for wildlife sake only. That there should be some protected areas that do not have development that goes with it."

When questioned about the main aims of the Green Network, the second respondent in SCC referred to the Green Environment Policy Background Report (SCC, 2013a):

Box 6. G2 The Green Network (in the Green Environment Policy Background Report, page 29)

The purposes of protecting and enhancing the Sheffield Green Network, identified in this policy (in no order of preference) are to:

- Increase biodiversity by allowing species to migrate over a wider area and respond to the impacts of climate change; and
- Allow for the dispersal and genetic exchange of species within the Sheffield City boundary, and also into the Peak District National Park and green spaces belonging to other neighbouring Local Authorities; and
- Avoid the fragmentation or isolation of habitats; and
- Strengthen the overall integrity of Sheffield’s network; and
- Assist in the provision of sustainable drainage systems (SUDS) and the storage of potential flood waters to limit the impact upon areas of Sheffield which are more vulnerable to flooding; and
- Encourage the movement of the people of Sheffield through activities such as walking, cycling, horse riding or boating; and
- Provide increased access to open or green spaces for the people of Sheffield to aid in a general improvement of health and well being and to assist in opportunities for social inclusion and community cohesion; and
- Continue in the provision of, and assist in the enhancement of, Sheffield as an attractive and healthy place to live in.

Box 6: G2 The Green Network in the Green Network Green Environment Policy Background Report (SCC, 2013a)

In terms of the Living Don ecological network, the respondent from SRWT stated that the main aim was to develop an ecological network pursuant to the recommendations of the recent national policy documents, such as Making Space for

Nature (Lawton et al., 2010), Natural Environment the White Paper (HM Government, 2011) and the National Planning Policy Framework (DCLG, 2012). Also, the respondent added that SRWT focuses on a more “landscape scale concept” of nature conservation when creating ecological networks:

> R3: "..... to enhance the ecology of Sheffield and Rotherham in a most effective way possible, so, and landscape scale ecology, or everyone calling ecological networks in the landscape is the most effective way of doing it rather than just managing individual nature reserves, or bits and bobs all over the place so it is trying to be strategic about the work that we want to do and who we would like to work with....."

Green and ecological networks are generally thought to deliver a variety of functions for biodiversity and people. The importance of multifunctionality has also been emphasised in the Green Network policies from the SNCS (1991) to the SLP (2013). In this regard, the first interviewee in SCC described the main function of the Green Network as to enable the movement of wildlife as well as supporting the use of the network by people. Here, the first respondent in SCC also emphasised the importance of multifunctionality of the Green Network, pointing out the increasing land demand for development:

> R1: "To enable wildlife to disperse really, to move around..... I think we are going to have to get more wise to what we do with our Green Links to justify them, especially with the impact now of more land being required for development. So I think we are going to have to look at our Green Links in a more multifunctional way, and I think that’s not a bad thing, but I think it means, from my point of view, I can argue much wider ones as well..... I am working on a site at Abbeydale Grange at the moment, and they have got an ancient woodland there. So we have actually negotiated a really wide green link on the basis that they can have a footpath in there as well, but it is also beneficial for the trees too. But that is the way forward; I think we are going to have to do that."

The respondent from SRWT described the main functions of the Living Don ecological network from a more wildlife and nature oriented perspective. However, when I asked about the use of the network by people as well as the wildlife, the interviewee also added that SRWT always has been working hard to engage people with the Living Don ecological network:

> R3: "I would say to provide the best chance for the improving habitats and species of Sheffield and Rotherham to thrive now and in the future in their changing climates as well, by providing connectivity, bigger better managed areas for the species to survive saying now and into future, is one of them. And to halt the loss of biodiversity and reverse it, reverse some losses of biodiversity locally and also to provide ways of engaging people in nature and nature conservation…..As a Wildlife Trust we are always striving to get people outdoors to understand appreciate and value natural spaces. And to be honest, I work as a mixture of engaging people in say this network areas but we also engage people across green spaces cross Sheffield-Rotherham wherever they are. So we do bit of, a bit of both really.....and my job is more looking at the ecological networks but some of my colleagues will continue to engage people in their, local green spaces....."

Landscape connectivity can be measured and evaluated both structurally and functionally. Structural connectivity refers to the physical / structural relationship between different landscape elements, functional connectivity identifies the degree to which the landscape actually facilitates or impedes the movement of species. In response to whether any objective measures of connectivity had been used in the creation of the Green Network, the first respondent from SCC indicated that:

> R1: "Habitat requirements certainly..... it was pretty ad-hoc before I think, but there is more of a conscious effort. Particularly where we are linking local wildlife sites up and we are looking for green corridors to link those we do start to think about that."

However, the second respondent in SCC was not sure if any objective measures of connectivity had been used when creating the Green Network, because the interviewee was not involved in the creation of the Green Network:

> R2: "I wasn’t involved in its creation so I’m not sure."

On the other hand, in the case of the Living Don ecological network, there were not any objective measures of connectivity used in creating the network since their methodological approach to develop the Living Don was based on existing data:

> R3: "Not much if I am honest..... Because, we had had to use sort of pragmatic approach that, so, the methodology is based on some existing data".

The evidence in the policy document analysis showed that all the SNCS, UDP and SLP include additional policies relating to the Green Network policy. Therefore, when we moved onto the application of the Green Network policy, I asked the interviewees if they thought that the Green Network has an influence over the other green and open space planning policies and their application in Sheffield. Both respondents in SCC and also the respondent in SRWT thought that the Green Network policy has been quite influential:

> R1: "Yes it does, I suppose the Green Network does have an influence over the other green space planning. Because we look before a site is designed as open space in development, for example, and we do look to see where can we link that, can we link that to that, is there a way we can do it, and whether that is for people as well, and whether that is like this defined green link….."
>
> R2: "Yes, see UDP policy GE10 on the Green Network and Core Strategy Policy CS47 on Safeguarding Open Space."
>
> R3: "…..I think, yeah, has the existing green network policy has had some influence on this on this on development management".

In SLP, Policy G2 defines the Green Network as "a network of open space that provides the means for wildlife and people to move through the built-up areas and to connect with the surrounding countryside" (SCC, 2013b). Also, the aim of the Living Don is defined as "to restore the Living Don network to a functioning ecological network of wildlife-rich habitats and green infrastructure, using the river and canal corridors as the backbone, to maximise its potential for biodiversity and people" (Rivers, 2013b). From these, we can clearly see that both the Green Network and the Living Don aim at multifunctionality. Accordingly, I asked if it is possible to integrate the needs of wildlife and people within an urban environment in other words to deliver multifunctionality, and how the needs for human access and nature conservation are managed in practice. The respondent from SCC Ecology Unit and the respondent from SRWT claimed that there are ways of managing conflicts but also underlined the difficulty of balancing the requirements of people and nature conservation:

> R1: "Yeah, with great difficulty. I suppose with woodlands and things, I think the problem is, for human access..... Abbeydale, because that is a very current one that

> we are dealing with.....Originally we looked and they had houses backing onto the woodlands, and so the automatic thing for people to do is to create an access into the woodlands from the back of the their gardens. So we have now made a conscious effort, all development where it’s near woodlands is pulled back, and we nearly always have, yeah a buffer zone, but also a pathway, so that people, and then there’s defined access points.....But if they degrade the whole of the woodland edge by moving in and out, that’s where we have the main conflict really, places like Ecclesall Woods, people's houses back on, they have created access and they dump their garden waste. And the impact on the ecology is quite sort of fundamental really, you end up with a wood, woodland edge, that is full of garden escapes, people’s rubbish. So there are conflicts, but there’s ways of managing it.... Out at Middlewood we produced leaflets to go into people's house buying packs, and just explained a little bit about the ecology of the surrounding woodlands, why it was important to, you know, there is badgers and all sorts of things.....So it is trying to get people to interact with wildlife, but to understand it a little bit, and I think sometimes it is just that people don’t know."

> R3: "I think they can, in our experience, for example, in Wildlife Trusts, Nature Reserves, they are all fully accessible to public with footpaths and events for the public, and things like that, and Nature Conservations, so that happens, and then other end of the scale sites have just value to human access and have very little like open space, some open spaces have very little value as a wildlife.....there are some more sort of wild places have few people and more conservations. I think this is a spectrum really, but I think it, things can be managed for both if people know what we are doing, there are conflicts sometimes. For example, between people like to walk their dog on the site and who do not want, there to be live-stock grazing, doing conservation grazing. Because, they think it interferes with their dogs. So, there are issues like that that come up on some sites. And to keep those sites as they are you need to manage them.....One of those ways to management is by conservation grazing not the only way, but, so there are some issues, but generally they can be managed."

In terms of the criteria for the identification and selection of sites that are part of the Green Network, the first interviewee from SCC referred to the SNCS (Table 6). In the SNCS, two main categories of criteria had been defined for site selection. The factors under Category 1 relate mainly to a site's inherent value for nature conservation, whereas the factors under category 2 consider the social context of the areas (Bownes et al., 1991).

Table 6: Criteria for Sites Selection in the SNCS

Criteria for Site Selection	
Category 1 (Site Characteristics)	(a) Richness / Diversity (b) Rarity / Uniqueness (c) Ancientness and Continuity of Land-use (d) Typicalness or Representativeness (e) Size (f) Replaceability (g) Fragility (h) Situated in Wildlife Corridor/Wildlife Link (i) Part of an important sequence of features (geology)
Category 2 (Community Factors)	(a) Community Value (landscape/aesthetic value, amenity, accessibility) (b) Educational Value (c) Situated in an Area of Deficiency (d) Threat of Disturbance or Destruction (e) History of Scientific Recording

Additionally, the first respondent from SCC stated that the sites within the inner-city area parts of the network had been identified on the basis of actual field work before the SNCS had been published.

> R1: ".....the sites were identified originally in the Nature Conservation Strategy….. But the inner-city area part of it, when I graduated in 1987 it was my first job, and I went out and identified within the inner city. So, there was 3 of us and we had a grant, and we just literally went out and recorded everything over about half a hectare. And that became the basis for the urban parts of the Nature Conservation Strategy, before they had any definitions, no designations to them or anything, other than probably open space, but then they tend to be managed by parks as open spaces. So these were really impromptu little areas, where local people might walk their dogs or just might enjoy it as their local space, but it was not particularly managed…..We also looked at sites for a particular good example of habitats, or whether they were particular good for birds, or whatever.....So there were kind of loose criteria that we use, but it was very much a sit-down with lots of people and defined what should be in, how you actually decided on what should be in and what should not be in. And we ended up with lots of little sites, which then formed the basis for the Green Network. We could start looking to see how we could link them up."

For the site selection and identification of the Living Don ecological network, the interviewee from SRWT referred to "the Living Don Network for Nature Mapping Methodology" (Rivers, 2013a). According to this report, the original area of the Living Don was identified in the *Regional Biodiversity Opportunity Areas Map*, by the Yorkshire and Humber Biodiversity Forum in 2009 (YHBF, 2009). Then, the *Regional Biodiversity Opportunity Areas Map* was used by the South Yorkshire Biodiversity Forum in order to identify "Priority Landscape-Scale Project Areas" as the most important areas for biodiversity delivery, in which the Living Don was one of these areas. Afterwards, as part of the Living Don mapping process existing datasets have been used to identify the details of potential network sites for the Living Don ecological network in Sheffield and Rotherham. Based on these datasets, these sites have been classified as either "Core" or "Opportunity" sites. "Core" sites were selected from the areas that were thought to have biodiversity potential or in good management and expected to have biodiversity potential (Table 7, Adapted from Rivers, 2013a).

Table 7: Datasets used to identify core sites in the Living Don ecological network (Rivers, 2013a)

SSSIs in favourable condition	BAP Habitats from Natural England Inventory
SACs	- Blanket bog inventory
SPAs	- Purple moor grass/rush pasture inventory
Sheffield LBAP sites to "maintain" (woodland, heathland, grassland, wetland)	- Lowland meadows inventory
Local Wildlife Sites (Sheffield & Rotherham) in positive management	- Lowland heath inventory
South Yorkshire Integrated Habitat Network (Forest Research) Core Networks, Core Habitats and Non-Core Habitats for	- Lowland dry acid grassland inventory
- Neutral grassland	- Lowland calcareous grassland inventory
- Fen/marsh/swamp	- Coastal and floodplain grazing inventory
- Calcareous grassland	- Fen BAP priority habitat
- Broad-leaved/yew woodland	- Deciduous woodland inventory
	- Upland heathland inventory
All Wildlife Trust nature reserves	- Upland calcareous grassland inventory
Sheffield Green Roofs	- Traditional orchard inventory
Woodland in EWGS	- Reedbed inventory
Land in Higher Level Stewardship	- Ancient Woodland
Core Green Space - Green Spaces from Sheffield PPG17 assessment scoring over 60%	
Core Green Space - Green Spaces Sheffield Standard Pass sites 2010/2012	

“Core” sites were further classified as “Core Wildlife Sites” and “Core Green Spaces”. On the other hand, “Opportunity Sites” were selected from the areas that were thought to have potential to improve the biodiversity in the Living Don ecological network (Table 8, Adapted from Rivers, 2013a).

Table 8: Datasets used to identify opportunity sites in the Living Don ecological network (Rivers, 2013a)

Sheffield LBAP sites to “restore or create” (woodland, heathland, grassland, wetland)	South Yorkshire Integrated Habitat Network potential habitat enhancement areas (not ground truthed)
Local Wildlife Sites (Sheffield and Rotherham not in positive management)	- Broad-leaved/yew woodland
SSSIs not in favourable condition	- Neutral grassland
Plantation on Ancient Woodland (PAWS)-NE	- Fen/marsh/swamp
	- Calcareous grassland
Green Spaces from Sheffield PPG17 assessment scoring < 60%	
Green Spaces Sheffield Standard Fail sites 2010/2012	

After mapping all these sites using MapInfo (a GIS software), the best areas for existing and potential ecological networks on the original Living Don map were visually determined and amended. Then, the Living Don ecological network was split up into six "Priority Landscape Areas" (PLAs) with the aim of obtaining more manageable areas for the development of detailed action plans. These PLAs are: Sheffield and Peak District Moors, Western Valleys (Rivelin Loxley and Porter Valleys), River Don, South Sheffield Greenway, Rotherham Rivers and Blackburn Valley. Following this, the next step was the identification of the network components for the each of individual PLAs in more detail. At this stage, the possibility of identifying core areas, corridors, stepping stones, restoration zones, buffer zones and sustainable land use areas for each of the priority areas will be considered as well as determining if there is a need for more local urban classification. As the final step, the further refinement of individual maps and the development of action plans were proposed to reveal what could be achieved in the short and / or longer term (Rivers, 2013a).

Both the Green Network and the Living Don include some sites with multiple designations as part of their network approaches. The first respondent in SCC and the respondent in SRWT explained the underlying reasons for having multiple designations as follows:

> R1: "Sometimes it is because they have been designated as Local Wildlife Sites before, and then they become Local Nature Reserves, and Green Network areas can become fairly rich, so then you then define what would have just been open space or whatever then becomes Local Wildlife Sites. I suppose most of our SSSI's they are also Local Wildlife Sites as well, which seems to be not worth having, but sometimes you can use both to get gains in planning and things….. But it is usually because ones started off as one, and then you designate it but you do not necessarily take the other one away."

> R3: "Yeah, a site, I mean all the local wildlife sites are also SSSI's, cause it is a hierarchy…..you meet this lowest hierarchy you automatically…..if you need a high hierarchy you automatically meet the low hierarchy…..."

Recently, the importance and crucial role of Sheffield's topography and river system in forming a natural network by providing connections between different landscape components have been emphasised (Beer, 2005; Lee, 2007). Also, as stated previously in the policy document analysis section, the main rivers and their valleys constitute the Strategic Green Network by providing various benefits to wildlife and people (under Policy CS73).

In this context, when I asked about the main physical features of the Green Network and the importance of water courses for the Green Network in terms of connectivity, the second interviewee from SCC referred me to the responses of the first interviewee from the Ecology Unit. The response of the first interviewee was:

> R1: "I suppose it is different habitats really, those are the main features that we would be looking for. Water courses, I suppose, and certainly the river corridors, they are fairly fixed really…..I suppose the features we had be looking for are reasonable habitats or whether there is potential to put in habitats, or if we have got this space what can we do with it, how can we make it work as a green network..... They (rivers) have been an absolutely wonderful thing for Sheffield, especially as we really value our rivers here..... I think they are crucial for movement for loads of species..... And they are the ones that show up on the map, I think we are phenomenally lucky to have those, I think they act as great green links….. And also our otter population, we have had our first otter records in the last, probably, they were not recorded before 20 years ago, and those have started to move now. Development now, they know they have to put planks in under bridges to enable

> otters to get through when there is work going ahead. So yeah, I think they are crucial for movement for loads of species. Fish passes we have been putting in, we've had a lot of problems with white-clawed crayfish, but we can actually work with those….. so our rivers are absolutely vital. "

Similarly, the respondent from SRWT claimed that:

> R3: " Sheffield has most a lot of big corridors that come out from our methodology are the river corridors, the River Don and the Canal River Don and Rotherham and the river Rother and then the tributaries coming in from the west, and then feeding all that is the moors and then the only one is not really and this is Blackburn Brookes is what we have called Sheffield Greenway which is more green space, but even that has a couple of little valleys in it. So we have not looked at the rivers and the drawn buffers around them. We have looked at the layers of the best habitats and they have come up that they are around the rivers, because that is, that is a kind of how the environment is…..there also obviously development things around the rivers but, but there is also a lot of natural areas around the rivers, so yeah, that is really important and the moors..... Yeah, vital really in Sheffield connecting from the moors right through the city, right through Rotherham….."

A buffer zone or an environmental buffer is generally a necessity to minimise the detrimental effects of development or other land uses on protected sites. In the Sheffield Local Plan, City Policies and Sites (pre-submission) document (SCC, 2013b), an environmental buffer is defined as "landscaping and / or siting of appropriate uses between sensitive and other uses to reduce harm or potential nuisance". Accordingly, the first respondent from SCC claims that they have been trying to include buffer zones particularly where the development goes ahead by saying:

> R1: "We put buffer zones in for every single development that goes ahead now..... It is a bit arbitrary really; I think it is as much as you can. I mean, I suppose like the Woodland Trust and things, they suggest 15m for ancient woodlands, so we can push for that. So like, for Abbeydale I said 15m, but if you are going to put a cycleway in that as well, then we would want them to also take that into account too, and if you want a footpath too, and you want something else in there, then it has to be wider than that....."

On the other hand, the Living Don ecological network does not include any areas acting as buffer zones at the moment. However, as it was mentioned in the mapping methodology of the Living Don, SRWT intends to designate buffer zones in their maps as a next step.

> R3: "There will be but we have not identified them yet, so it is the next stage."

4.4.2 Map Analysis

4.4.2.1 Examination of the Green Network Map

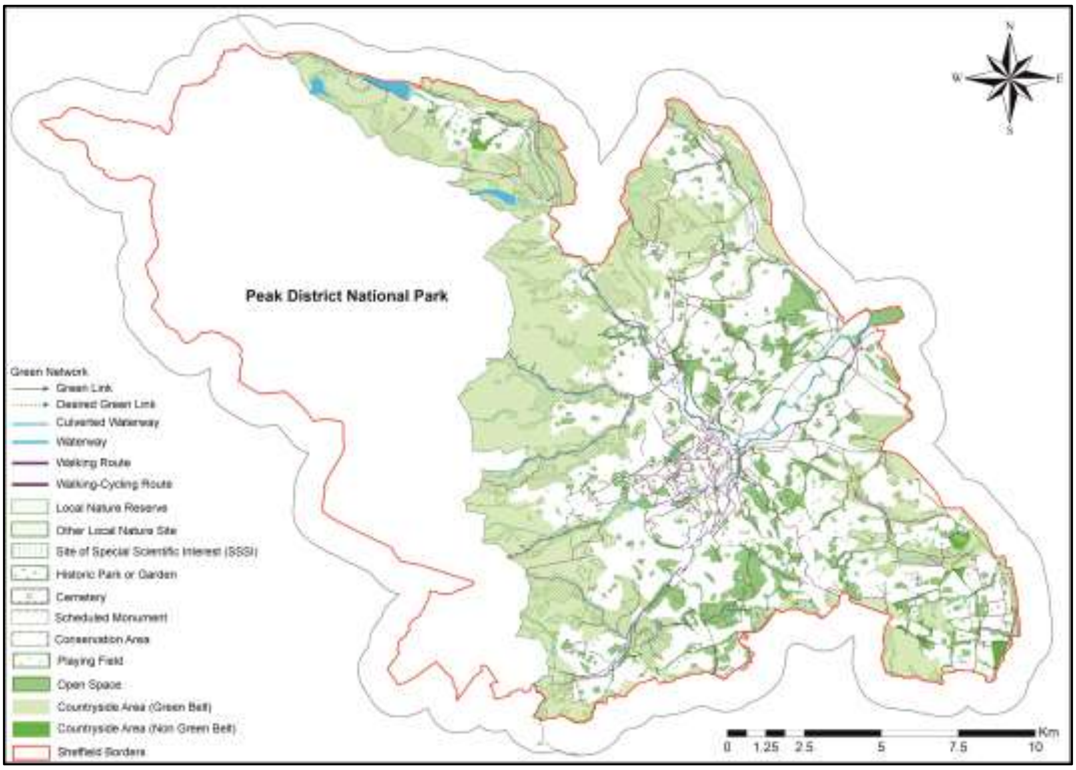
Initially, the map of the Sheffield Green Network was obtained from the Sheffield City Council, Forward and Area Planning Development Services in 2011 by e-mail, in *ESRI Personal Geodatabase* format. Then, the up-to-date Green Network map was obtained from the Sheffield City Council, Parks and Countryside Service in shape file format by e-mail in 2014.

The examination of these maps was conducted in ArcGIS10. In addition to this, I also used the Sheffield City Council 2008 PPG17 Audit Green and Open Spaces layer (SCC, 2008).

The map of the Green Network does not include the areas within the Peak District Park, since this area is not within the Sheffield Local Planning Authority boundaries. On SCC Proposals Map, while the Green Links are represented with continuous green lines, green dashed lines shows the Desired Green Links on the Sheffield Local Plan, Proposals Map. Likewise, waterways and culverted waterways are represented in blue continuous and dashed lines, respectively.

Map 6 represents the Green Network in the SLP. The main components of the Green Network are defined in the City Policies and Sites (pre-submission) document (SCC, 2013b), which states that "The full Green Network is identified on the proposals map and includes linked open spaces, some footpaths, watercourses and corridors of dense vegetation without public access". However, actually the Green Network has been represented by lines with an arrow instead of having an indicative width, and the actual area of its components is not shown. Thus, we may see where the Green Network goes through, but cannot define the actual area of the network.

Additionally, the Green Network map shows the areas of open space, however, it does not specify the different types of green and open spaces that are connected by the Green Network. The definition of "open space" has been given in the Core Strategy (under CS47) as part of the SLP (SCC, 2013b).



Map 6: The Sheffield City Council - Green Network

As seen in the definition of open spaces in Box 7, no uses are specified for open space areas. Therefore, in addition to the Green Network dataset, I also used the Sheffield City Council 2008 PPG17 Audit Green and Open Spaces (SCC, 2008) layer; in which all accessible open spaces, sports and recreation areas are identified and mapped. After overlapping the Sheffield City Council 2008 PPG17 Audit Green and Open Spaces with the Green network, I tried to find what type of green and open spaces have been included and connected by the Green Network. As a result, when examined the overlaps between the Green Network and PPG17 Audit Green and Open Spaces, I found that Green Links and Desired Green Links connect all of these green and open spaces including *Parks and Gardens, Natural and Semi-natural Greenspaces, Outdoor Sports Facilities, Amenity Greenspaces, Provision for Children and Young People, Allotments*, and *Cemeteries and Churchyards*.

Box 7. Under Policy CS47 - Safeguarding of Open Space (SLP)

"Open space- a wide range of public and private areas that are predominantly open in character and provides, or have the potential to provide direct or indirect environmental, social and/or economic benefits to communities. For the purpose of assessment, this includes ancillary buildings that contribute to the use of an area as open space."

There are also some Green and Desired Green Links between other open spaces, such as agricultural land, landscaped areas and other open spaces that are not included in the Sheffield City Council 2008 PPG17 Audit Green and Open Spaces layer (SCC, 2008). As seen in Maps 5 and 6, the Sheffield Green Network connects designated sites (some of them with multiple designations) except from those within the boundaries of the Peak District National Park. The details of the designated areas are given below in Table 9.

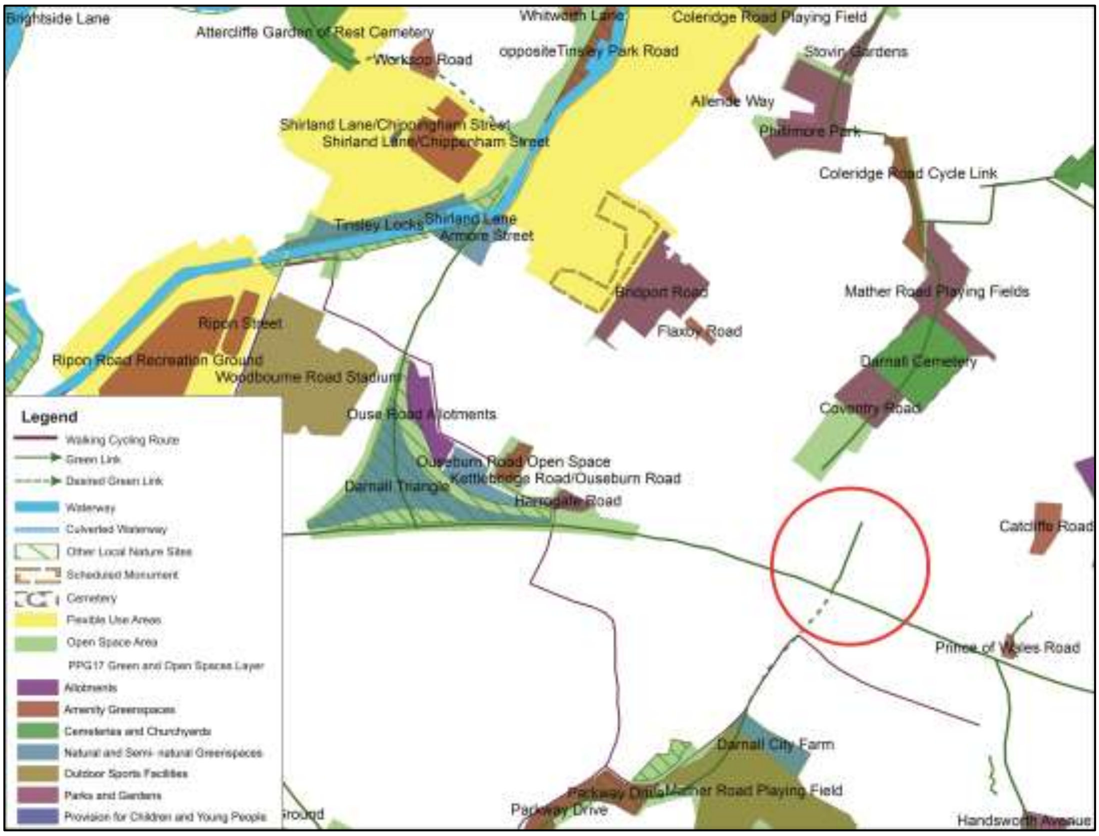
Table 9: Designated sites connected by the Green Network

Designation	Site Name
Sites of Special Scientific Interest (SSSI)	Moss Valley, Totley Wood, Stannington Ruffs, Wharncliffe Crags, Wadsley Fossil Forest, Neepsend Brickworks, Neepsend Railway Cutting, Little Don Stream Section
Local Nature Reserves (LNR)	Bowden Housteads Wood/ Carbrook Ravine, Ecclesall Woods, Fox Hagg, Gleadless Valley, Loxley and Wadsley Common, Porter Valley Woodlands, Roe Woods and Crabtree Ponds, Shire Brook, Salmon Pastures, Sunnybank, Town End Common, Sheffield General Cemetery, Wharncliffe Heath, Wheata Woods, Woodhouse Washlands and Woolley Wood
Local Nature Sites (LNS)	e.g. Cocksfoot Hill, Fox Glen Wood and Glen Howe Park (263 sites totally)
Conservation Areas	e.g. Porter Brook Conservation Area, Endcliffe Conservation Area and Birkendale Conservation Area (36 sites totally)
Scheduled Monuments	e.g. Abbeydale Works, Manor Lodge and Glass Furnace, Bolsterstone (22 sites totally)
Historic Parks or Garden	e.g. Barnes Hall, Glen Howe Park and Porter Valley, Forge Dam (48 sites totally)
Cemeteries	Beighton Cemetery and Burton Cemetery (29 sites totally).

The identification of Green Links as part of the Green Network and the underlying reasons for their designation have been given in the Local Plan Background Reports 2013, Green Environment Policy Background Report, Appendix 1. This appendix includes information on the descriptions of green links, the justifications for designations, included habitat types, and other notes (SCC, 2013a).

According to this appendix, the main habitat types included in Green Links are: rivers and ponds (watercourses), culverted watercourses, woodlands, scrubland, shrubs, informal open spaces, sports grounds, historic parklands, foot routes along roads to rivers, vegetated and wooded embankments along roads and railways, farmlands, grasslands, parks, mature landscaped areas, cemeteries, footpaths, landscaped verges, areas with mature trees, derelict lands and large private gardens.

Map 7 was derived from the Green Network that I received from SCC and represents the details of the Green Network. As can be seen from this map, the representation of the Green Links and Desired Green Links creates inconsistencies in terms of the representation of the Green Network.



Map 7: Details of the Green Network

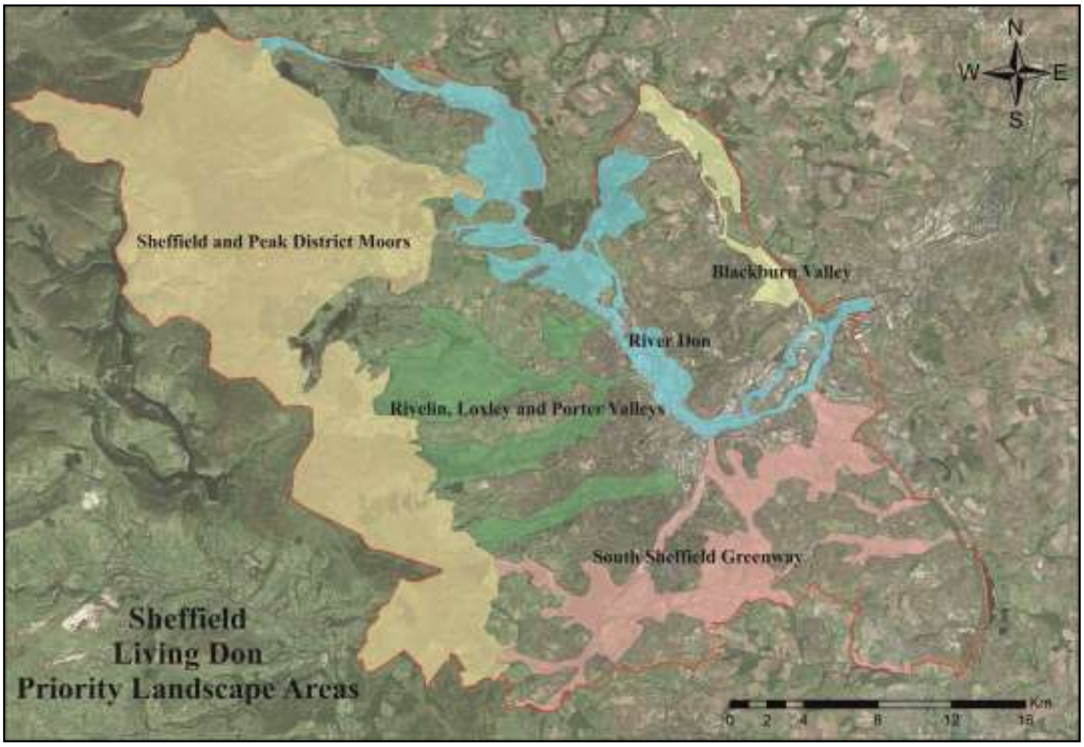
For example, while some of the Green Links pass through the Local Nature Sites and open spaces, others just link the components of the Green Network but do not pass through any open or specified spaces. Also, some Green Links do not join with other open spaces or defined components of the network, as highlighted by the red circle. Therefore, it is not clear how and why these areas are connected to each other.

4.4.2.2 Examination of the Living Don Map

The digital map for the Living Don ecological network was obtained from the Sheffield and Rotherham Wildlife Trust and examined using ArcGIS 10.1. The Sheffield and Rotherham Living Don ecological network is split up into six Priority Landscape Areas (PLAs). However, the development of the map for the Living Don and its PLAs is still in progress and it was stated that "the maps will continue evolving over time as the areas are looked at in more detail" (Rivers, 2013a).

The whole Living Don covers a total area of 92966.09 ha. Out of all the PLAs, the Sheffield and Peak District Moors has the most extensive coverage (78690.95 ha), and the largest part of its area is found within the Peak District National Park (53306.53 ha). Next is the River Don PLA, which covers a total area of 4199.55ha and links the valleys throughout the River Don. Being situated in the southern part of Sheffield, the South Sheffield Greenway extends into North East Derbyshire and covers an area of 3901.94 ha. The Western Valleys PLA (2711.21 ha) is located in the central and western part of the Sheffield and stretches away to the Peak District National Park. On the other hand, the Rotherham Rivers PLA (2517.22 ha) is located in Rotherham, throughout the eastern borders of Sheffield, following the River Don, the River Rother and their rivers valleys. Finally, Blackburn Valley is the smallest part of the Living Don network, situated to the north east of Sheffield and covering an area of 947.97 ha.

This chapter gives an account of examining the green and ecological network approaches in Sheffield. Thus, to be able to examine the Living Don network within the boundaries of Sheffield, I clipped the whole network in ArcGIS10.1, to exclude the areas that extend beyond Sheffield. In this way, I obtained the Living Don ecological network covering a total area of 20953.08 ha. The Living Don ecological network, within the boundaries of Sheffield is composed of Sheffield and Peak District Moors, South Sheffield Greenway, River Don, Western Valleys (Rivelin, Loxley and Porter Valleys), Blackburn Valley (Map 8).



Map 8: The Living Don- within the boundaries of Sheffield

A. Sheffield and Peak District Moors

Sheffield and Peak District Moors are situated on the western edge of Sheffield and covers a total area of 11672.47 ha. This area includes very important habitats for species. Moorland, upland heath, blanket bog, rough pasture and improved pasture constitute the main habitats present in this area. Some of the designated sites in the Sheffield and Peak District Moors are shown below in Table 10.

Table 10: Designated sites within the Living Don PLA

Designation	Site Name
Sites of Special Scientific Interest (SSSI)	Canyards Hills, Dark Peak, Eastern Peak District Moors
Special Areas of Conservation (SAC)	South Pennine Moors
Special Protection Areas (SPA)	Peak District Moors (South Pennine Moors Phase 1)
Local Nature Sites (LNS)	Yew Trees Wood, Carr House Meadows, More Hall Reservoir
National Park	Peak District National Park
Environmentally Sensitive Areas (ESA)	North Peak

For the Sheffield and Peak District Moors PLA, the Sheffield Wildlife Trust is involved in the partnerships for the “Moors for the Future: Peak District National Park” project. The key partners of this project include the Peak District National Park Authority, Yorkshire Wildlife Trust, Sheffield City Council, National Trust, Natural England, and the Royal Society for the Protection of Birds. Within the context of this project, a master map has been prepared aiming to increase public access and recreational facilities, achieving sustainable land management, dealing with issues related to the local economy and tourism, and increasing the involvement of the public (Sheffield Moors Partnership, 2014). Sheffield and Rotherham Wildlife Trust proposed the following management actions to deal with the main issues in the area: blanket bog restoration, appropriate grazing and burning regimes, woodland re-establishment.

B. South Sheffield Greenway

The South Sheffield Greenway lies within the western edges of the Peak District National Park and extends over Rotherham to the east. The total area of the South Sheffield Greenway PLA is 3019.39 ha. The main habitats included in this PLA are: river, ancient woodland, woodland, heathland, parkland and pasture. Some of the designated sites within this area are shown below (Table 11).

Table 11: Designated sites within the South Sheffield Greenway PLA

Designation	Site Name
Sites of Special Scientific Interest (SSSI)	Totley Wood, Moss Valley, Moss Valley Meadows
Local Nature Reserves (LNR)	Ecclesall Woods, Gleadless Valley, Bowden Housteads Wood / Carbrook Ravine, and Shire Brook
Local Nature Sites (LNS)	e.g. Leeshall Wood, Ecclesall Wood, Oakes Park

The South Sheffield Greenway PLA includes three of the Wildlife Trust’s Nature Reserves: Blacka Moor, Carbrook Ravine and Moss Valley Woodlands. Blacka Moor nature reserve constitutes a part of the Eastern Peak District Moors and includes 180 ha of heathland, woodland, grassland and bog habitats. Carbrook Ravine nature reserve covers 6.5 ha and contains different types of woodlands and extensive meadows. Lastly, the main habitat within the Moss Valley is woodland. The main issues in this area are invasive species and poor management. Thus, the management decisions and actions include the restoration of semi-natural habitats, the control of invasive species, getting connected lands into good management to enhance their ecological functionality and reduce the risk of flooding. The partners involved in this area include the South Yorkshire Forest Partnership as well as local businesses and industry.

C. River Don

The River Don PLA connects the habitat corridors of the River Don starting from its headwaters on the Barnsley Moors and passing through the city centre of Sheffield, and reaching to Rotherham. Within the boundaries of Sheffield, it covers a total area of 2820.60 ha. The main habitat types included in this PLA are: woodland, ancient woodland, grassland, wetland, heathland and farmland. Table 12 show some of the designated sites found in the River Don PLA.

Table 12: Designated sites within the River Don PLA

Designation	Site Name
Sites of Special Scientific Interest (SSSI)	Little Don Stream Section, Neepsend Brickworks, Neepsend Railway Cutting and Wharncliffe Crags
Local Nature Reserves (LNR)	Town End Common, Wharncliffe Heath, Wheata Woods, and Salmon Pastures
Local Nature Sites (LNS)	e.g Wharncliffe Woods, Beeley & Great Hollins Wood, Greno Wood

The River Don PLA is composed of two main parts, including 5 Wildlife Trust nature reserves. While Greno Woods and Carr House Meadows are located in the Upper Don PLA, Blackburn Meadows, Centenary Riverside and Salmon Pastures are situated in the Lower Don PLA.

D. Western Valleys (Rivelin, Loxley and Porter Valleys)

The Western Valleys PLA is composed of the Rivelin, Loxley and Porter river corridors, extending along the area between the edges of the Peak District National Park in the west and the River Don in the east. The Western Valleys PLA covers an area of 2711.20 ha, and the main habitats included in this area are: rivers, ancient woodland, woodland, parkland, pasture, meadow, wetlands and heathland. The Wildlife Trust nature reserves in this PLA are: Wyming Brook, Fox Hagg and Sunnybank, where the first two are located in the Rivelin Valley and Sunnybank is situated at the lower part of the Porter Valley (SRWT, 2014a). Some of the designated sites within this PLA are shown below in Table 13.

Table 13: Designated sites within the Western Valleys PLA

Designation	Site Name
Sites of Special Scientific Interest (SSSI)	Eastern Peak District Moors, Stannington Ruffs, Wadsley Fossil Forest
Special Areas of Conservation (SAC)	South Pennine Moors
Local Nature Reserves (LNR)	Loxley and Wadsley Common, Fox Hagg, Porter Valley Woodlands, Sheffield General Cemetery, and Sunnybank
Local Nature Sites (LNS)	e.g. Fox Hagg, Dam Flask to Rowel Bridge, Whitely Woods

As part of the Living Don project, the Sheffield Wildlife Trust aims to create an ecologically functional landscape in this PLA. The project partners of this PLA are: Sheffield City Council, Yorkshire Water, Sheffield Wildlife Trust, Environment Agency, Natural England, and the Friends of Porter Valley. The key actions targeted in this PLA are: woodland management, unimproved meadow and pasture conservation, wetland management of old mill ponds, industrial archaeology conservation and heathland management.

E. Blackburn Valley

Located in the north east part of the Sheffield, Blackburn Valley PLA covers the smallest total area of 689.47 ha, in which the main habitats are woodland and open water. This PLA includes Woolley Wood Local Nature Reserve, and also some of the LNSs, such as Westwood Country Park, Hesley Wood and Chapletown Park. The partners involved in Blackburn Valley are: Sheffield City Council, Sheffield Conservation Trust, and the Environment Agency. Although there is no project at present for the Blackburn Valley PLA, the issues and required actions have been identified on its map. Accordingly, any future project should take into account the antisocial behaviours in this area, and produce actions for community involvement in woodland and open ground habitat enhancements as well as supplying investment for recreational facilities.

4.5 Conclusions

The Sheffield City Council and Sheffield and Rotherham Wildlife Trust have attempted to define green and ecological networks spatially based on different methods and criteria. In this context, the main aims of the this chapter are to analyse the approaches used by planners and conservation organisations to define green and ecological networks in Sheffield and to identify the criteria according to which spaces and their associated habitats are included in connectivity routes. The Green Network and the Living Don have been examined in the light of the data collected through semi-structured interviews and spatial / visual map analysis.

This chapter firstly analyses the planning policy documents related to the Green Network to provide a better understanding of the evolution of the Green Network in Sheffield. This analysis revealed that the Green Network approach in Sheffield was first introduced into the planning policies with the SNCS in 1991. The SNCS was a highly` innovative and pioneering document at that time even though it was not entirely integrated with the rest of Sheffield’s planning policy. After the replacement of the SNCS with the UDP, the Green Network policy and the Proposals Map were included as part of the UDP. Thereafter, the Green Network policy and its Proposals Map have continued to undergo changes. Subsequent planning policy documents (the UDP and the SLP) have attempted to clarify and strengthen the original Green Network policy in the SNCS and have also integrated nature conservation with mainstream planning policies in Sheffield. Throughout this process, the Green Network policy has gradually evolved as a more “landscape scale concept” of nature conservation. Furthermore, for the first time the value of wildlife has been emphasised by referring to species of national, regional or local importance.

Both the Green Network and Living Don ecological network aim at protecting and enhancing biodiversity and its associated habitats, supporting ecological processes as well as maintaining human well-being by creating connections between the wildlife habitats and green spaces. However, some areas have been allocated purely for the benefit of wildlife within both approaches. Additionally, interviewees from SCC and SRWT also claimed that the need for human access and nature conservation can generally be managed together in practice, depending on the site characteristics. Hence, one of the main strengths of the Green Network and Living Don approaches is to deliver multiple functions for biodiversity and people as part of a comprehensive and integrative planning strategy.

In spite of having similar goals, the methods and the site selection criteria used for developing the Green Network and Living Don ecological network in Sheffield have resulted in two different approaches, in which there are significant differences in the spatial extent, components and representation.

When comparing the networks within the boundaries of Sheffield, the most striking difference is in their spatial extent. On the one hand, the Sheffield Green Network has been developed and mapped within the boundaries of the Sheffield Local Planning Authority. Accordingly, although there are Green Links heading towards the Peak District National Park which aim to allow the dispersal and genetic exchange of species (SCC, 2013a), the Green Network excludes the areas in the Peak District National Park, since this area is under the responsibility of the Peak District National Park Authority. On the other hand, the Living Don ecological network has its largest PLA, the Sheffield and Peak District Moors, within the boundaries of the Peak District National Park.

Both approaches focused on the potential connectivity of different habitats for identifying those networks, but neither has been developed in the light of a structural or functional connectivity analysis, nor have they defined the corridors or links with explicit reference to the permeability of the different habitats and the landscape matrix for the movement of species and people.

Relating to biodiversity and wildlife, the approaches have not specifically referred to the ecological requirements of associated species or species groups and accordingly, it was not explicitly spelt out which habitats in these networks will support the movement of particular species. This is contrary to informed opinion that ecological connectivity requires the consideration of the ecology and requirements of species (Taylor et al., 1993; Opdam et al., 2006; Ramalho and Hobbs, 2012). Therefore, the lack of information on the ecological requirements and movement behaviours of species is one of the most obvious weaknesses in both approaches. On the other hand, both of these approaches defined the routes for public accessibility by including currently accessible routes or areas for people.

In terms of their spatial components, both the Green Network and the Living Don are composed of a diversity of habitats, such as woodland, grassland and watercourses. In this context, the most obvious similarity between the two approaches was the use of watercourses as the main connectivity routes across Sheffield. This similarity can be explained by the fact that the watercourses generally tend to provide the best habitats for wildlife and the best recreational resources for people. Thus, both approaches aimed to benefit from the linear connectivity along the main rivers, streams and their valleys.

In the City Policies and Sites Pre-submission document of the SLP (SCC, 2013b) under the Policy F1 Pollution Control, it was stated that if a sensitive area requires to be protected from development, then it would include an environmental buffer. For example, the need for a buffer area with an approximate width of 6m has been mentioned between new development and the Black Bank Local Nature Site (SCC, 2013b). In spite of this, the areas allocated for buffer zones have not been shown on the Proposals Map. Whilst the first interviewee from SCC indicated that the Ecology Unit (SCC) tries to include areas acting as buffer zones as part of the Green Network, it was claimed that the determination of the distance for buffer zones was arbitrary.

The spatial components of the Green Network have been identified and explained in the policies of the Sheffield Local Plan. However, they have not been represented explicitly on the Proposals Map. Instead, the Green Network has been shown on the Proposals Map as a conceptual plan in the Sheffield Local Plan (SCC, 2013b). Therefore, we can claim that another weakness of the Green Network is its current representation on the Proposal Maps. This issue was emphasised by both interviewees as a weakening factor for the implementation of the Sheffield Green Network and its related policies. In particular, the interviewee from SCC pointed out the potential problems related to new development within the Green Network by stating that if you do not have clearly defined areas then it is really hard to argue the benefits of the Green Network in the planning process, and losses within the network seem to be inevitable.

Conversely, the development of the Living Don ecological network involves a pragmatic approach, in which the mapping process is based upon the use of existing datasets and the explicit spatial definition of the components of the network as “Core” and “Opportunity” sites, based on the biodiversity potential of these sites. “Core” sites have been further split into two categories taking into account their ecological value and overall quality: “Core Wildlife Sites” and “Core Green Spaces”. “Opportunity” sites are identified in terms of the potential for existing sites to improve biodiversity across the network. The whole Living Don has been further split into six Priority Landscape Areas to make them a more manageable size for the development of detailed action plans. Hence, the resulting map of the SRWT explicitly represented the spatial extents of all the components of the Living Don ecological network.

Although the interviewee from SRWT intended to include some areas to act as buffer zones, they have not yet been identified and shown on the map of the Living Don ecological network, since the mapping process was still in progress. Furthermore, as another positive point of the Living Don, SRWT intends to determine core areas, corridors, stepping stones, restoration zones, buffer zones and sustainable land use areas within each of these PLAs as the structural elements of the network. But, the digital map of the Living Don that I have received did not show the “Core” and “Opportunity” sites as it was mentioned in its methodology document, since the mapping process is still in progress. Therefore, it was not possible to determine which areas have been defined as “Core” and “Opportunity” sites and which functions are intended to be achieved within each PLA (such as supporting the movement of particular species, movement of people by walking or cycling).

In conclusion, these findings clearly show that although the Green Network and Living Don have established planning processes and outcomes, there is room for further improvements in both approaches. Additionally, the examination of current approaches to green and ecological networks provides some support for the conceptual premise that the definition of a green / ecological network is highly dependent on the methodology and site selection criteria for the inclusion of different habitats within the network. Since this research aims to evaluate alternative methods of defining potential connectivity and accessibility routes in urban areas, the following chapter is therefore dedicated to developing methods for deriving the potential routes of connectivity and public accessibility from underlying land cover and land structure and using their physical continuity as objective connectivity criteria for the selection of sites to be included in the potential routes.

Chapter 5 Landscape Structural Analyses and Development of Structural Connectivity Routes for Biodiversity and People

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5. 1 Introduction

Ecological and green networks have been considered one of the most important planning tools to deliver different ecological and social functions for biodiversity and people by providing landscape connectivity (Benedict and McMahon, 2006; Bennett, 2004; Forest Research, 2011). Broadly speaking ecological and green networks have been developed on the basis of two measures of landscape connectivity: structural connectivity and functional connectivity. Structural connectivity focuses on the actual physical connections between habitat patches and it is generally derived from physical / structural characteristics of the landscape (e.g. size and location of habitat patches, the distance between habitat patches) (Bennett 1998, 2003; Watts et al., 2008). Functional connectivity, on the other hand, does not necessarily require actual physical connections between habitat patches, and broadly refers to "the degree to which landscapes actually facilitate or impede the movement of organisms and processes" (Taylor et al., 2006; Meiklejohn et al., 2009).

The examination of the Green Network (SCC) and the Living Don ecological network (SRWT) as current approaches in the previous chapter has shown that neither SCC nor SRWT have used structural and / or functional connectivity to define green and ecological networks. In this regard, this chapter now focuses on identifying the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data, by addressing the following research questions:

1. Can criteria be derived to identify the potential routes of connectivity?
2. What forms do the potential routes of connectivity constructed using these criteria take?

This chapter considers structural connectivity as the main criterion to derive potential routes of connectivity for biodiversity and people. Accordingly, the chapter investigates the main characteristics of different land cover / use types to support structural connectivity in the landscape, and then derives potential connectivity routes for biodiversity and people without references to the requirements of particular species or people.

The chapter is divided into two parts. The first part focuses on the development of structural connectivity routes for biodiversity without reference to habitat requirements of species, and the second part concentrates on modelling structurally connected network of green spaces for people in the study area. Both these approaches make use of a specific technique for measuring landscape structure: landscape metrics.

5.2 Quantification of Landscape Structure

Landscape ecology emphasises the interactions between landscape structure (pattern), processes (function) and change (Forman and Godron, 1986; Urban et al., 1987; Turner, 1989; Turner et al., 2001). Landscape structure is an inherent and crucial aspect of landscapes and much work in landscape ecology involves assessing the relationships between structure, functions and change by quantifying landscape structure, and a significant number of these are on urban areas, often with an emphasis on the investigation of the changes in landscape structure by using time-series GIS datasets, high resolution remotely sensed data, and landscape metrics to characterise landscape functions (Herold et al., 2002; Matsushita et al., 2006; DiBari, 2007; Weng, 2007; Uy and Nakagoshi, 2007). In addition, quantifying landscape structure has been useful in providing baseline information to identify the potential ecological impacts of different land management options and setting suitable decision-makings for sustainable urban development (Deng et al., 2009; Aguilera et al., 2011), and for understanding the relationships between species' ecological requirements and the spatial structure of landscapes (Clark et al., 1998; Glennon and Porter, 1999; Bender et al., 2003; Kumar et al., 2009; Martensen et al., 2008; Shanahan and Possingham, 2009).

There are a range of methods and tools that have been developed to quantify landscape structure. These generally use vector or raster based categorical maps which divide the landscape into patches of different land cover / use types or classes. Landscape metrics are widely used to analyse, determine and evaluate the spatial structure of patches, classes and whole landscapes by providing information on the composition and configuration of landscapes (McGarigal and Marks, 1995; McGarigal, 2002; Botequilha-Leitão and Ahern, 2002; Botequilha-Leitão et al., 2006).

Landscape composition metrics (which are non-spatial: i.e. do not take account of the shape of patches or their spatial relationship to each other) describe the diversity and abundance of all patch types, such as the proportion, diversity, number and area of patches. Landscape configuration (spatial) metrics, on the other hand, require spatial information for their calculation which is associated with patch geometry or the spatial distribution of patches, such as the size and shape of patches, and the distance and connectedness between the patches of the same land cover / use classes (Gustafson, 1998).

Landscape metrics quantify the landscape structure at three levels (multilevel structure): patch, class and landscape level (McGarigal and Marks, 1995; McGarigal, 2002). Patch level metrics are computed for each of the individual patches within the given landscape and generally constitute the base for the calculation of class and landscape level metrics. Class level metrics take into account all the patches of a given land cover/use type (all woodland or all grassland patches), and because of this, they are generally considered to measure the extent and fragmentation of a given land cover/use type. On the other hand, landscape level metrics integrate all class types for the whole of the landscape and are concerned with the pattern of the entire landscape. Some metrics are specific to certain levels in this hierarchy, and each has to be interpreted in the context of the particular level in the hierarchy at which it is applied.

5.3 Methods

5.3.1 Dataset Preparation

In order to analyse landscape structure and derive potential connectivity routes I used two datasets, which were previously created hierarchical land cover and land use maps (see Chapter 3, Part 2). The land cover map with 34 classes at the highest level of detail (level 3) was used for the quantification of ecological connectivity. The land use map with 49 classes at the highest level of detail (level 3) was used for the quantification of different land uses which might allow people to move through the urban environment with maximum contact, or opportunity for contact, with vegetation and non-built areas.

The structural connectivity of land cover and land use types were quantified using a core set of landscape metrics. I used the software FRAGSTATS 4.1 (McGarigal et al., 2012) together with ArcGIS 10.1 to calculate landscape metrics. FRAGSTATS is standalone software and uses categorical maps which represent the landscape mosaic model of landscape structure in the raster data structure.

Since FRAGSTATS works with different raster dataset formats, I used ArcGIS 10.1 for the conversion of vector formatted land cover and land use layers (previously mentioned in Chapter 3), into raster format. After preparing all datasets in ArcGIS 10.1, FRAGSTATS 4.1 was used to compute a set of landscape metrics to quantify landscape structure and structural connectivity.

The following parameters were applied to the calculations of landscape metrics for all analyses conducted in this chapter (Table 14).

Table 14: Parameters that are applied for the calculation of landscape metrics

Parameter	**Land Cover and Land Use Maps**
Data Format	Raster format (Erdas Imagine Grid-.img)
Pixel Size	2 m
Neighbour Rule	Takes into account all of the 8 adjacent cells in the calculations (4 orthogonal and 4 diagonal neighbours)
Multilevel Structure	Class Level (the set of patches of the same land cover/use type)
Search Radius for Proximity (m)	100 m, 500 m, 1000 m

Within FRAGSTATS, patches are defined and described based on the specification of "Patch Neighbouring" rule. Firstly, the 4-cell neighbouring rule takes into account only the four adjacent cells sharing a common side with the central cell to determine the membership of patches.

On the other hand, the 8-cell rule considers all neighbouring eight cells, diagonal and orthogonal, to define patch membership. In the real world, landscape components have many different shapes. However, due to the rasterisation of dataset, those can be split into two or more diagonal patches, resulting in more fragmented patches. Therefore, for the calculations of landscape metrics, the 8-cell neighbouring rule was selected and hence the diagonally neighbouring cells were treated as one patch.

In addition to this, I calculated landscape metrics at class level, as they broadly characterise the fragmentation of a land cover / use class in a landscape and may provide a more in depth structural connectivity analysis.

As a measure of patch isolation / fragmentation, I computed the *Proximity Index* (PROX). In terms of the calculations of PROX, I set the search radii to 100 m, 500 m and 1000 m in order to obtain the change in the values for PROX. The variation in the values of PROX, contingent upon the selected search radius distances, was estimated to reflect whether there was a certain threshold which has a significant meaning for the interpretation of PROX index. Considerable differences in PROX values indicate the existence of such a threshold at which an important change in the degree of patch isolation and fragmentation occurs. In this specific case, even though the PROX values for three search radii distances show small variation, considering the extent of research area, to obtain a comprehensive result in the interpretation of *Proximity Index*, 1000 m was used.

The choice of resolution for raster datasets depends on its capability to represent landscape features accurately and also disk memory size for loading and processing. In order to determine the most suitable raster resolution, I converted vector layers into raster with 1 m, 2 m and 5 m (Figure 7).

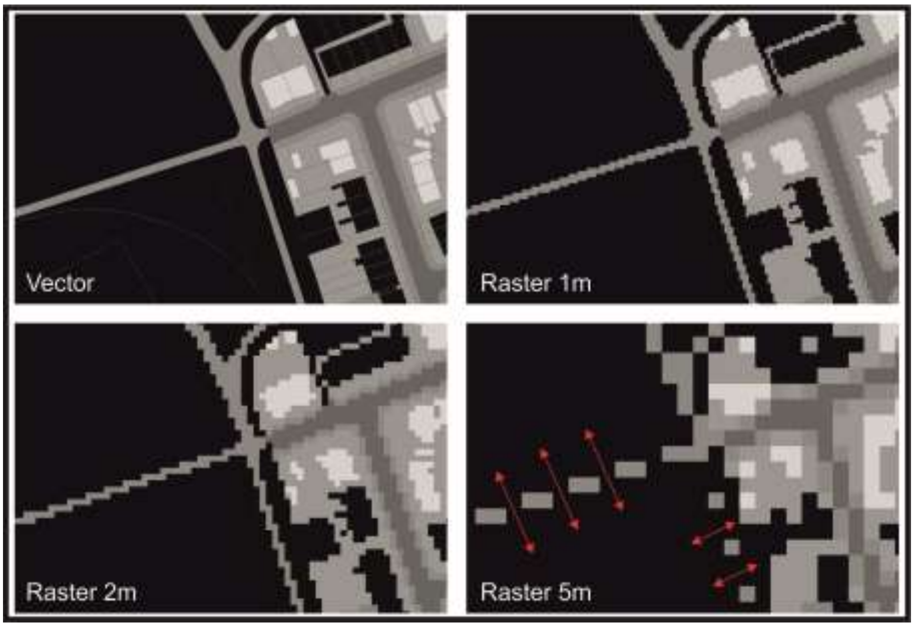


Figure 7: Vector and raster data representation with different resolutions

Raster data with 1 m cell size is the most realistic and preserved the data (especially for small and linear features) for the representation of vector dataset. However, due to the memory restrictions, I could not compute landscape metrics at 1 m resolution. When I used 5m raster resolution, I lost some details in my data as with many cracks in linear map objects. Because of this, I decided to run landscape structural analyses with 2m cell sized raster layers.

5.3.2 The Definition of Selected Landscape Metrics

I selected and calculated 7 landscape metrics in FRAGSTATS 4.1, because of their widespread use, straightforward interpretation, and capacity to represent landscape connectivity. Table 15 represent the summary of selected landscape metrics and the main reasons for their use in this study.

Table 15: Selected core set of landscape metrics (Botequilha-Leitão et al., 2006; McGarigal, 2014).

Metric	**Acronym and Range**	**Description and**	**Reason for Selection**
Percentage of Landscape (%)	0 < PLAND ≤ 100	The proportion of landscape occupied by a particular class type	PLAND and CA represent the proportional abundance of each land cover / use type as an indication of dominance in the landscape
Total Area (ha)	CA > 0, without limit	The sum of the areas of all patches for the given land cover / use type	
Patch Area (ha)	AREA_MN and AREA_AM > 0, without limit	The arithmetic and area-weighted mean size of the given land cover / use type	AREA is a fundamental characteristic of landscape structure
	AREA_SD and AREA_CV	Variability in Patch Area	
Radius of Gyration (m)	GYRATE_AM ≥ 0, without limit	GYRATE is the mean distance between each cell in a patch and the patch centroid	As a function of patch area, GYRATE measures the patch extent and physical connectivity. Also in combination with Patch Area gives an indication of the relative quality of patches found in the landscape
Number of Patches	NP ≥ 1, without limit	The number of patches of the given land cover type	NP Indicates the subdivision of landscape as a simple measure of fragmentation
Euclidean Nearest Neighbour Distance (m)	ENN_AM > 0, without limit	The shortest edge to edge distance between the adjacent patches of the same land cover / use type	Basic measures of patch fragmentation and isolation; in turn structural connectivity.
Proximity Index	PROX_AM ≥ 0	The degree of isolation and fragmentation within a specified search radius for the given land cover / use type	

5.3.2.1 Area-Edge Metrics

Area-edge metrics quantify the basic characteristics of landscape structure. Basically they measure the area of the patches and the amount of edges of these patches. *Class Area* (CA) is the total area of all patches in a class (e.g. total area of all woodland patches). *Percentage of Landscape* (PLAND) measures the percentage of the landscape covered by each class type. Both of these metrics are important to quantify the proportional amount of each class type and indicate the dominance in a landscape. The *Mean Patch Area* (AREA_MN), *Area-weighted Mean Patch Area* (AREA_AM), *Patch Area Standard Deviation* (AREA_SD) and *Patch Area*

Coefficient of Variation (AREA_CV) represent the distribution statistics of the patch area. AREA_MN equals the average patch size and AREA_AM equals the value of the total mean patch size multiplied by the proportional amount of a given patch. AREA_MN does not describe the whole landscape conditions, whereas, the area weighted mean patch size provides a landscape based perspective of the whole landscape structure.

Conversely, AREA_SD and AREA_CV measure the variability in patch size and they reflect the level of heterogeneity of patch structure in the landscape. AREA_SD measures the absolute variation in patch size. However, as the absolute variation is dependent on the mean patch size, it is difficult to measure variation in patch size without considering the mean patch area. Because of this, AREA_CV is generally preferable to AREA_SD, especially when comparing variability in the patch area among different classes or landscapes. AREA_CV measures the relative variability as a percentage of the mean patch area. However interpretation of AREA_CV can be misleading if there is no information on the number of patches, therefore it is important to take into account the other structural properties, such as the number of patches and the mean patch size, when using AREA_CV.

Radius of Gyration (GYRATE) quantifies how far across the landscape a patch extends its reach, on average. *Area-weighted Radius of Gyration* (GYRATE_AM) represents the average distance that an organism may traverse in a landscape from a random starting point and travelling in random directions in the particular patch (Keitt et al., 1997). Therefore, GYRATE_AM measures physical connectivity of the given patch type at the class level. The examination of values for GYRATE_AM in combination with AREA_AM allows determination of the relative quality of patches in the landscape.

Area-edge metrics reflect basic, but important, information that can be used to interpret the connectivity of the given landscapes. However, it is important to keep in mind that all those metrics are affected from both the resolution of the dataset and the extent of the study area.

5.3.2.2 Aggregation Metrics

Aggregation metrics reflects the tendency of landscape patches to be spatially clustered. *Number of Patches* (NP) simply refers the number of the given patch type at the class level and quantifies the degree of subdivision of the corresponding class. When evaluated with AREA_AM, it is interpreted as the simplest measure of landscape fragmentation. If AREA_AM of a patch type is low with a large number of patches, this patch type can be evaluated as much more fragmented relative to another with a few but bigger sized patches.

As the simplest measure of isolation, *Euclidean Nearest Neighbour Distance* (ENN) measures the shortest edge to edge distance between surrounding patches of the same land cover/use class. As a form of ENN, *Area-weighted Mean Euclidean Nearest Neighbour Distance* (ENN_AM) is the total mean distance between each patch and its nearest neighbour multiplied by the proportional abundance of the given patch for the all patches. The area-weighted mean gives greater weight to larger patches and emphasises the importance of larger patches in the functioning of the landscape. However, the single nearest patch may not indicate the entire neighbourhood and isolation for a given patch, so combining the information on the patch size and proximity within a specified search radius for the corresponding patch type, *Proximity Index* (PROX) quantifies both the degree of isolation and fragmentation. This metric gets larger values if the corresponding patches are separated by shorter distances with a large area and closer proximity to each other. Again, using *Area-weighted Mean Proximity Index* (PROX_AM), we can take account of the dominant role of large patches in the landscape. Particularly, when combined with ENN_AM, PROX_AM can be evaluated as an indicator of isolation and fragmentation.

5.3.3 Analysis of Structural Connectivity

As mentioned earlier, structural connectivity refers to the degree to which habitat patches are physically / structurally linked to each other. Therefore, the construction of structural connectivity routes initially requires the identification of individual land cover /use types. These individual land cover / use types can be defined at different levels of hierarchy, from a single land cover / use type to the aggregation of multiple land cover / use types which belong to a broader land cover / use category.

For this study, I used two types of dataset to identify individual land cover / types to construct structural connectivity routes. The first dataset was the hierarchical land cover map which includes 34 classes at the most detailed level (level 3). This map was used to identify potential habitat patches to construct structural connectivity routes for biodiversity. At the broadest level (level 1), this land cover map includes 4 main land cover categories: *Vegetation*, *Surfaces*, *Water and Wetlands*, and *Buildings and Structures*. Among these broad land cover categories, only *Vegetation* and *Water and Wetlands* were taken into account as habitats for biodiversity to construct structural connectivity networks (totally 24 land cover categories at level 3).

The second dataset was the hierarchical land use map which includes 49 classes at the most detailed level (level 3) and this map was used to identify potential green spaces to construct structural connectivity routes for people. At the broadest level (level 1), the land use map includes 4 main land use categories: *Artificial, Natural and Semi-natural Land, Agriculture and Open Lands,* and *Water*. Among these broad land use categories, *Natural and Semi-natural Land* and *Artificial* land uses were taken into account to construct structural connectivity networks (in total 13 land use categories at level 3).

Afterwards, I conducted the structural analyses of land cover and use datasets using the FRAGSTATS landscape metrics explained in the previous section. The reason for land cover structural analysis was to determine the land cover and use types which can provide the greatest gain in connectivity to structural connectivity routes. I calculated the selected 7 landscape metrics in FRAGSTATS 4.1 for each land cover and use category, and then examined the results to determine their structural connectivity. When evaluating structural connectivity, the larger patch size with a small number of patches, and closer proximity of the same land cover patches were considered as an indication of high structural / physical continuity.

5.3.4 Deriving Structural Connectivity Networks

Regarding the biodiversity, I focused on the sub-classes of *Vegetation* and *Wetlands and Water* land covers as habitats for species. Hence, the land cover categories of *Surfaces, and Buildings and Structures* were excluded from structural connectivity networks for biodiversity. The structural connectivity routes for biodiversity were delineated without reference to the requirements of particular species, since I examined the potential contribution of different land cover types into structural connectivity networks.

In order to construct structural connectivity routes for biodiversity, each land cover type (at level 3) of *Vegetation* and *Wetlands and Water* was considered as discrete habitat units of a habitat network (at level 2). Accordingly, the individual land cover categories of the same class (at level 3) were added together to construct structural connectivity routes (habitat networks). The most structurally connected land cover categories at level 3 were regarded as the starting point for deriving structural connectivity routes, as they were thought to provide the greatest gain in connectivity for the networks. Then, adding less connected land cover categories to the most connected ones in ArcGIS 10.1, I obtained the networks of habitats at each classification level. As a result, I created 7 structural connectivity networks for biodiversity based on the original land cover map but with different hierarchical level of land cover types: *Woodland and Shrub, Mixed Vegetation, Grasslands, Heathlands, Cultivated Land, Water* and *Wetlands*.

As an example, at the highest level of land cover classification (at level 1), *Water and Wetlands* broad category is split into *Water* and *Wetlands* (at level 2). Further to that, *Water* land cover sub-class is composed of *Standing Water* and *Running Water*, and *Wetlands* are composed of *Heath Dominated Bog, Grass Dominated Bog,* and *Marsh, Reeds and Saltmarshes* (at level 3). If we assume that the *Heath Dominated Bog* has the highest, and *Marsh, Reeds and Saltmarshes* has the lowest structural connectivity. In this case, *Heath Dominated Bog* regarded as the first component of the network of *Wetlands*. So, adding the less connected *Grass Dominated Bog* patches to *Heath Dominated Bog*, and then *Marsh, Reeds and Saltmarshes* to these land covers, the network of *Wetlands* was obtained.

Also, at each stage of the network construction process, I determined whether the new habitat units (a set of aggregated land cover categories) show a change in the degrees of structural connectivity relative to the previous set of aggregated habitat units. The change in structural connectivity was examined using landscape metrics in FRAGSTATS 4.1, as I added the less connected land cover types to the network.

With regard to structural connectivity routes for people, each land use type (at level 3) of *Natural and Semi-natural Land* were considered as a discrete green space unit of a wider green network (at level 2), and *Paths* and *Pavements* (at level 3) under *Artificial* land uses were considered as the main routes for the movement of people by walking (at level 2). Using the same approach to construct networks for biodiversity, the individual land use categories of the same class (at level 3) were added together, resulting in *Recreation and Leisure* and *Mixed Vegetation* networks. I then added *Paths* and *Pavements* to the *Recreation and Leisure* and *Mixed Vegetation* to construct the final structural connectivity routes for people. As a result, I created 2 structural connectivity networks for people, based upon the original land use map: the *Recreation and Leisure* and the *Mixed Vegetation.*

Part 1 Ecological Connectivity

The part aims to prioritise the different land cover types for the inclusion in the potential routes of connectivity without reference to the requirements of particular species. The prioritisation criteria is based on actual physical connections between land cover patches as potential habitats for biodiversity and used to determine which land cover types into the potential networks gives us the greatest gain in connectivity.

Based on land cover structural analysis, this part addresses the following sub-research questions:

3. Taking into account the structural characteristics, what are the most favourable land cover types to support structural landscape connectivity?
4. What forms do the potential routes of connectivity take and how does the structural connectivity change by aggregating less connected land cover types of a broad land cover category to the most connected ones?

5.4 Land Cover Structural Analyses

5.4.1 Methods

I used FRAGSTATS metrics to estimate structural connectivity through a joint interpretation of Area-Edge and Aggregation Metrics at the class level, using the hierarchical land cover map that I created previously (see Chapter 3, Part 2). This land cover map consists of 4 land cover types at the level 1, 10 and 34 subclasses at the level 2 and level 3, respectively.

Initially, the results derived from the most detailed land cover classification level (level 3) were evaluated to find out the structural connectivity of each land cover in the study area. The structural connectivity of each land cover type was assessed on the basis of information obtained from landscape metrics (see section 5.3.2 for the details of landscape metrics). In general terms, this information relates to the area and number of patches, and the proximity of the same land cover patches. When evaluating the results of landscape metrics, I started from the dominant land cover types.

There are 34 land cover classes in the study area at level 3. The structural connectivity of each of these land covers were measured using landscape metrics at the class level. However, as I aimed at prioritising land cover types to derive the potential routes of connectivity for biodiversity, only the sub-classes of *Vegetation*, and *Water and Wetlands* land covers at level 3 were considered in the analysis. At level 3, *Vegetation* and *Water and Wetlands* include 19 and 5 sub-classes, respectively (see Chapter 3, Part 2, page 78). Therefore, totally 24 land cover types were analysed and only the results of those with high structural connectivity were reported. Because the focus of this analysis was on biodiversity, I did not include the sub-categories of *Surfaces,* and *Buildings and Structures* land cover classes to derive potential structural connectivity networks.

Then, I aggregated the individual land cover types of the same class (see above for a description of classes), starting from most structurally connected to less connected to delineate structural connectivity routes for biodiversity and measured the change in structural connectivity in the derived connectivity routes using FRAGSTATS.

5.4.2 Results of Land Cover Structural Analysis

The overall results for the analysis of the land cover structural network, together with their landscape metrics, are given in Appendix 6.

As the dominant land cover types, *Improved Grassland, Broadleaved Woodland* and *Private Gardens* cover 13.10%, 10.94% and 9.62% of the total research area, respectively. Among these three land cover types, *Improved Grassland* has the highest AREA_MN (2.46 ha) with the lowest number of patches (NP= 2580). However, the significant difference between AREA_MN and AREA_AM suggests that *Broadleaved Woodland* and *Improved Grassland* show higher variation in their patch sizes compared to *Private Gardens*. Further analysis of variation in patch size confirms that the patches of these two classes show a heterogeneous pattern ranging from very large patches to small ones with high values for AREA_SD and AREA_CV.

The common structural properties of *Broadleaved Woodland* and *Improved Grassland* have low values for ENN_AM, high values for PROX_AM and GYRATE_AM with coarse grain size (AREA_MN) and fewer numbers of patches (NP), implying that those land cover types are structurally more connected compared to all other land cover types at level 3. As expected, *Private Gardens* reported the highest NP (19413) with the lowest AREA_MN and AREA_AM among these three land cover types. The low values for PROX_AM (635.44) and GYRATE_AM (69.56) further confirmed that the patches of *Private Gardens* are structurally less connected. Contrary to expectations, it reported very low ENN_AM (9.17 m). This may be a result of clustered distribution of the patches of *Private Gardens* around *Buildings and Structures*, especially in the city centre.

Another dominant land cover type in the study area, *Heath Dominated Bog* (8.36%), has the highest AREA_MN and AREA_AM but a small number of patches (NP = 143). Considering the fact that AREA_AM (2128.67 ha) is more than 50% of its CA (4055.34 ha), with the largest AREA_MN of 28.36 ha, we can conclude that *Heath Dominated Bog* contains one extremely large patch as well as many small sized ones. This result is also confirmed with the highest AREA_SD (244.06) and a considerably high AREA_CV (860.59). *Heath Dominated Bog* reported the highest PROX_AM (40236.13) with a considerably low ENN_AM (9.56 m) and the second highest value for GYRATE_AM (2755.77). Hence, it appears to be the most connected land cover type in the study area at this level of classification.

Another important finding of the landscape structural analysis is that *Heather* and *Heather Grassland* together occupy 12.53% of the total landscape, with a lower number of patches and higher mean patch size. However, comparing values for GYRATE_AM, ENN_AM and PROX_AM, it can thus be suggested that *Heather Grassland* represents higher structural connectivity than *Heather* land cover type. In addition to this, occupying an area of 2633.57 ha, *Arable* reported a slightly higher number of patches with lower AREA_MN (0.97 ha) and AREA_AM (20.73 m). Even though *Heather* reported moderately high mean and area-weighted mean patch size, examination of ENN_AM, PROX_AM and GYRATE_AM values for *Heather* and *Arable* altogether, revealed that *Arable* has relatively higher structural connectivity than *Heather*.

Occupying only 3.33% of the total landscape area, the patches of *Rough Grassland* have a highly scattered and isolated pattern (PROX_AM= 526.12, ENN_AM= 42.11 m). With the lowest mean patch area (AREA_MN=0.01 ha), *Roadside Vegetation* is composed of a large amount of small sized patches covering 1.31% of the whole landscape. The data obtained from the calculation of connectivity metrics (GYRATE_AM= 108.89, PROX_AM= 184.28, ENN_AM= 8.69 m), imply that *Roadside Vegetation* has a weak structural connectivity compared to the aforementioned land cover types. On the other hand, the rarest three land cover types are *Orchard, Felled* and *Young Trees* with 12.27 ha, 16.07 ha and 17.59 ha, respectively. Even though *Felled* land cover type has the smallest number of patches (44), its values for AREA_MN and AREA_AM are the highest compared to the *Orchard* and *Young Trees*. In addition, the highest AREA_SD and AREA_CV values for *Felled* represents relatively high patch size variability. Covering the lowest percentage of area (PLAND=0.03%) in the landscape, *Orchard* land cover type has the smaller patches on average among these three land cover types. Taking into account the information on its mean and area weighted mean patch size, it seems that the sizes of *Orchard* patches are more similar to each other than those of *Young Trees* and *Felled*, since the difference of these two metrics is the lowest.

The structural landscape analysis at class level has shown that amongst 34 land cover classes *Improved Grassland, Broadleaved Woodland, Private Gardens* and *Heath Dominated Bog* occupy 42.01% of the landscape with a total area of 20386.47 ha. The results of this investigation also show that among these, *Heath Dominated Bog* represents the strongest structural continuity with a significantly large grain size. This is followed by *Broadleaved Woodland* and *Improved Grassland*. *Improved Grassland* covers a larger area (13.10%) than *Broadleaved Woodland* (10.94%) with a smaller amount of patches; therefore we may assume that its structural connectivity is stronger. However, examining upon connectivity metrics, the values for PROX_AM, ENN_AM and GYRATE_AM revealed a contradiction as an indication of higher structural continuity of *Broadleaved Woodland*. Another important finding was that *Heather Grassland*, on average, has a slightly higher level of structural connectivity compared to *Arable* and *Heather* land cover category. This is followed by *Conifer Woodland, Amenity Grassland* and *Unimproved Acid Grassland*.

5.4.3 Deriving Networks and Measuring Their Structural Connectedness

The potential structural connectivity networks for biodiversity were delineated by aggregating the sub-classes of the same land cover categories at a higher level. Hence, taking into account the relative physical connectivity of different land cover types to each other, I first aggregated the second most connected land cover type to the most connected one at level 3. I continued this process until I obtained the broader land cover category at level 2. In this way, I generated 7 different routes of connectivity. During this process, the sub-classes of a broad land cover category, which do not have significant importance in terms of structural connectivity and total area, were added to the network together as a one land cover patch. The change in the physical continuity was also examined for each step of network delineation. As mentioned earlier, these networks were derived by adding the less connected land cover type to the most connected one. Therefore, in the following sections, the derived structural connectivity networks were organised starting from the most connected land cover type at level 3.

Water and Wetlands

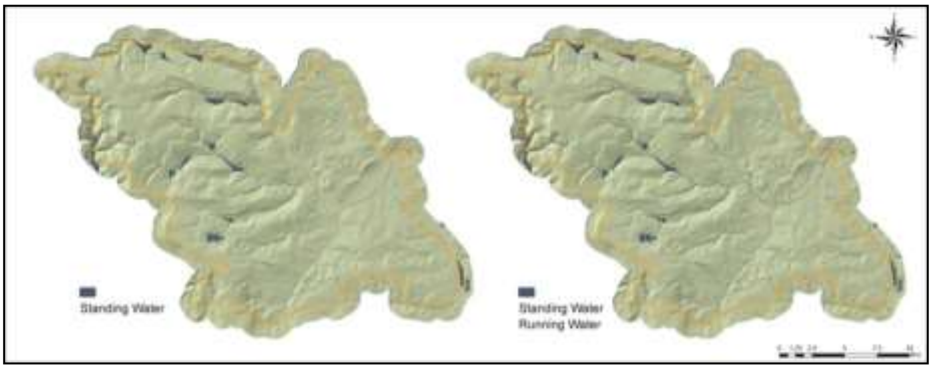
Heath Dominated Bog, as a component of *Wetland* at level 2, is the most connected land cover type at level 3. *Grass Dominated Bog*, and *Marsh, Reeds and Saltmarsh* do not have high structural connectivity at level 3. Therefore, I added the patches of *Grass Dominated Bog*, and *Marsh, Reeds and Saltmarshes* to *Heath Dominated Bog* to delineate the network of *Wetlands* (Map 9, for details see Appendix 6A).

Map 9: Network of *Wetlands*

When these 3 sub-classes are aggregated, *Wetlands* reported higher AREA_AM, PROX_AM with a lower ENN_AM compared to the *Heath Dominated Bog*. Also, even though *Marsh, Reeds and Saltmarshes* land cover class reported very weak physical connectivity at level 3, when we consider *Wetlands* as a system, together with *Heath Dominated Bog* and *Grass Dominated Bog*, its structural connectivity gets stronger.

The network of *Wetlands*, with the lowest NP (372) and the highest AREA_MN (15.54 ha), occupy almost one eighth of the whole landscape at level 2. However, its values for NP and CA (5781 ha) altogether with a big discrepancy between its AREA_MN and AREA_AM values, implies the existence of one or a few quite large patches with many quite small sized patches in the landscape. Upon examining results for GYRATE_AM, ENN_AM and PROX_AM for *Wetlands*, I found that this land cover type reported the highest GYRATE_AM (26772.19) and PROX_AM (49597.34) with a quite small distance between its individual patches (ENN_AM=13. 01 m) at level 2. Taking these together, it seems that the *Wetlands* network has the highest structural continuity of all networks as well as the clustered spatial distribution of its patches within the Peak District National Park.

Water broad land cover type consists of *Standing Water* and *Running Water*, occupying 1.29% and 0.34% of the total landscape area, respectively (Map 10, for details see Appendix 6B).



Map 10: Network of *Water* features

While at level 3, *Standing Water* reported slightly higher structural connectivity, when I aggregated the patches of *Standing Water* and *Running Water* land cover types together, they reported a significant increase in NP (from 1386 to 5004) with very low AREA_MN (from 0.46 ha to 0.16 ha), AREA_AM (from 32.42 ha to 26.10 ha) values and much higher variability in mean patch size (AREA_CV from 834.24 to 1279.35). However, considering the substantial decrease in ENN_AM (from 40.90

m to 17.12 m) and increase in PROX_AM (from 437.29 to 869.07), we can claim that together *Standing Water* and *Running Water* represent structurally more connected patches at level 2.

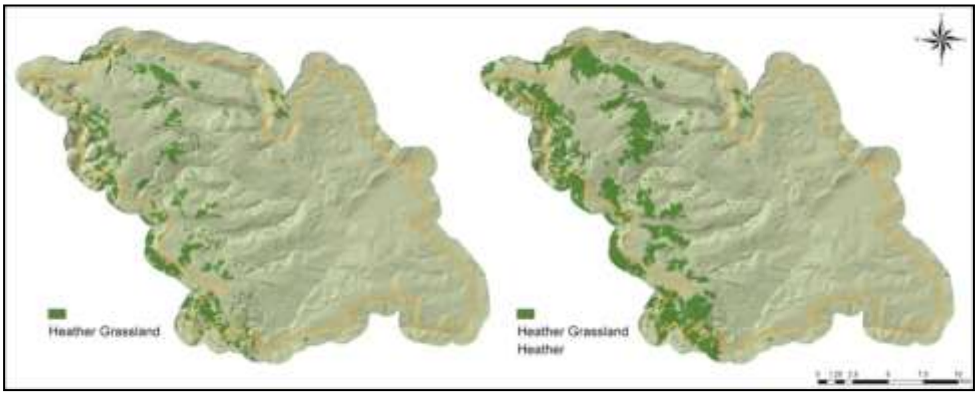
In terms of its spatial pattern, the *Water* network is well distributed throughout the study area. While, *Standing Water* patches are mainly located in and around the Peak District National Park, *Running Water* features are generally characterised with linear landscape features and distributed across the study area. Overall, the network of *Water* features reported the second lowest total area (CA= 793.16 ha) by covering 1.63% of the whole landscape. The high value of AREA_CV and the difference between AREA_MN (0.16 ha) and AREA_AM (26.10 ha) can be explained by the existence of many small sized lakes and ponds or other water features. Another important structural characteristic of *Water* is that it has relatively high GYRATE_AM (289.52). It can, therefore, be assumed that the *Water* land cover category is characterized by high inter-patch connectivity due to the presence of rivers and brooks, and large reservoirs. However, low PROX_AM (869.07) value indicates that the patches of *Water* land cover category are relatively more isolated and fragmented compared to other land cover types.

Additionally, overall the *Water* network is characterised with the lowest structural connectivity in all derived habitat networks. But, this result was unexpected since the *Water* network includes the linear *Running Water* features which generally have strong physical connections in the landscape. This inconsistency may be due to the rules of land cover map creating process, where each land cover category was identified and mapped on the basis of available data sources. In general, *Water* features that have overlaps with roads and bridges are classified under these land cover categories. Hence, it is important to bear in mind the possible bias in these results.

Vegetation

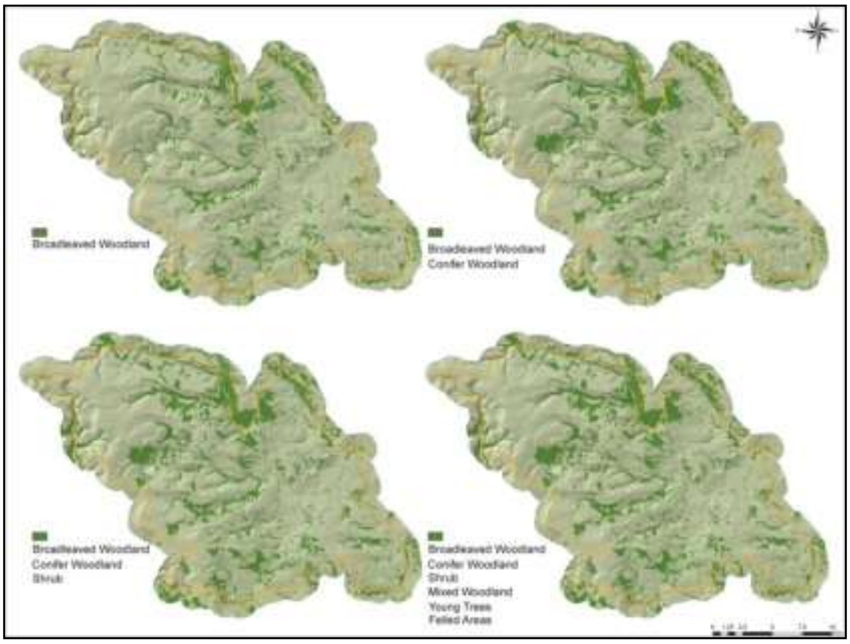
The *Heather Grassland* land cover category is the fourth physically most connected category at level 3. However, when I aggregated this land cover type with *Heather* (sixth most connected land cover type at level 3) under *Heathlands* land cover category at level 2, it gets structurally more connected by reporting much higher

PROX_AM (35535.92), AREA_AM (158.23 ha), GYRATE_AM (557.70 m) and lower ENN_MN (18.47 m) than its individual components. This is assumed to be a function of the addition of very large and close or adjacent patches from *Heather* to *Heather Grassland* (Map 11, for details see Appendix 6C). The *Heathlands* network is mainly distributed in and around the Peak District National Park, and particularly in the surrounding areas of the *Wetlands* network.



Map 11: Network of *Heathlands*

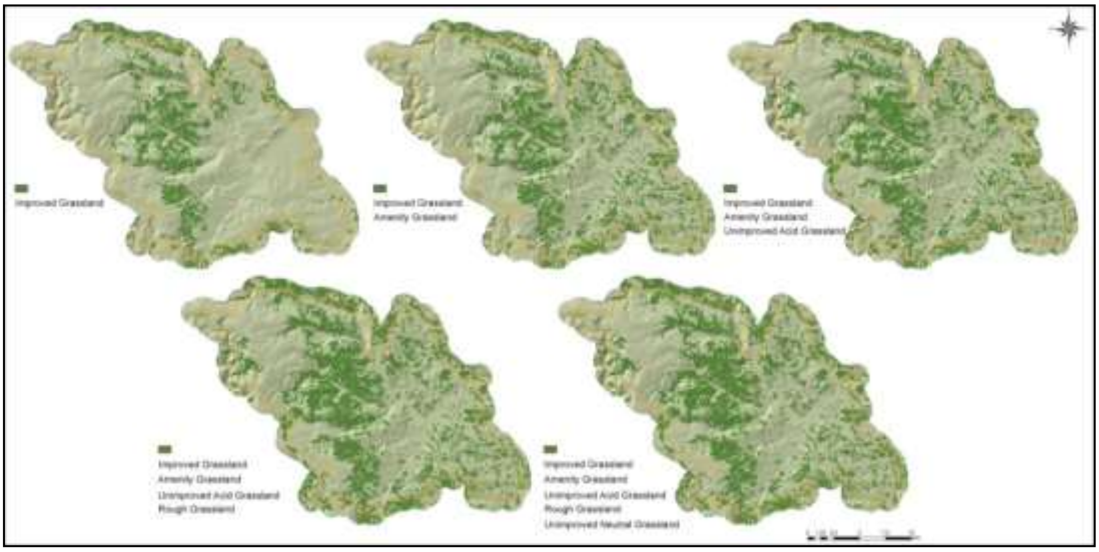
Map 12 represents the network of *Woodland and Shrub* land cover categories (for details see Appendix 6D). *Broadleaved Woodland* is the second most connected land cover types occupying 10.94% of the total landscape area at level 3.



Map 12: Network of *Woodland and Shrub*

When I added the patches of *Conifer Woodland* to *Broadleaved Woodland*, together they reported higher PROX_AM (from 13907.14 to 16861.90) and lower ENN_AM (from 12.15 m to 9.44 m) with a small amount of increase in its NP (from 8258 to 8502) as a result of aggregation. Additionally, values for AREA_MN and AREA_AM are increased with a slight increase in GYRATE_AM (from 336.51 m to 357.16 m), as an indication of higher degrees of structural connectivity. However, when I continued to add *Shrub*, *Young Trees, Felled* and *Mixed Woodland* land cover types to the network, did not show an important change, since the values for PROX_AM, ENN_AM, GYRATE_AM and AREA_AM were almost the same. In general, the *Woodland and Shrub* network is spatially distributed throughout suburban parts of the study area, excluding the lands in the Peak District National Park and the built-up areas of Sheffield.

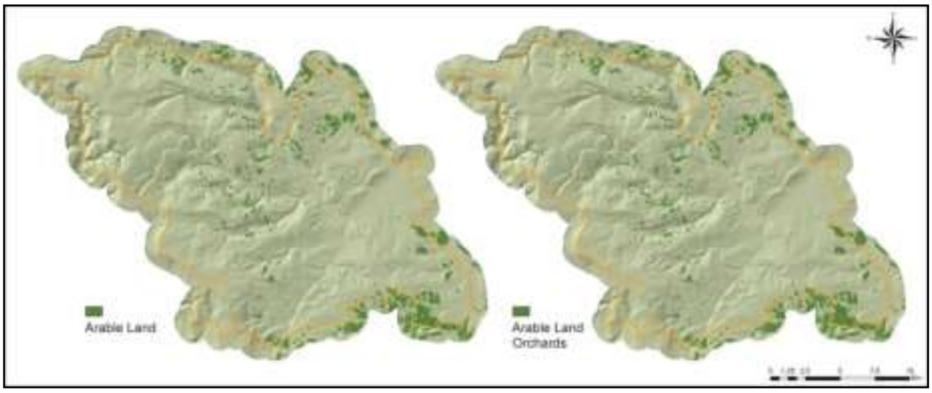
In order to delineate the *Grasslands* network, initially I added the patches *Amenity Grassland* to *Improved Grassland* and (Map 13, for details see Appendix 6E).



Map 13: Network of *Grasslands*

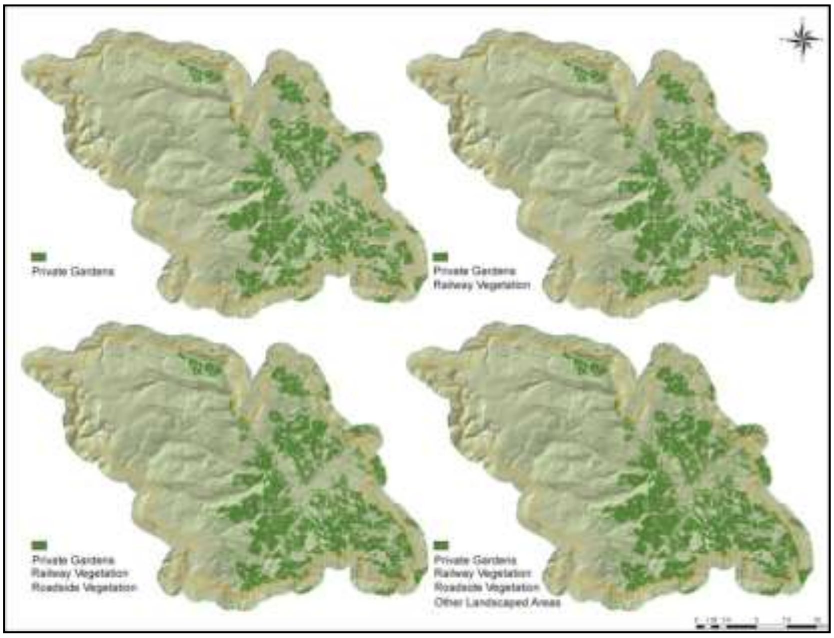
Even though *Improved Grassland* (13.10% of the total landscape) at level 3, has been found as the third most connected land cover type, when joined with the patches of *Amenity Grassland* (6.68% of total landscape), together they reported lower values for GYRATE_AM (from 224.12m to 203.97 m), PROX_AM (from 10055.18 to 8159.70, AREA_MN (from 2.46 ha to 0.79 ha) and AREA_AM (from 28.57 ha to 23.96 ha). These results were interpreted as lower degrees of connectivity, depending on joining many small sized patches of *Amenity Grassland* to the network. Also, the decrease in AREA_MN and AREA_AM with higher AREA_CV (from 325.49 to 540.73) confirmed this interpretation. On the other hand, when I added all the remaining land cover sub-classes of *Grasslands* to the network, altogether they reported very high PROX_AM and GYRATE_AM with much larger AREA_AM and lower ENN_AM. Hence, we can simply suggest that the network of *Grasslands* is more structurally connected than its individual subclasses. The spatial distribution of the *Grasslands* network shows a very similar pattern with *Woodland and Shrub* network, where its components are mainly located in and around the sub urban areas of the study area, excluding the Peak District National Park and built-up areas of Sheffield. Additionally, even though the *Grasslands* network covers the largest area compared to all derived networks, its structural connectivity is lower than *Heathlands* and *Woodland and Shrub* networks due to the effects of far distant and small sized patches in the network.

At level 2, *Arable* (5.43%) and *Orchard* (0.03%) land cover sub-types constitute the *Cultivated Land* network which is mainly located in and around the Green Belt with scattered patches distribution of its constituents (Map 14, for details see Appendix 6F). Adding the patches of the *Orchard* to *Arable*, while the values for PLAND and NP increased, together the patches of these two land cover types reported slightly lower values for PROX_AM, ENN_AM, GYRATE_AM, AREA_MN and AREA_AM. Therefore, we can say that structural connectivity remains almost constant even when we aggregate these land cover sub-classes.



Map 14: Network of *Cultivated Land*

Mixed Vegetation is composed of *Private Gardens*, *Roadside Vegetation*, *Railway Vegetation* and *Other Landscaped Areas* at level 2 (Map 15, for details see Appendix 6G). Among these, *Private Gardens* land cover is the most connected land cover type at level 3. Adding *Railway Vegetation* to *Private Gardens* resulted in an increase in NP (from 19413 to 20072) with almost the same AREA_MN and AREA_AM values. Also, very similar values for GYRATE_AM, ENN_AM and PROX_AM showed us that the structural connectivity of the network remained almost the same. On the other hand, when I added the patches of *Roadside Vegetation* to the network, the NP increased sharply (from 20072to 46252) with a lower value for AREA_MN and slightly larger AREA_AM.



Map 15: Network of *Mixed Vegetation*

However, examining the values for ENN_AM and PROX_AM showed that the distance between the patches of the network became shorter, indicating stronger physical connectivity. Finally, *Other Landscaped Areas* was added to the network to obtain *Mixed Vegetation* network. The resulting network had the same AREA_MN and slightly larger AREA_AM. In addition to this, relatively lower ENN_AM with higher GYRATE_AM and PROX_AM were altogether evaluated as a slight increase in the structural connectivity for the *Mixed Vegetation* network as a whole. Therefore, we can say that the network of *Mixed Vegetation* has stronger structural connectivity than its individual components at level 2.

As expected, the resulting *Mixed Vegetation* network is largely distributed around the built-up area of Sheffield, where the patches of *Roadside Vegetation* provide linear connection towards to the Peak District National Park.

5.4.4 Summary

The first part of Chapter 5 aimed to determine potential land cover types to be included in potential networks based on high structural connectivity, without reference to the requirements of particular species. This aim was achieved by measuring the structural connectivity of individual land cover types, determining the most connected ones, deriving networks of the same broad land cover categories and measuring the change in their connectivity.

The land cover structural analysis revealed that *Heath Dominated Bog* represents the highest structural connectivity with a small amount of large grain sized patches in all land cover classes. When it was aggregated with *Grass Dominated Bog, and Marsh, Reeds and Saltmarshes* to form the *Wetlands* network, structural connectivity increased. Also, the *Wetlands* network was characterized by the greatest structural continuity with a dense cluster of larger patches amongst all structural connectivity networks. Regarding the *Water* features network, the number of patches increased when I added them together; however, the closer proximity of its patches indicated an increase in its structural connectivity. While the network of *Wetlands* reported the highest landscape connectivity, *Water* features network was the least connected among all derived networks.

Within the networks of *Vegetation*, I initially derived the *Heathlands* network. Similar to the *Wetlands* network, the *Heathlands* network showed stronger structural connectivity with a smaller amount of patches than its individual components, namely *Heather Grassland* and *Heather*. As a constituent of the *Woodland and* Shrub network, Broadleaved *Woodland* has the second highest level of structural continuity at level 3. However, when aggregated with the patches of *Conifer Woodland*, the structural connectivity became stronger with a larger patch area and closer proximity. As I continued to add the remaining sub-classes to the *Woodland and Shrub*, the structural connectivity remained almost the same.

On the other hand, *Improved Grassland* was the third most connected land cover category at level 3. However, when it is aggregated with the patches of *Amenity Grasslands*, its connectivity became weaker, due to the inclusion of numerous small sized and far distanced patches of *Amenity Grasslands* in the network. But, when aggregated with remaining *Grasslands* land cover types, the network represented much more connected pattern. The *Cultivated Land* network did not show an important change in its structural connectivity as a result of aggregation.

In terms of the *Mixed Vegetation* network, when I added the patches of *Railway Vegetation* to the *Private Gardens*, the structural connectivity of the network remained almost the same. As I continued to add the remaining sub-classes to the network, structural connectivity continued to increase slightly. Aggregating *Roadside Vegetation* showed a sharp increase in connectivity, whereas, the *Other Landscape Areas* resulted in a slight gain to the structural connectivity of the whole network.

Overall, these findings show that generally structural connectivity gets stronger when we aggregate the subclasses of a land cover category, starting from the most connected to the least connected. When I added neighbouring large sized patches together, then the structural connectivity of networks became stronger. Contrary to this, when smaller sized and widely spaced patches were added together, structural connectivity became weaker. Hence, the structural connectivity of derived networks largely depends on the spatial characteristics of land cover types that we add to the network, such as the size of the patches, the distance between the patches of added land cover categories and the distance between the aggregated land cover categories.

Part 2 Social Aspects

The crucial role of urban greenspaces in delivering benefits to public has been recognised and accordingly reflected into public policy commitments in an attempt to provide access to greenspaces for the all residents in the UK (Barbosa et al., 2007). In the widest sense, accessibility is defined as “the ease of reaching destinations from a location using a particular transport system” (Dalvi and Martin, 1976; Levine and Garb, 2002). Typically, the public accessibility to different destination in urban areas has been assessed by measuring the proximity of residences to the available facilities (e.g. green spaces, public utilities), or the proportion or number of facilities based on specified rules (e.g. the proportion of facilities within a buffer zone per population, or the closest public facilities to residences over a road / transport network) (Barbosa et al., 2007; Comber et al., 2008; Sotoudehnia and Comber, 2010; Dai, 2011).

Pauleit et al. (2003) state that the concept of accessibility involves a wide range of interactions between people and green spaces, “from the purely visual to the right to enter a green space, move about freely and experience it without disturbance”. In this context, I am interested in networks of greenspaces which might allow people to move through the urban environment with maximum contact, or opportunity for contact, with vegetation and non-built areas. Therefore, for this research a landscape structural analysis approach was used to determine the contribution of different green spaces into potential networks for people.

This part of Chapter 5 aims to prioritise the sub-classes of *Natural and Semi-natural Land*, which would provide the strongest structural connectivity together with the patches of *Paths and Pavements*. Regarding this, the following questions are addressed:

3. To what extent are different land use types more connected inherently considering their structural properties?
4. How differently do the structural landscape connectivity patterns appear for public accessibility when we add less connected land use patches to the most connected ones?

5.5 Land Use Structural Analyses

5.5.1 Methods

As with land cover structural analysis, FRAGSTATS landscape metrics were used to estimate structural connectivity through a joint interpretation of Area-Edge and Aggregation Metrics at the class level, using the hierarchical land use map that I created previously (see Chapter 3, Part 2, page 79). This land use map consists of 4 land use types at the level 1, 11 and 49 subclasses at the level 2 and level 3, respectively. As I aimed to determine different types of green spaces in order to derive the potential routes of connectivity for people, the results of landscape metrics for *Natural and Semi-natural Land* sub-classes, and *Paths* and *Pavements* were taken into account.

Initially, the results derived from the most detailed land use classification level (level 3) were evaluated to find out the structural connectivity of each land use type in the study area. The structural connectivity of each land use type was assessed on the basis of information obtained from landscape metrics (see section 5.3.2). The results of landscape metrics were evaluated in the same way as land cover structural analysis.

In order to delineate the structural connectivity routes for people, I aggregated the individual sub-classes of *Natural and Semi-natural Land* (at level 2), starting from the most structurally connected to the lesser connected land uses. Afterwards, I added the patches of *Paths and Pavements* to the generated networks as the main routes for pedestrian movement. As a result, I obtained two networks where *Paths and Pavements* were thought to be the main routes of movement for people i.e. the *Recreation and Leisure*, and the *Mixed Vegetation*. I then measured the change in structural connectivity in these.

5.5.2 Results of Land Use Structural Analysis

The overall results for the analysis of the land use structural network, together with their landscape metrics, are given in Appendix 7.

At level 2, there are 2 land uses under *Natural and Semi-natural Land*, namely *Recreation and Leisure* and *Mixed Vegetation*. Furthermore, *Recreation and Leisure* is split into 8 sub-classes and *Mixed Vegetation* is split into 3 at level 3.

Although I analysed these 11 land use types at level 3, for simplicity, I only reported the results of landscape metrics for those with high structural connectivity. The results of landscape metrics for *Paths* and *Pavements* are also given in this section, since they constitute the main routes for pedestrian movement.

According to the results of land use structural analysis, the *Countryside / Urban Fringe* is the most dominant land use type in the whole study area with the highest AREA_MN (8.25 ha), AREA_AM (4588.63 ha) and includes relatively a small number of patches (1668). Furthermore, reporting the lowest ENN_AM (4.37 m) and the highest GYRATE_AM (2498) and PROX_AM (296658.99), together with previous landscape metrics, these figures indicated that *Countryside / Urban Fringe* land use type has the strongest structural connectivity in the whole landscape. Following this, *Natural and Semi-natural Greenspaces* was the second most connected land use type based on its values for GYRATE_AM, ENN_AM and PROX_AM. On the other hand, *Parks and Gardens* (729.71 ha) and *Outdoor Sport Facilities* (875.07 ha) represent very similar spatial coverage with small differences in their AREA_MN and AREA_AM. The remaining *Recreational and Leisure* land uses, *Amenity Greenspaces, Allotments, Cemeteries and Churchyards* and *Provision for Children and Young People,* covers 5.52% of the whole research area. In general, all these land uses reported very low structural connectivity compared to aforementioned land uses.

Under *Mixed Vegetation* land uses, there are *Private Gardens, Roadside Vegetation* and *Railway Vegetation*. The fourth dominant land use type in the study area, *Private Gardens* has a large NP (19413) with an even distribution in their patch areas (AREA_SD= 0.61 and AREA_CV= 252) compared to *Countryside / Urban Fringe* and *Natural and Semi-natural Greenspaces*. In addition to this, *Private Gardens* reported very low values for GYRATE_AM (70) and PROX_AM (635.45). Despite its small spatial coverage in the whole study area, *Parks and Gardens* reported a high value of PROX_AM and low value of ENN_AM. Hence, *Parks and Gardens* have a stronger level of physical continuity compared to *Private Gardens*. The remaining two land uses, *Roadside Vegetation* and *Railway Vegetation,* did not report high structural connectivity compared to *Private Gardens*.

With a very similar AREA_MN (around 0.01ha) *Paths* and *Pavements* constitutes the main walking routes for people. *Paths and Pavements* altogether constitute only 1.91% of the total landscape area, where *Pavements* occupy 734.92 ha (1.51%) and *Paths* cover 194.34ha (0.40%). *Pavements* land use category reported the highest NP (59136) compared to *Paths* (22193), and also the sub-classes of *Natural and Semi-natural Land*. In addition to this, *Pavements* reported relatively a high value of PROX_AM (58.84) and low value of ENN_AM (6.83m) compared to *Paths* (PROX_AM=25.84 and ENN_AM=17.03m), as an indication of higher structural connectivity.

In summary, the results of all the selected landscape metrics showed that *Countryside / Urban Fringe, Natural and Semi natural Greenspaces, Parks and Gardens, Outdoor Sport Facilities,* and *Amenity Greenspaces* are the most connected land uses under the *Recreation and Leisure* broad category. On the other hand, the sub-classes of *Mixed Vegetation, Paths* and *Pavements* did not report high structural connectivity compared to the *Recreation and Leisure*.

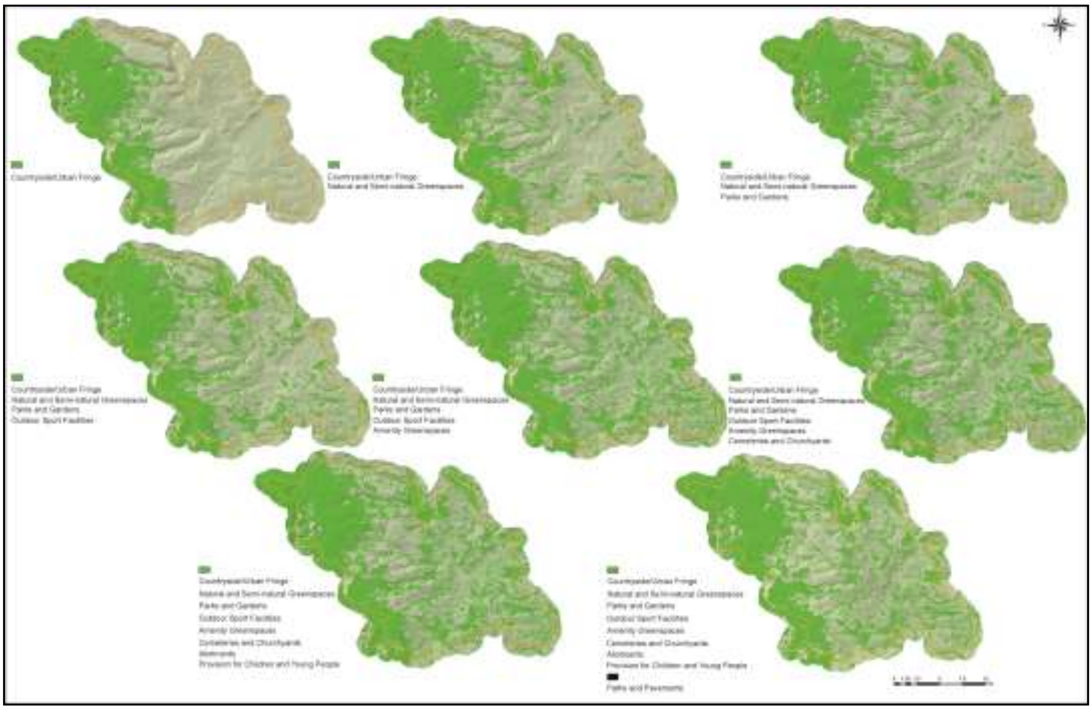
5.5.3 Deriving Networks and Measuring Their Structural Connectedness

In order to derive structural connectivity networks for people and analyse the change in their physical connectedness, initially I aggregated sub-classes of the *Recreation and Leisure*, starting from physically the most connected land uses to least connected ones. Then, I added *Paths and Pavements* to the network. I repeated the same process to generate the network of *Mixed Vegetation*. Afterwards, I analysed how their structural connectivity changes when I added the other patches of the same land use classes at an upper level. During this process, the sub-classes of a broad land use category, which do not have significant importance in terms of structural connectivity and total area, were added to the network together as a one land use patch, and the change in the physical continuity was examined for the each step of network delineation. The derived structural connectivity networks were organised starting from the most connected land use type at level 3 in the following sections.

Recreation and Leisure

The network of *Recreation and Leisure* is shown in Map 16 (for details see Appendix 7A). Among the sub-classes of *Recreation and Leisure* land use, *Countryside / Urban Fringe* was the structurally most connected and the dominant land use type and it was followed by *Natural and Semi-natural Greenspaces*.

When I added the patches of *Natural and Semi-natural Greenspaces* to *Countryside / Urban Fringe*, the total area and the number of patches increased significantly with an important decrease in the AREA_MN and AREA_AM. Together with a more than fivefold increase in NP and larger AREA_CV, it is clear that *Natural and Semi-natural Greenspaces* are made up with smaller patches.



Map 16: Network of *Recreation and Leisure*

In addition to this, the increase in the value of ENN_AM (from 4.37 m to 5.40 m) and the substantial decrease in the values of GYRATE_AM and PROX_AM indicates a lower degree of structural connectivity than the *Countryside / Urban Fringe* land use category on its own. Visual examination further confirms this result where the distribution of *Natural and Semi-natural Greenspaces* are not as clustered like *Countryside / Urban Fringe*.

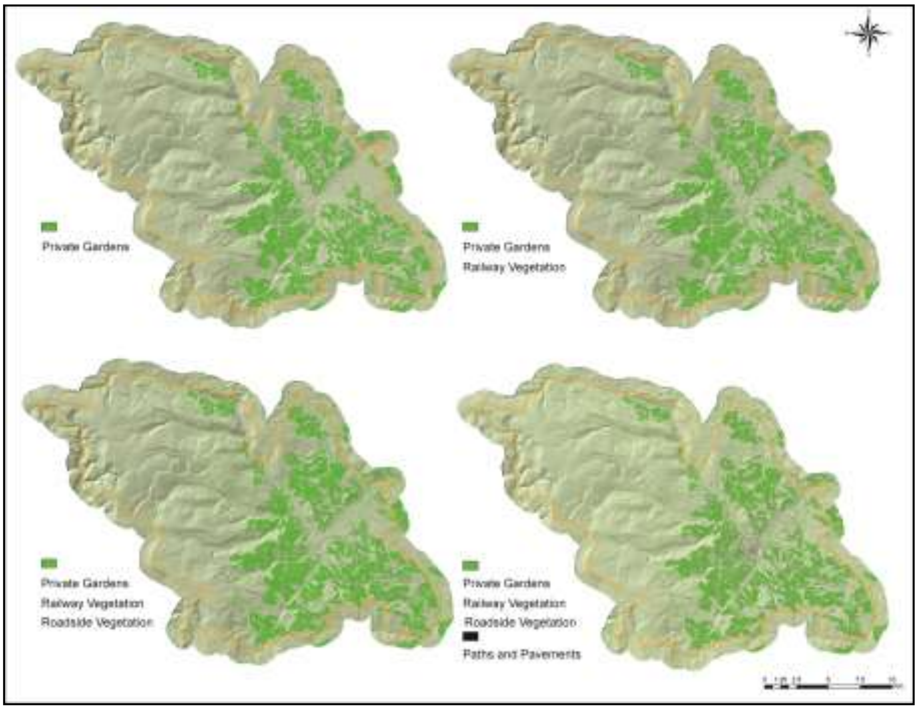
As I continued to add the patches of *Parks and Gardens,* and *Outdoor Sport Facilities* to the network, the number of patches decreased from 9972 to 9760 (as a result of the aggregation of neighbouring patches) with an increasing ENN_AM value and decreasing GYRATE_AM and PROX_AM values. This figures confirmed that the network became structurally less connected as a result of small area and the distance between its components. When I continued to add *Amenity Greenspaces* to the network, number of patches reported a substantial increase (around 2.5 times). The value of ENN_AM decreased slightly as an indication of short distance between patches. However, the moderate decrease in GYRATE_AM and PROX_AM interpreted as a weaker physical connectivity compared to the previous network. I obtained similar results when I added the patches of *Cemeteries and Churchyards,* and *Provision for Children and Young People* to the network. Consequently, the network of *Recreation and Leisure* reported less structural connectivity than the individual land use type of *Countryside / Urban Fringe,* and structural connectivity became weaker as I kept adding less connected land use patches to the network.

Finally, I added the patches of *Paths and Pavements* together to the network as the main routes for people to walk. The substantial increase in the number of patches (from 24943 to 65586) resulted in a decrease in the AREA_MN and AREA_AM (from 0.92ha to 0.37ha and from 2776.24ha to 2739.72ha). Even though the value of ENN_AM (from 4.97m to 4.64m) decreased slightly as an indication of short distance between patches, the decrease in the values of GYRATE_AM (from 1634.74 to 1625.32) and PROX_AM (from 196639.47 to 180906.25) interpreted as a weaker physical connectivity compared to the previous network. Considering the larger value of AREA_CV (from 5485.76 to 8654.61), the decrease in the structural connectivity in the *Recreation and Leisure* network thought to be a result of adding a large number of small sized patches to the network.

Overall, it is obvious that physically the most connected components of the *Recreation and Leisure* network are located in and around the Peak District National Park and suburban parts of the study area. As I continued to add the other components to the network, the network distributed in the all study more evenly, but its structural connectivity became weaker. Furthermore, contrary to what was expected, when I added the linear patches of *Paths and Pavements* to the network, the structural connectivity became weaker. This result was attributed to the presence of many small sized patches in the final form of *Recreation and Leisure* network.

Mixed Vegetation

Mixed Vegetation network is composed of *Private Gardens*, *Railway Vegetation*, *Roadside Vegetation* and *Paths and Pavements* occupying an area of 6394.53 ha (Map 17, for details see Appendix 7B). Here it is important to note that the difference between the *Mixed Vegetation* network for biodiversity and people is in their components. Because, the *Other Landscaped Areas* land cover type was classified under *Amenity Greenspaces* in land use map based on how they are used by people, hence these areas were used to construct the *Recreation and Leisure* network for people.



Map 17: Network of *Mixed Vegetation*

As with the *Mixed Vegetation* network for biodiversity, *Private Gardens* land use category is the most connected land use type in this category, followed by *Railway Vegetation* and *Roadside Vegetation*. Therefore, I added the patches of these land uses to the *Private Gardens*. After I aggregated the patches of *Private Gardens* and

Railway Vegetation, structural connectivity remained almost the same, based on the values of ENN_AM, GYRATE-AM and PROX_AM. As I added the patches of *Roadside Vegetation*, its structural connectivity gets stronger. Here, even though the NP increased (from 20072 to 46252), the distance between the patches of network became shorter (from 9.17 m to 5.41 m) with a larger PROX_AM value (from 639.98 to 1118.21).

When I added the patches of *Paths and Pavements* to the *Mixed Vegetation* network, AREA_MN and AREA_AM showed an increase (from 0.12ha to 0.14ha and 1.90ha to 3.40ha, respectively) with a slight increase in the NP (from 46252 to 46437). This was an expected result, since *Paths and Pavements* are generally adjacent to *Roadside Vegetation* and *Private Gardens*. Also, the slight increase in the NP compared to the *Recreation and Leisure* network was attributed to the adjacency of *Paths and Pavements*, *Roadside Vegetation* and *Private Gardens*, since the adjacent patches of the same classes are treated as one patch in FRAGSTATS. Additionally, the increasing values of PROX_AM (from 1118.21 to 2990.46) and GYRATE_AM (from 83.34 to 117.33) with a decrease in the value of ENN_AM (from 5.41m to 5.10m) interpreted as a stronger structural connectivity for the resulting network of *Mixed Vegetation*.

5.5.4 Summary

The aim of this part of the chapter was to delineate different structural connectivity routes for people and to determine the change in their structural connectivity when we added lesser connected land uses to the most connected ones. I have only taken into account *Recreation and Leisure*, *Mixed Vegetation* and *Paths and Pavements* land use categories, because of their potential contribution to a network in an urban case. After generating the networks of *Recreation and Leisure*, and *Mixed Vegetation,* I analysed how their connectivity changes as I added the less connected patches to the most connected land use types.

Contrary to expectations the structural connectivity of *Recreation and Leisure* network became weaker compared to previous connectivity routes for each land use type. Overall, *Recreation and Leisure* reported lower degrees of physical connectivity as I added less connected land use patches to most connected one starting from *Countryside / Urban Fringe*. This result may be explained by a number of different factors. Firstly, since the mean patch size of additional land uses was very small with a high number of patches. In addition to this, the additional patches were far from each other and they were not in a closer proximity to the most connected land uses. On the other hand, under the broad *Mixed Vegetation* land use category, when I added its sub-classes to each other, this resulted in a stronger structural connectivity at each stage of network construction.

As with networks for biodiversity, these results confirm that both the composition and configuration of additional land uses are the major determinants influencing the structural connectivity of the derived networks for people.

5.6 Conclusions

The objective of this chapter was to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data, without reference to a particular species / species group or the requirements of people. The chapter was divided into two parts. Both parts provide a prototype approach to model structural connectivity routes for biodiversity and people by quantifying landscape structure and physical connectivity in FRAGSTATS.

The derived structural connectivity routes for biodiversity and people stem from an actual physical distance based approach to connectivity. Overall, all of the derived networks are resulted in spatially discrete connectivity models for biodiversity and people, where each of the individual land cover / use category was regarded as potential components of structural connectivity networks. However, for both models the effects of matrix on the movement were not taken into account.

The first part initially determined which land cover types may provide the greatest gain in connectivity, as the criterion for the delineation of habitat networks for biodiversity. In order to quantify landscape structure for biodiversity, firstly I identified the potential habitat types in the study area on the basis of the previously generated 3 level hierarchical land cover map with 34 land cover categories (at level 3). As a result, 24 land cover categories were quantified in terms of their structural connectivity as potential habitats for biodiversity. When constructing networks for biodiversity, each individual land cover type was regarded as a discrete habitat patch of a larger habitat unit (in other words a habitat network) based on the hierarchical levels of the input land cover map. Each network was constructed starting from the individual land cover type (at level 3) which may provide the greatest gain in connectivity for the habitat network. In this way, I also found an opportunity to measure the change in structural connectivity as I continued to add physically less connected land cover categories to the network. Totally, 7 habitat networks were delineated for biodiversity: *Wetlands*, *Water*, *Heathlands*, *Woodland and Shrub*, *Grasslands*, *Cultivated Land* and *Mixed Vegetation*.

The spatial extent of the derived structural connectivity routes for biodiversity ranges from 1.63% to 26.50% coverage of the whole study area. The *Wetlands* network is mainly located in the boundaries of the Peak District Park with a clustered pattern, the lowest number of patches, largest mean area. The *Wetlands* network represents the highest structural connectivity of all networks for biodiversity. It is also important to note that the *Wetlands* network reported an increase in the structural connectivity at each stage of the network construction process. This result is due to the effects of the inclusion of quite large patches in a closer proximity in the Peak District Park.

With the second highest structural connectivity, the *Heathlands* network is located largely in the areas surrounding the *Wetlands* network in the Peak District National Park. Showing very similar spatial pattern and characteristics with the *Wetlands* network, the structural connectivity of *Heathlands* network increased as I aggregated the individual land cover types together.

The *Grasslands* network has the largest spatial extent in all derived networks (26.50%) and is mainly distributed around the suburban parts of the study area. Similarly, the *Woodland and Shrub* network is distributed around the suburban parts of the study area with a spatial extent of 15.27% of the whole landscape, particularly alongside of *Water* features. On the other hand, during the network construction process of *Woodland and Shrub*, the overall structural connectivity of this network was increased as I added the patches of *Broadleaved Woodland* and *Conifer Woodland* together, but afterwards did not show an important increase. So, we can claim that the overall structural connectivity of this network is largely depends on the spatial characteristics of *Broadleaved Woodland* and *Conifer Woodland*. However, the structural connectivity of the *Grasslands* network was decreased when I aggregated the patches of *Amenity Grasslands* to *Improved Grasslands,* as a result of adding many small sized patches to the network. But, as I continued to add the remaining grassland categories to the network, the structural connectivity was again increased. In this context, contrary to expectations the overall structural connectivity of *Woodland and Shrub* network was higher than the *Grasslands* network, because of having larger patch size as well as the closer proximity of its individual components to each other.

As expected the *Mixed Vegetation* network is mainly distributed around the built-up areas of Sheffield, with an overall coverage of 12.44% of the whole landscape. The overall structural connectivity of the *Mixed Vegetation* network was increased, as I aggregated its individual components to each other. However, its overall structural connectivity was weaker than the *Cultivated Land* network (5.45% of the total landscape). This result can be explained partly by the proximity of the components of the *Mixed Vegetation* network. But, the most important factor caused this result was the mean area of the patches that made up the overall network. The area of individual patches was thought to be an important determinant in connectivity (Botequilha-Leitão et al., 2006). Hence, even though the distance between the individual components of the *Mixed Vegetation* network is smaller than those for the *Cultivated Land* network, the larger mean area in combination with area-weighted mean area, area-weighted proximity index indicated the opposite situation for these networks.

Regarding biodiversity, a structural connectivity approach has been found useful, in particular where the movement of species largely depends on certain habitat types, such as rivers, ponds and hedgerows (Hinsley et al., 1994; Fortuna et al., 2006; Erős et al., 2011). Additionally, such an approach and resulting spatially explicit network models can be particularly useful to evaluate the relative importance of each patch in connectivity for the overall network pattern (Andersson and Bodin, 2009).

Galpern et al. (2011) suggest that the structural connectivity should be determined and analysed on the basis of the maximum dispersal distance of species under consideration (which is called effective distance). Hence, we should select a core set of landscape metrics quantifying different aspects of the landscape structure which may reveal meaningful information on the landscape processes or organism of interest (Turner et al., 2001). For example, determining the search radius of Proximity Index (PROX) according to the dispersal distances of species that are under consideration can be useful to relate the level of structural connectivity and the species dispersal distances. However, Galpern et al. (2011) remind us of the difficulty of determining the exact movement distances of species.

Moreover, Taylor et al. (2006) argue that networks based on structural connectivity do not necessarily provide functional connections for species if they are not actually used by the species under consideration. Likewise, Metzger and Décamps (1997) state that the extent to which species can benefit from structural connectivity highly depends on species-specific requirements and high levels of structural connectivity may or may not meet the ecological requirements of different species living in the same landscape. Hence, we can conclude that even though some land cover types (or habitats) are structurally connected to each other, actually they may not be functionally connected depending on species-specific habitat requirements. Functional connectivity for named species of wildlife is explored in Chapter 6.

On the other hand, the main aim of the second part of this chapter was deriving the networks of greenspaces for people, which may allow the movement of people throughout the landscape with maximum contact, or opportunity for contact with vegetation and non-built areas. The structural connectivity networks for people were derived on the basis of the same criterion and approach. Hence, initially I determined different greenspaces as potential components of the network using the previously created land use map (11 individual land use categories in 49 land uses). Each of these land uses was examined in terms of providing highest gain in connectivity for the delineation of networks. I constructed 2 different structural connectivity networks for people, namely *Recreation and Leisure* and *Mixed Vegetation*. I also took into account *Paths and Pavements* in the network construction processes of *Recreation and Leisure* and *Mixed Vegetation,* as the main features of pedestrian movement.

The first network, *Recreation and Leisure* was composed of 10 different land uses by covering 49.35% of the whole study area. With very large mean patch size and clustered distribution, *Countryside / Urban Fringe* reported the highest structural connectivity in all land use categories. Also, as the most connected component of the

Recreation and Leisure network, *Countryside / Urban Fringe* is entirely located within the boundaries of the Peak District National Park and constitute almost 60% of the whole network (and covers 28.37% of the study area). On the other hand, when I added the patches of the second most connected land use category, *Natural and Semi-natural Greenspaces* to the *Countryside / Urban Fringe,* the structural connectivity became weaker with much smaller mean area and far distant individual patches. However, the spatial distribution of the network became much more even, where the network expanded through the suburban parts of the study area. As I continued to add the remaining *Recreation and Leisure* land use types to the network, at the each stage of network construction process, the structural connectivity decreased with a more even spatial distribution throughout the study area. Finally, when I added the patches of Paths and Pavements to *Recreation and Leisure* network, its structural connectivity continued to became weaker. The most important factors, causing relatively weak structural connectivity for the *Recreation and Leisure* network are the area and the neighbourhood relationships between the individual patches of the whole network. As mentioned previously, *Countryside / Urban Fringe* is composed of very large and clustered patches, however, the other components of the network are generally distributed throughout the landscape and have relatively far distant smaller patches.

The second network for people, the *Mixed Vegetation,* is composed of *Private Gardens, Roadside Vegetation, Railway Vegetation* and *Paths and Pavements*. It is mainly distributed around the built-up area of the study area with small sized and closer patches. The overall structural connectivity of the *Mixed Vegetation* network became stronger as I added its individual patches together. This was a natural result of having larger patches within a closer proximity. However, the *Mixed Vegetation* network reported weaker structural connectivity compared to the *Recreation and Leisure* network, depending on the size and location of its individual components, as well as the distance between them.

To some extent, the delineation of networks for people based on structural connectivity may help researchers and planners to analyse the landscape structure, availability of different greenspaces, and the relationships between them in the landscape, as potential components of a network. However, as with the networks for biodiversity, a more comprehensive approach may be required in the case of functionally connected networks for people. This is particularly important for the *Recreation and Leisure* network, where the network represented weaker structural connectivity as I added the other land uses of *Recreation and Leisure* to *Countryside / Urban Fringe*.

As pointed out earlier, even though the *Countryside / Urban Fringe* land use has the strongest structural connectivity in all other components of the network, it is entirely located in the Peak District National Park and the distance between *Countryside / Urban Fringe* and the urban part of the study area is quite long compared to the other *Recreation and Leisure* uses. On the other hand, the importance of greenspaces within a walking distance in urban areas has been emphasised by researchers to support physical and mental health and well-being (Takano et al., 2002; Groenewegen et al., 2006). Hence, considering the fact that the urban parts of Sheffield is one of the most populous urban areas in the UK (Pointer, 2005), it is obvious that this approach may underestimate the value and actual functionality of other land uses of *Recreation and Leisure* network, which are mostly located in the urban parts of the study area.

In recent years, researchers also draw our attention to the actual use of greenspaces and their qualities as well as motivations to use or not use particular greenspaces (Bell et al., 2007; Forest Research, 2011). Within this framework, there is a need for refining the physical distance-based measures of access to greenspaces as part of a green network by incorporating information on the use of, and travel in-between greenspaces; such as physical or legal barriers to movement (Barbosa et al., 2007; Forest Research, 2011; Moseley et al., 2013). Hence, we can conclude that in order to achieve a comprehensive and viable planning approach to green networks, structural connectivity cannot be the only criteria to take into account when we are looking for the actual movement of people across the landscape.

Consequently, the overall results suggest that landscape metrics appear to have potential for understanding the main characteristics of landscape structure and prioritising the landscape components to be included in a potential network based on their physical characteristics. However, the definition and design of networks just based on the structural properties of landscape can fail to consider the requirements of species and people, and would result in an inappropriate provision for a functional network approach. Therefore, in the following chapter, I attempt to derive potential routes of connectivity for species and people, using the least-cost corridor modelling approach in ArcGIS 10.1, where I will have the opportunity of incorporating information on the ecological requirements of species and the public accessibility to the network modelling process.

Chapter 6 Modelling Ecological Connectivity Routes for Biodiversity and the Networks of Green and Open Spaces for People

6. 1 Introduction

The previous chapter examined landscape structure in the research area and derived different connectivity routes for biodiversity and people based on landscape structural properties of different land cover / land use types. The objective of this chapter is to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data. This chapter takes into account the potential habitat use and movement of species through the landscape, and the physical / legal accessibility of different green and open spaces as criterion to derive potential connectivity routes for wildlife and people. The chapter is divided into two parts. The first part focuses on the development of functional connectivity routes for a selected group of species in Sheffield, based on the suitability of different land cover types as habitats, and the species' likely dispersal characteristics in each type of land cover. The second part concentrates on modelling a functionally connected network of green and open spaces for people in the urban part of Sheffield based on physical / legal accessibility and the effects of slope on their movement.

Both these approaches make use of a specific technique for modelling movement across landscapes: least-cost corridor modelling. Initially, therefore, the key features, strengths and limitations of this approach will be outlined.

6.2 The Least-cost Corridor Modelling Approach

Recently, least-cost analysis has been widely applied to model ecological connectivity routes for a range of species (Singleton et al., 2002; Verbeylen et al., 2003; Zetterberg, 2011) and also accessibility routes for people (Chiou, Tsai and

Leung, 2010; Moseley et al., 2013). This approach provides an effective measure of functional connectivity, in which the distance between specified land cover / use types is modified by a cost value for the movement through the landscape (Verbeylen et al., 2003). Here, different cost values indicate the capacity of different land cover/use types to impede or enable the movement through the intervening landscape matrix. The cost value is also known as friction (Vuilleumier and Prélaz-Droux, 2002; Zetterberg, 2011), resistance (Verbeylen et al., 2003; Zeller et al., 2012) or permeability (Singleton et al., 2002; Watts and Handley, 2010) value. The terms cost (friction or resistance) and permeability express opposite meanings. Higher cost values indicate greater difficulty in moving through specified land cover / use types compared with lower values. On the contrary, lower permeability values represent the relative hostility of the given land cover/use types to movement (i.e. higher cost).

The main input requirements of a least-cost model are a source and a cost layer. A source layer indicates the patches between which the functional connectivity is calculated, and a cost layer identifies the capacity of intervening land cover / use types to impede or enable the movement through the landscape. Source layers can be either raster or vector formatted, whereas cost layers should be raster formatted.

6.2.1 The Least-cost Algorithm

The least-cost modelling approach is based on the notion that the landscape patches in question are surrounded by a mosaic of different land cover / use types, which range from the most hospitable land cover / use patches to the most hostile ones for movement (Ricketts, 2001). The primary objective of a least-cost analysis is the determination of the least costly paths or corridors between a source and a destination (ESRI, 2014a).

A least-cost analysis starts with the preparation of source and cost layers as the main inputs. The source layer represents the starting points of movement (particular land cover / use patches), and the cost layer can reflect one or several variables which would influence the ease (or cost) of movement in a single raster dataset. The cost layer can be obtained by assigning cost values to each of the land cover / use types according to their capacity to impede or enable movement. If there are multiple variables affecting the ease of movement, they should be combined in a single cost layer.

The second step in least-cost modelling is running a cost distance tool to determine the least accumulative cost distance between source patches over a cost layer. Instead of representing the actual distance in geographic units, the cost distance layer indicates the least accumulated cost between the specified land cover / use types. Figure 8 represents a cost distance layer on which a Euclidean path and cost distance path are defined. As can be seen, a Euclidean distance path follows a straight line (yellow line). On the other hand, a least-cost distance path follows the cells of the least accumulated cost (red line). Therefore, a cost distance layer is also referred to as an accumulative cost raster. Least-cost analysis is essentially based on eight neighbour cell algorithms in which orthogonal and diagonal movements are allowed along cells (ESRI, 2014b).

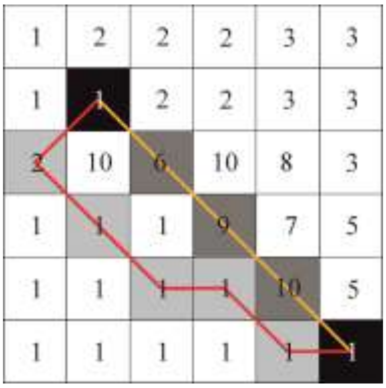


Figure 8: Schematic representation of a cost distance layer

The cost distance between two cells for horizontal/vertical movement is calculated as:

$$\mathbf{c = (cost1 + cost2) / 2}$$

The cost distance between two cells for moving diagonal movement is calculated as:

$$\mathbf{c = \sqrt{2}\,(cost1 + cost2) / 2}$$ where,

- ***c*** is the cost for moving horizontally or vertically between two cells,
- ***cost1*** is the cost of cell 1, and
- ***cost2*** is the cost of cell 2 (ESRI, 2014b).

After generating the least-cost distance layer(s), the next step is developing least-cost paths or least-cost corridors. The most important difference between least-cost path and least-cost corridor analyses is their respective outputs. The least-cost path is found by an algorithm that calculates all possible paths between two patches and picks the one with the least cost. Therefore, only a cell size wide path is created between sources and destinations (ESRI, 2014c). Because of this, least-cost paths are highly dependent on the cell size. Additionally, in order to obtain ecologically and spatially meaningful corridors, a buffer should be created around least-cost paths. On the other hand, the inputs of a least-cost corridor analysis are composed of two accumulated cost raster layers (cost distance layers) (ESRI, 2014c). In a least-cost corridor analysis, the least-cost corridor of cells is calculated over these cost distance layers where the range of accumulative costs between the sources is identified. Hence, the algorithm results in a corridor instead of a single least-cost path.

6.2.2 Limitations and Advantages of the Least-cost Modelling Approach

The least-cost modelling approach has long been established in landscape ecology and planning to model landscape connectivity for biodiversity and people (Verbeylen et al., 2003; Moseley et al., 2013). However, the method has a number of limitations, particularly the sensitivity of least-cost models to the quality of input datasets. The main limitation of a least-cost modelling approach lies behind the determination of cost values. One of the most common ways to determine cost values is the use of habitat suitability models for one or a group of focal species (Rouget et al., 2006; Wang et al., 2008). Eliciting expert opinion is another way of determining cost values, if there is insufficient data on the species occurrence (Brouwers et al., 2009). However, the use of expert opinion has been criticised by researchers, since cost values are generally estimated on an arbitrary scale, from a single expert opinion process or through a Delphi approach (Epps et al., 2007; Janin et al., 2009; Richard and Armstrong, 2010). Such estimates may increase the bias and variability in the least-cost models (Sawyer et al., 2011). Another problem with this approach is related to the resolution or the grain size of input datasets. Calabrese and Fagan (2004) claimed that the resolution of the habitat dataset should be able to capture the landscape perception of species. This issue is especially important for least-cost path analysis where only a single cell size path is created between habitat patches.

Despite their limitations, least-cost modelling approaches have been one of the principal ways of analysing and modelling the potential connectivity routes for different species as part of long-term landscape planning and management studies (LaRue and Nielsen, 2008). Their strength is that they provide a way of taking the contribution of the landscape matrix to the species movement into account, in a spatially explicit way (Richard and Armstrong, 2010; Watts et al., 2010; Sawyer et al., 2011; Galpern et al., 2012). According to Sawyer et al. (2011), least-cost modelling approaches allow researchers to make comparisons between potential connectivity routes within extensive study areas in a quantitative way. This is one of the most important features of the least-cost modelling approach, when researchers are dealing with large scale planning and management tasks.

Part 1 Modelling Ecological Connectivity: birds, mammals and reptiles

In the previous chapter, the connectivity routes for biodiversity were modelled on the basis of structural connectivity. In this part, as an alternative approach, functional connectivity is taken into account. In order to model the potential connectivity routes for the selected bird, mammal and reptile species a least-cost corridor modelling approach is chosen, since it integrates the contribution of the landscape matrix to the species' movement into the models by taking into account the ecological requirements of species. This part of Chapter 6 aims to develop different potential routes of connectivity based on the habitat preferences and the ease of species' movement across habitat and non-habitat patches. This aim is addressed in two parts. In the first place, I address the following research questions:

1. Can criteria be derived to identify the potential routes of connectivity?
2. What forms do the potential routes of connectivity constructed using these criteria take?

6.3 Methods

6.3.1 Selection of Target Species

Generally, the main concerns for ecological / green networks are to maintain the biodiversity and functioning of ecosystems as well as promoting the sustainable use of natural resources by allowing the movement of animal and plant species (Bennett and Wit, 2001; Jongman and Pungetti, 2004). When planning connectivity routes for the maintenance of biodiversity, the primary foci are the species of conservation concern and the ecologically important areas. The target species of conservation efforts are called as surrogate species and they are generally selected on the basis of the requirements of a small number of species: area-sensitive species, habitat specialist species, dispersal limited species, species which are sensitive to barriers, or other ecologically important species (Lambeck, 1997; Beier et al., 2007; Caro & O'Doherty, 1999; Caro, 2010).

The first step in the species selection process was, therefore, to compile a list of candidate species that are of conservational importance in Sheffield. For this purpose, I used the 2002 Sheffield Local Biodiversity Action Plan (LBAP) Priority Species and species associated with them which were mentioned in LBAP reports in 2002. The LBAPs aims to identify the most threatened species and habitats at local levels (Lawton et al, 2010). Accordingly, the first Local Biodiversity Action Plans in Sheffield were produced in 2002 by the Sheffield Biodiversity Steering Group. The 2002 Sheffield LBAP species were composed of the following taxa: birds, mammals, invertebrates and herptiles. The following criteria were applied to select a group of target species from each taxon as an attempt to highlight the differences between the potential ecological connectivity routes.

Step 1. Assembling a local species pool based on their local conservation status: I assembled a local species pool consisting of 50 species from different taxon groups. This list was constructed from the 2002 Sheffield LBAP Priority Species (29) and from species associated with them (21) (Table 16).

Table 16: Assembling a local species pool

Step 1. Assemble a local species pool based on their local conservation status

A. Sheffield LBAP Priority Species listed in the 2002 Local Species Action Plans

A1. Birds

Urban Birds: House sparrow, Starling, Song thrush, Pied wagtail

Farmland Birds: Tree sparrow, Barn swallow, Corn bunting, Linnet, Twite, Grey partridge, Lapwing, Skylark

A.2. Terrestrial Mammals

Otter, Water vole, Pipistrelle Bat,

Local Bat Species (Brown long-eared bat, Noctule bat, Leisler's bat, Daubenton's bat, Whiskered bat, Brandt's bat)

A3. Freshwater Invertebrates

White-clawed crayfish

A.4. Herptiles

Amphibian: Great-crested newt Reptiles: Common lizard, Slow-worm, Grass snake, Adder

B. Include any additional species associated with LBAP priority species

B.1. Species Associated with Birds

Species Associated with Urban Bird Species: Blackbird, Mistle thrush, Fieldfare, Redwing, Waxwing, Bullfinch, Dunnock, Black redstart, Siskin, Goldfinch, Greenfinch, Kestrel

Species Associated with Farmland Bird Species: Brown hare, Bullfinch, Yellowhammer, Reed bunting, Lesser redpoll, Turtle dove, Barn owl

B.2. Species Associated with Terrestrial Mammals

Otter: Kingfisher, Dipper, Grey Wagtail

B.3. Species Associated with Freshwater Invertebrates

White-clawed crayfish: Water vole, Otter, Dipper, Grey wagtail, Kingfisher

Step 2. Identification of the association between species and land cover types: Initially, I exported data from the Recorder 6 species database (maintained by the Sheffield City Council, Ecology Unit) in order to identify the relationship between selected species and land cover types as their potential habitats. However, the spatial resolution of the output dataset for species was not sufficient to match the distribution of species and the prepared land cover maps. Therefore, I attempted to associate each of the selected species to one or more land cover types using relevant reports and literature. For each species I extracted information on their habitat use from various sources, including the Local Biodiversity Action Plans (Sheffield City Council) and publications from the Sorby Natural History Society as well as more general references. From these data I was able to characterise the main habitats important for each species. I used this information to then remove all species whose key habitats were poorly represented in the urban area which was the focus of the modelling. These were: Otter, Water Vole, Brandt's Bat, White-clawed Crayfish, Adder, Kingfisher, Dipper and Grey Wagtail.

Step 3. Characterising each of the remaining 42 species for their vulnerability to threats: The remaining species were characterised for their populations' vulnerability to major threats (Table 17). For this purpose, I used the Sheffield City Council Local Biodiversity Action Plan Reports (2002 Species Action Plans) and the IUCN Red List of Threatened Species.

Table 17: List of major threats to the selected species

Major Threats
The loss, degradation and/or destruction of preferred habitat
Habitat fragmentation
Changes in habitat features
Intensive farming
Changes in farming practices
Land use and land cover changes
Changes in weather or climate conditions
Accidental kills (road and/or traffic kills)
Human disturbances
Hunting, killing, collecting
Presence of other species
Pollution (water, soil, air)
The use of intensive herbicides, pesticides or other chemicals
The lack of public understanding, sympathy or poor public perception

Species were allocated a “YES” or “NO” designation to represent their vulnerability to each of the below threats. Species allocated 4 or more "YES" designations were included in the draft target species group. Species in respect of which there was no information on major threats, or having no threats specified, were excluded. Most of the associated species were dropped from the candidate species list due to lack of information on major threats. For the remaining species, special consideration was given to the most vulnerable species, which are particularly sensitive to habitat fragmentation and changes in their habitats. Therefore, species those represent the dominant land cover types and the majority of threats constituted the final candidate list for target species. Eighteen species were left, including 8 bird, 6 mammal and 4 reptile species.

Step 4. Final List of Target Species: In order to highlight the differences in connectivity routes in each taxon, a final selection was made based on the differences in the habitat requirements of species, and capturing a range of individual characteristics for the modelling. The final list included species with varying habitat requirements and of conservation concern from each taxon.

- **Birds (4 spp):** With regard to the habitat requirements of bird species, I also used information gathered from DEFRA Wild Bird Populations in the UK, 1970 to 2013 - Annual statistical release (DEFRA, 2014). As a result, Song thrush (woodland generalist) and Skylark (farmland specialist) were selected as target species as they represent the habitat requirements of other candidate species as well as having different habitat requirements to highlight the contrasts between the networks. Also, Greenfinch (farmland generalist) and Blackbird (woodland specialist) were added to the birds species group as they favour a variety of different habitats (See Appendix 9 for general information on selected bird species).

- **Mammals (3 spp):** In addition to Sheffield LBAP priority bat species of Pipistrellus bat and Leisler's bat, I also included Brown long-eared bat in mammals for its wide range of habitat preferences. Hence, I concluded with a group of 3 bat species with varying habitat requirements, as a result of applied criteria (See Appendix 10 for general information on selected bat species).

- **Reptiles (3 spp):** As well as the differences in their preferable habitats, the movements of Common lizard, Grass snake and Slow-worm highly differ from each other. While the movements of common lizard (a few ten meters) and slow-worm (within a home range of several hundred square meters) is usually very limited (a few ten meters), Grass snake is one of the most mobile species among reptiles in the UK (Edgar et al, 2010). As a result, 3 reptiles are selected with a range of habitat requirements and different movement behaviours (See Appendix 11 for general information on selected reptile species).

6.3.2 Preparation of Input Datasets for Least-cost Corridor Analysis

I applied the following procedures to all selected species in order to prepare required inputs.

6.3.2.1 Land Cover Map Manipulation

The main input for modelling potential connectivity routes was the previously created level 3 land cover map (see Chapter 3, Part 2). This land cover map was composed of 34 categories at the most detailed level. At this stage, considering the general habitat requirements of target species, I aggregated some of the land cover types to a broader land cover category based on their relevance to each other at level 2. For example, "*Heather*" and "*Heather Grassland*" land cover classes were aggregated into "*Heathlands*" broad category. This way, I aimed at preventing unnecessary time consumption for the modelling process.

The final land cover map consists of 14 broad land cover categories including: *Woodland, Coniferous Woodland, Shrub, Mixed Vegetation 1* (roadside and railway vegetation), *Mixed Vegetation 2* (private gardens and other landscaped areas), *Improved Grassland, Amenity Grassland, Unimproved Grassland, Heathland, Arable Land, Standing Water, Running Water, Wetland, and Buildings/Structures and Constructed Surfaces* (see Appendix 12 for the explanations and Appendix 13 for land cover map).

6.3.2.2 Gathering Expert Opinion for the Parameterisation of Models

Landscape connectivity for organisms is affected both by how close together habitat patches are, and also by how easily the organisms can move though the surrounding landscape. When modelling landscape connectivity based on least-corridor analysis, the following input datasets are required for the parameterisation of modelling process:

- two source layers to represent suitable habitat patches which are assumed to be the starting and end points of species’ movement, and
- a cost layer to reflect the ease of species' movement through the landscape.

Where the empirical data on the ecology and movement behaviours of species does not exist or are not sufficient for the parameterisation of the model, we can get an estimate of this by consulting people with expertise in this area (Murray et al., 2009; Zeller et al., 2012). For this research, expert opinion was gathered on:

- the suitability of each land cover type as being habitat for the successful breeding and survival of the selected species,
- minimum habitat area that is large enough to support at least one successful breeding unit for selected species, and
- the cost value for each land cover type considering the relative difficulty for the species to move between habitat and non-habitat patches (see Appendix 14).

The first two estimates were intended to be used in the determination of suitable habitats for source layers, and the third one was to be used for obtaining the cost layer.

Initially I set out to use a Delphi process, but for reasons of expert availability and capacity to participate in the multistage process, you ended up opting for a single expert opinion approach. I recruited 5 research participants from 60 potential experts over a period of three months. These 5 participants provided one response for each of the 4 bird species, one response for each of the 3 bat species, and 3 responses for each of the 3 reptile species.

6.3.2.4 Preparation of Source, Cost and Cost Distance Layers

The required source layers were extracted from the final land cover map using expert opinion as to the suitability of each land cover category as habitat for each target species, and each species' minimum habitat area requirement. The habitat suitability estimations were made in a probabilistic way, on a scale of 1 to 100. On this scale, 1 represents habitat in which individuals would struggle to survive for any period and would never breed successfully, 50 is a habitat where individuals could survive for some time, and might attempt to breed, but with low likelihood of success, and 100 is habitat in which mortality is low and most breeding attempts are successful. According to this scale, a high score reflects a land cover category with a higher probability of being a habitat for the selected species.

Therefore, I initially identified land cover categories that were ranked with the higher scores by experts (e.g. 50 and more). Then, I extracted these land cover categories from the land cover map in ArcGIS 10.1, and split them into 2 classes based on the minimum habitat area requirement estimations for the target species. In this way, I obtained two source layers by combining the habitat suitability and minimum habitat area estimations for each land cover category, where:

- the first source layer was composed of suitable land cover types with an area greater than or equal to the minimum habitat area thus representing the most suitable habitat patches (core habitats) for each target species,

- the second source layer consists of suitable land cover types with a smaller area than the minimum habitat area requirement representing the potential habitat patches for each target species (the least suitable habitat patches).

In terms of the cost values for each land cover type, experts were asked to make an estimate anywhere on a scale from 1 to 100, considering the relative difficulty for the species to traverse across habitat and non-habitat patches. On this scale the value 1 represents the habitat in which the species would normally reside / breed and movement is not restricted, 50 indicates habitat in which a species would not breed, but may be able to survive in and move through if it has to, without high likelihood of mortality, though movement may be restricted, or slow, and 100 indicates habitat that is either a complete physical barrier to movement, or one in which there is a high likelihood of mortality in crossing the habitat for any distance.

The required cost layer was generated by reclassifying the land cover map based on the given cost value estimations. The same process was applied for all species when creating required source and cost layers. The only difference was the use of habitat suitability and cost value estimations based on the number of responses. As stated previously, I received three responses for each reptile species. Therefore, I used the mean values for habitat suitability and cost estimations. For example, habitat suitability estimates for the "*Woodland*" land cover category for the Common lizard were 85, 90 and 75 on a scale of 100. By calculating the mean value of these estimates, I obtained a final habitat suitability score of 83 for the *Woodland* land cover category. I calculated the final habitat suitability and cost values by applying the same procedure to all reptile species. On the other hand, because I received only one response for the each of bird and bat species, the original estimated values were used to obtain the source and cost layers.

After preparing the required source and cost layers for each target species, I created two cost distance layers. As mentioned earlier, the least-cost corridor analysis connects the habitat patches of selected species over two cost distance layers. Each cost distance layer represents the cumulative cost (or the ease of movement) to the determined source habitat locations. For the first cost distance layer, the most suitable habitat patches layer was used as the source layer, whereas for the second one, the potential habitat patches layer was used.

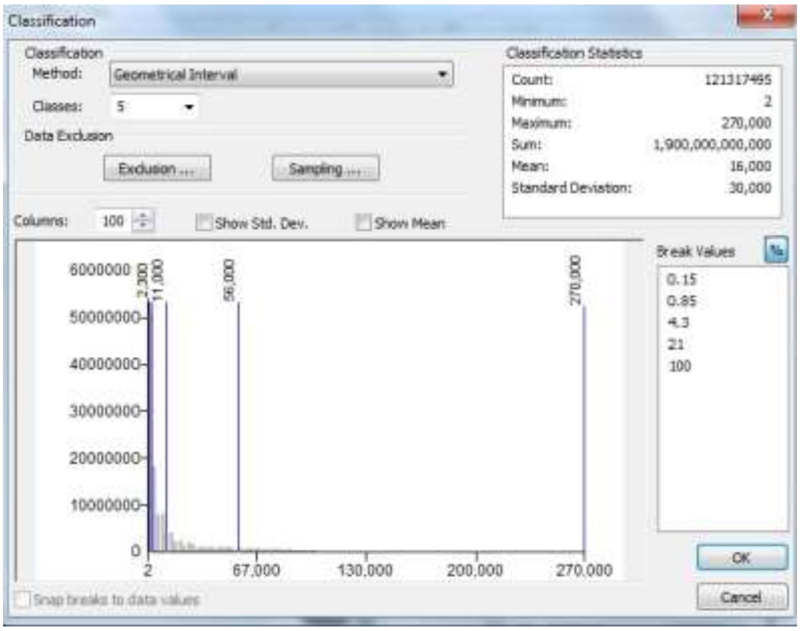
6.3.3 Modelling Least-cost Corridors and Determination of the Corridor Width

The aim of the least-cost corridor modelling approach is to find out the most permeable areas with the lowest cost values for the movement of selected species through the landscape. The least-cost corridors between the suitable and potential habitat patches for each of the selected species were generated by running the *Spatial Analyst Toolset, Distance Tools* and *Corridor Tool* in ArcGIS 10.1. The least-cost corridor tool generates a continuous raster surface (a graded cost map) in which the lower values represent the most suitable areas for the corridor. However, as we change the classification method and the number of classes, the representation and width of the least-cost corridors change. Therefore, it is important to identify the best classification method and threshold to determine an optimum corridor width for the least-cost corridors.

Even though there is no clear guidance to determine the width of a least-cost corridor, researchers suggest that the width of a least-cost corridor should be sufficient to contain at least the minimum habitat requirements of the selected species (Beier et al., 2008b; Pinto and Keitt, 2009). Within this context, Pinto and Keitt (2009) suggested using the top 10% of cells with the lowest cost values in order to delineate the potential ecological connectivity corridors. At this stage the distribution of cell values should be examined carefully in order to obtain a meaningful corridor width. For example, Dixon (2012) selected 5% of the cells with the lowest cost values since 10% included too many cells in his least-cost model.

In order to determine the width of the generated least-cost corridors, I analysed the outputs of the least-cost models for each species visually, using different classification methods in ArcGIS, such as the natural breaks, quantile, and geometric interval. I found that the geometric interval classification method works best to identify the least-cost corridor map.

The geometrical interval classification method organises continuous datasets by balancing the differences between the middle and extreme values, based on the natural grouping of data values. Another benefit of the geometric interval classification method is its ability to work on data that are heavily skewed and not normally distributed. As a result, it creates a comprehensive representation of least-cost corridors. Firstly, I reclassified the least-cost corridor into 5 classes using the geometrical interval classification system (Figure 9).



Classification
Method: Geometrical Interval
Classes: 5
Data Exclusion
Columns: 100

Classification Statistics

Count:	121317495
Minimum:	2
Maximum:	270,000
Sum:	1,900,000,000,000
Mean:	16,000
Standard Deviation:	30,000

Break Values
0.15
0.85
4.3
21
100

Figure 9: Distribution of cost values with the *Geometrical Interval* classification method for the Song thrush

Since my data are positively skewed (most of the lowest cost values fall into a very small interval), I used the first three break values as thresholds and compared the binary maps generated on the basis of these values. The last two break values were neglected due to the distribution of my data. Here it is important to note that all habitat patches are not included in corridors with the determined threshold values. This can be explained by the fact that the input cost raster cannot include the value 0, because the least-cost algorithm is a multiplicative process (ESRI, 2014d). Hence, even though all habitat patches were assigned the lowest permeability value of 1, they may get higher cost values in the least-cost corridors because the least-cost corridor algorithm sums the accumulative cost values identified in two cost distance layers.

As a result, when determining the optimum thresholds for the representation of least-cost corridors, the following procedure was applied to determine the optimum threshold for the delineation of the optimum corridor width for each of the target species. Initially, I intersected the corridor with all habitats (the most and least suitable habitats) and calculated the percentage of the corridor which is made up by all habitats. Then, I calculated the percentage of all habitats that are covered by the corridor. Finally, I intersected the corridor with the most suitable habitats and calculated the percentage of the corridor made up by the most suitable (core) habitats.

Each of these percentages was calculated for the three pre-determined threshold values. The high percentage of the corridor which is made up by all habitats indicates that the corridor is largely composed of all habitat patches. This may also mean that the area of the corridor is too small, and so the corridor and all habitat patches largely overlap. However, the percentage of the corridor which is made up by all habitats alone may lead to a misleading evaluation of the threshold, since it does not provide information on the proportion of all habitats included in the corridor. Therefore, I examined the percentage of all habitats that are covered by the corridor. A low percentage of all habitats that are covered by the corridor together with a high percentage of the corridor which is made up by all habitats confirm that the area of the corridor is too small to include all habitats.

Additionally, we must make sure that the corridor at least includes all core habitats to meet the minimum habitat requirements of the selected species. Therefore, the percentage of the corridor made up by core habitats is particularly important to determine the width of the least-cost corridor. However, the binary least-cost corridors for the Brown long-eared bat and Leisler's bat respectively did not include all core habitats with the lowest cost values for the chosen thresholds. Hence, for these species, I forced each binary least-cost corridor maps to include the remaining patches of core habitats by adding them to the corridor. Therefore, the optimum threshold for the identification of the corridor width was determined to make sure that the corridor is large enough to cover as much habitat patches as possible, in which at least all core habitats are included. In addition to this, the selected threshold needs to give a usable option in a planning context considering the total area of the corridor in the study area.

6.4 Results of the Least-cost Corridors for the Selected Species

The least-cost corridor analyses for the selected species are based on the information obtained from experts. The total number of experts involved in the expert opinion process was 5, where I received one response for each bird species, one response for mammal species and 3 responses for each reptile species. The information gathered from experts includes the suitability of different land cover types as being habitat for the selected species, the minimum habitat area requirement of the species and the cost value for each land cover type as an indication of the relative difficulty for the species to move between habitat and non-habitat patches. The information on the habitat suitability of different land cover categories and the minimum habitat requirement of species were used to determine the core and least suitable habitat patches.

Initially, all land cover types that scored a high habitat suitability value by the expert(s) were considered as part of potential habitats for the selected species. Then these land cover types were split into two categories. In the first category, the land cover patches which meet the minimum habitat area requirement were assigned as the core habitats. In the second category, the remaining land cover patches were assigned as the least suitable habitats. The core and least suitable habitat patches were used as the source layers and represents starting and end points of species' movement.

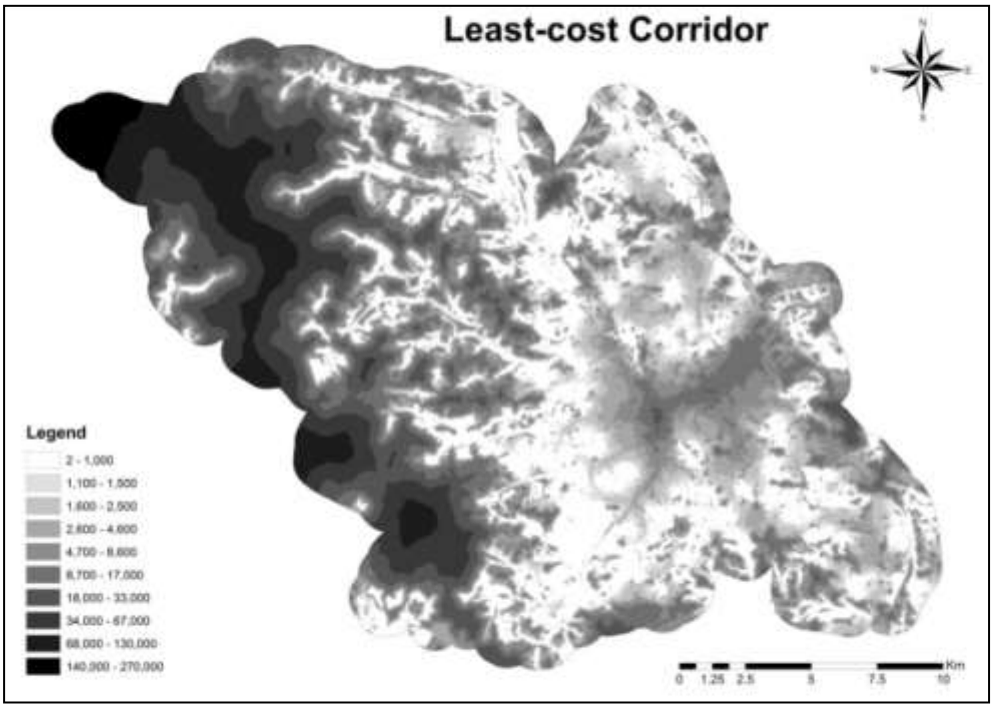
The cost values determined by the expert(s) were used to generate a cost layer which represents the difficulty of each land cover type for the movement of each species. Afterwards, using source layers (core and least suitable habitats) and the cost layer, I created two cost distance layers. While, the first cost-distance layer shows the difficulty for the species to move through the landscape starting their movement from core habitats, the second cost-distance layer considers the least suitable habitats as the starting point of the species' movements. Finally, over these cost-distance layers, the least-cost corridor of each species was modelled.

For each target species the following sub-sections represent the output least-cost corridor and the least-cost corridor with different thresholds for the determination of optimum corridor width. The key parameters for each species, together with the input layers and least-cost corridor outputs, are shown in Appendices.

6.4.1 Song thrush (*Turdus philomelos*)

The details of the parameters used for least-cost modelling approach and the input cost distance layers for Song thrushes are given in Appendices 15A and 15B in Volume II.

Based on the expert opinion, the core habitats for Song thrushes are composed of *Woodland, Shrub*, *Private Gardens* and *Other Landscaped Areas*. The most suitable areas of the least-cost corridor for Song thrushes are represented in the white and lighter colours, which have the lowest cost values (Map 18, for details see Appendix 15C).



Map 18: Least-cost corridor for Song Thrushes

The potential movement corridors for Song thrushes are concentrated around the urban periphery, following the valleys of the upper River Don, River Loxley, River Rivelin, River Sheaf and the Porter Brook.

After modelling the least-cost corridor, I determined three threshold values to identify the corridor width for Song thrushes. Figure 10 represents the least-cost corridor with different thresholds. While the first value for each threshold in Figure 10 represents the percentage of the corridor which is made up by all habitats, second and third values indicate the percentage of all habitats that are covered by the corridor and the percentage of the corridor made up by the most suitable (core) habitats, respectively.

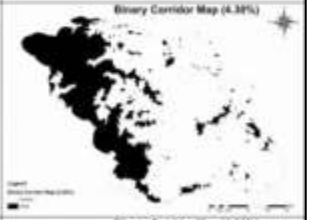
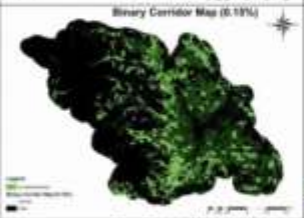
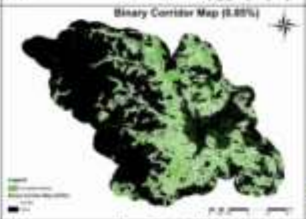
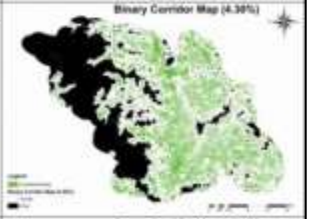
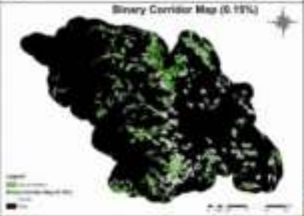
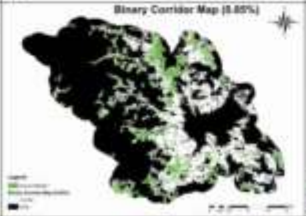
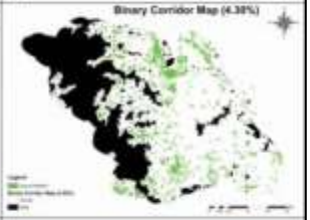
Song thrush (*Turdus philomelos*)			
Classification Thresholds	0.15%	0.85%	4.30%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	83.9%	56.2%	33.2%
Percentage of all habitats covered by the corridor	46.9%	85.2%	99.3%
Percentage of the corridor made up by core habitats	83.1%	100%	100%

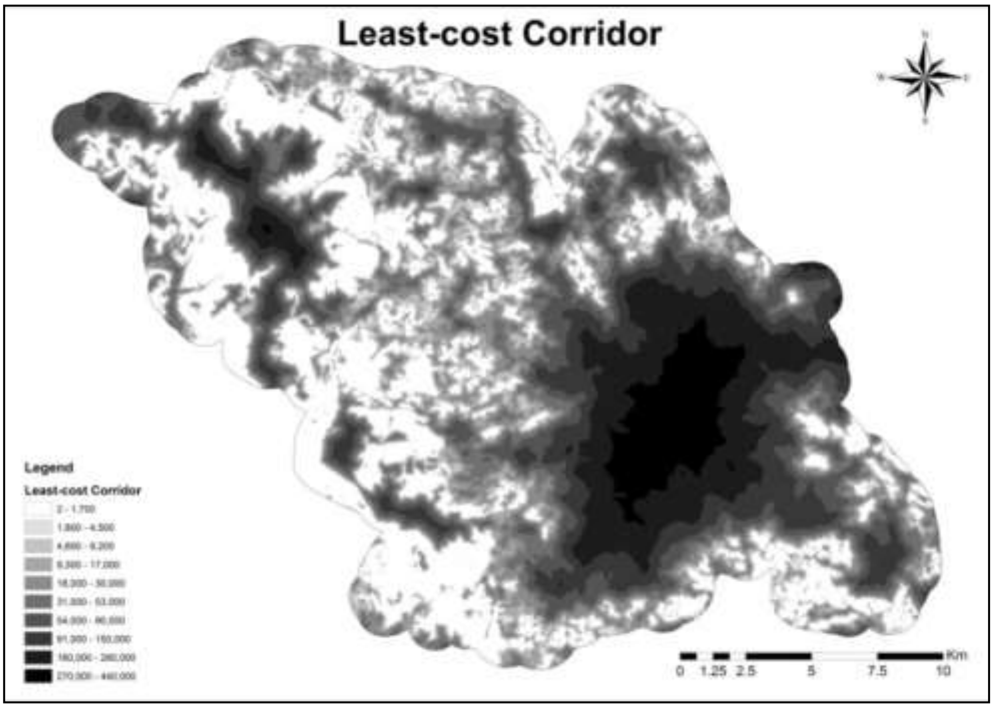
Figure 10: Least-cost binary maps with different thresholds for Song Thrushes

Here, the 0.15% threshold results in the highest percentage of corridor made up by habitats (83.9%). This is because the total area of corridor is too small and so the percentage of the corridor made up by all habitats is too large. However, when examined it is clear that the percentage of all habitats covered by the corridor is the lowest with this threshold (46.9%). Also, when the threshold of 0.15% is used all of the core habitats are not connected by the corridor.

On the other hand, even though the threshold of 4.30% covers most of the habitat patches, it expands to the whole of the study area. In theory, the widest corridor is the most preferable option. However, a corridor of sufficient width to meet the minimum requirements of the target species is a more preferable option in planning terms as it is unlikely that the provision of habitat for the Song Thrush could be a planning priority for the whole of Sheffield. Hence, even though the threshold of 4.30% seems to be best option for the determination of the least-cost corridor for the Song thrush, it is not an optimum option from planning perspective. The 0.85% threshold connects most of the habitat patches as well as including all core habitats within the network. Therefore, for the determination of the corridor width for Song thrushes, it was decided to use 0.85% (see Appendix 15D).

6.4.2 Skylark (*Alauda arvensis*)

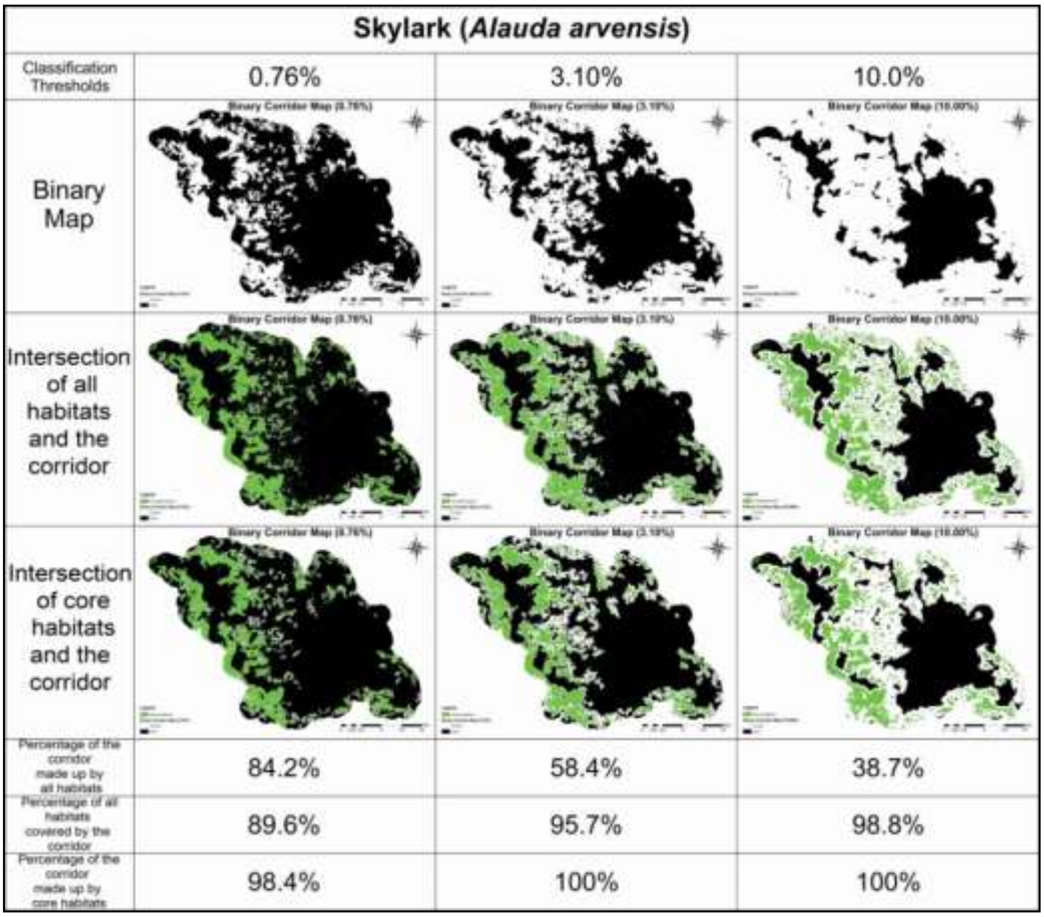
The details of the parameters used for modelling least-cost corridor for Skylarks and its input layers are given in Appendices 16A and 16B in Volume II. The main routes of a connectivity corridor for Skylarks are concentrated in the west part of the study area, in and around the Peak District National Park and the Green Belt (Map 19, for details see Appendix 16C).



Map 19: Least-cost corridor for Skylarks

The potential connectivity routes extend over the patches of *Unimproved Grassland* and *Arable Land* into the Peak District National Park, where the patches of *Heathlands* cover most of the area. However, the built up area of Sheffield with the areas of *Mixed Vegetation* and *Wetlands* in the Peak District National Park do not provide sufficient habitat connectivity for the movement of Skylarks.

As seen on Figure 11, the use of different thresholds resulted in different spatial configurations for the representation of the least-cost corridor.

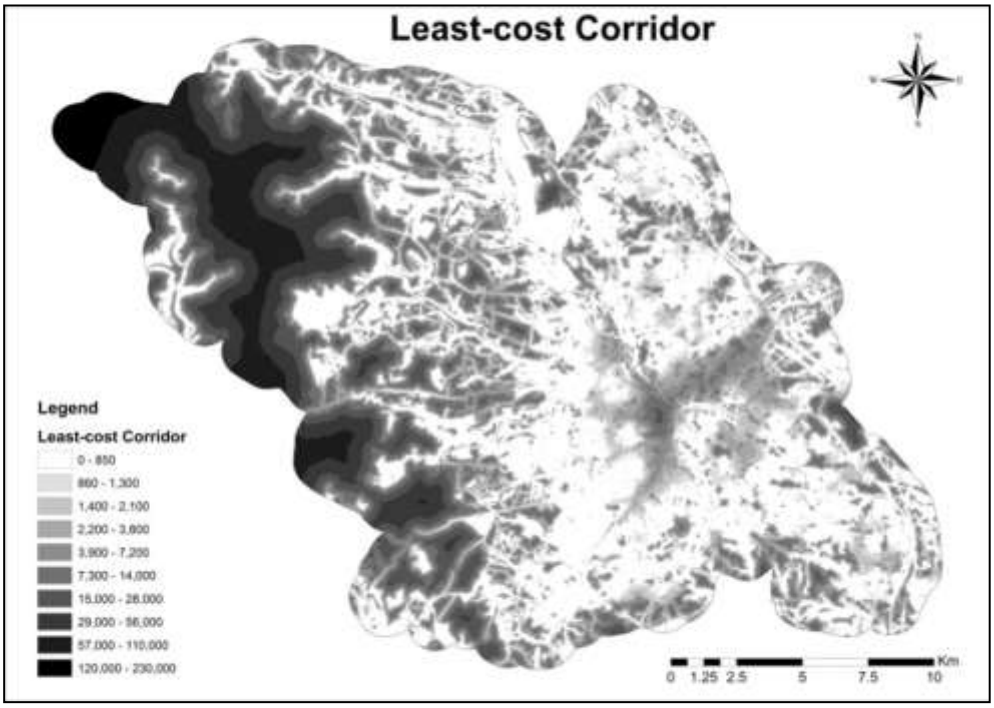


Skylark (*Alauda arvensis*)

Classification Thresholds	0.76%	3.10%	10.0%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	84.2%	58.4%	38.7%
Percentage of all habitats covered by the corridor	89.6%	95.7%	98.8%
Percentage of the corridor made up by core habitats	98.4%	100%	100%

Figure 11: Least-cost binary maps with different thresholds for Skylarks

The corridor with the threshold of 0.76% includes the highest percentage of all habitats (84.2%). This result arose from the fact that the corridor is the smallest in area and consequently the overlap between the corridor and all habitats resulted in the highest percentage of corridor made up by habitats. However, the proportion of all habitats covered by the corridor is the lowest with this threshold (89.6%) and the corridor does not include all core patches. With the threshold of 10%, only the built up area of Sheffield and the land covered with *Wetlands* in the Peak District National Park area are excluded from the corridor. Additionally, the percentage of the corridor made up by all habitats is the lowest with 38.7%, as the corridor with this threshold has an extensive area. On the other hand, the threshold of 3.10% generates a corridor that includes 95.7% of the all habitats. This corridor also includes all core habitat patches in the study area. Therefore, it was decided to use the threshold of 3.10% for Skylarks (see Appendix 16D).



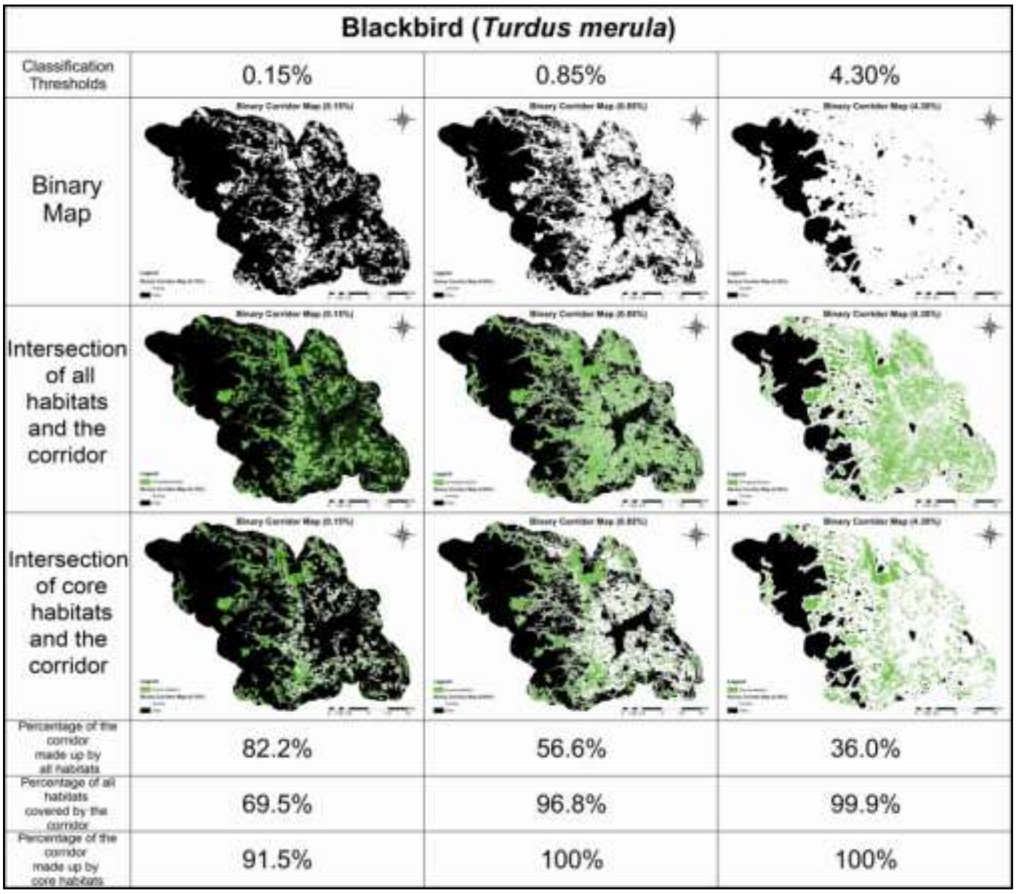
Map 20: Least-cost corridor for Blackbirds

6.4.3 Blackbird (*Turdus merula*)

The parameters used for modelling least-cost corridor for Blackbirds and its input layers are given in Appendices 17A and 17B in Volume II. The least-cost corridor for Blackbirds is distributed through the study area, excluding the areas of *Wetlands* and *Heathlands* in the Peak District National Park, the city centre, the lower River Don corridor and upper parts of the River Sheaf corridor (Map 20, for details see Appendix 17C).

In general, the corridor is well connected and assumed to allow the movement of Blackbirds throughout the research area. While the patches of *Roadside Vegetation* and *Woodlands and Shrub* play an important role in connecting the corridor, *Private Gardens* make a crucial contribution to the potential connectivity routes for Blackbirds.

Figure 12 shows the representation of the least-cost corridor for Blackbirds with the determined three thresholds.



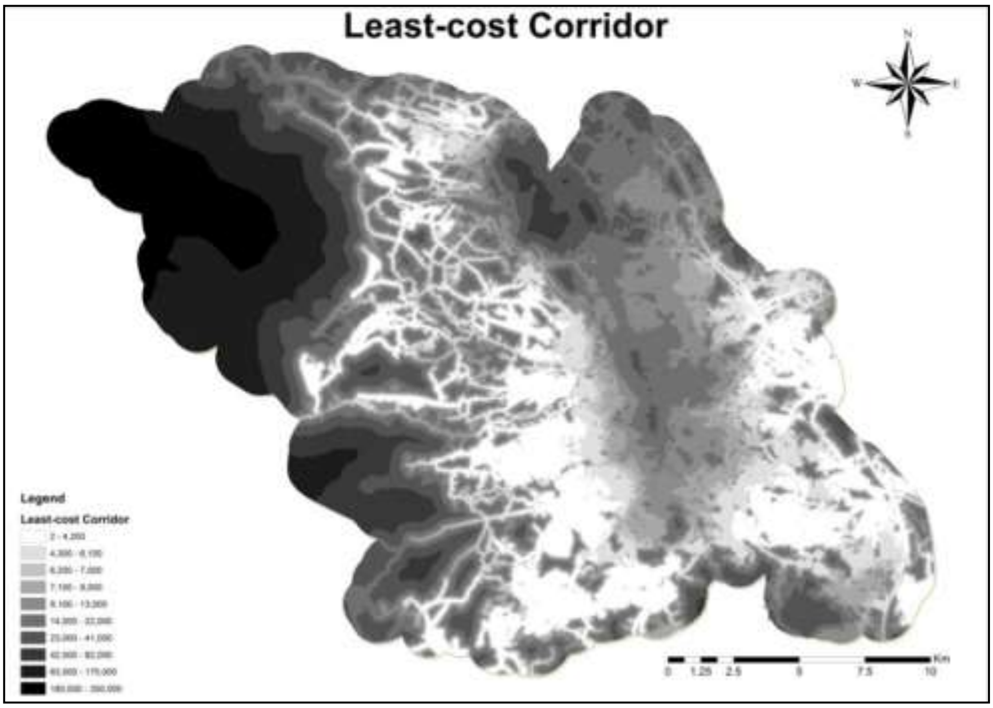
Blackbird (*Turdus merula*)			
Classification Thresholds	0.15%	0.85%	4.30%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	82.2%	56.6%	36.0%
Percentage of all habitats covered by the corridor	69.5%	96.8%	99.9%
Percentage of the corridor made up by core habitats	91.5%	100%	100%

Figure 12: Least-cost binary maps with different thresholds for Blackbirds

While the potential habitats for Blackbird cover a large part of the study area, the corridor area is the smallest with the thresholds of 0.15%. Therefore, the percentage of corridor made up by habitats is the highest among three threshold values with 0.15% threshold (82.2%). Despite this, the percentage of all habitats covered by the corridor and the percentage of core habitats included in the corridor are the lowest with this threshold. On the other hand, using a threshold of 4.30% means that most of the study area is covered by the least-cost corridor. With the threshold of 0.85%, all core habitats and most of the all habitats are covered in the corridor. Therefore, the threshold of 0.85% was selected for the determination of corridor representation and width for the Blackbird (see Appendix 17D).

6.4.4 Greenfinch (*Carduelis chloris*)

The parameters of least-cost corridor and its input layers for Greenfinches are given in Appendices 18A and 18B in Volume II. Similar to Song thrushes, the least-cost corridor for Greenfinches is concentrated around the urban periphery, following the valleys of the River Loxley, River Rivelin, River Sheaf and the Porter Brook (Map 21, for details see Appendix 18C).



Map 21: Least-cost corridor for Greenfinches

The corridor is mainly covered by Grasslands, Broadleaved Woodland and large Private Gardens. However, the areas between the River Don and the borders of Rotherham do not provide sufficient habitat connectivity for Greenfinches. Additionally, the patches of *Roadside Vegetation* play a fundamental role in providing connectivity towards to the Peak District National Park in western part of the study area. However, the connectivity gets weaker towards to the inner built-up areas of Sheffield and the Peak District National Park where there are some potential habitat patches. Even though they make a slight contribution to the network, these areas are not large and well-connected enough to support potential connectivity routes.

Figure 13 represents the binary corridor maps with different thresholds for the determination of optimum corridor width. When the threshold of 1.91% is used, the resulting least-cost corridor includes 33.5% all habitats, covering 64.7% of the all habitats area.

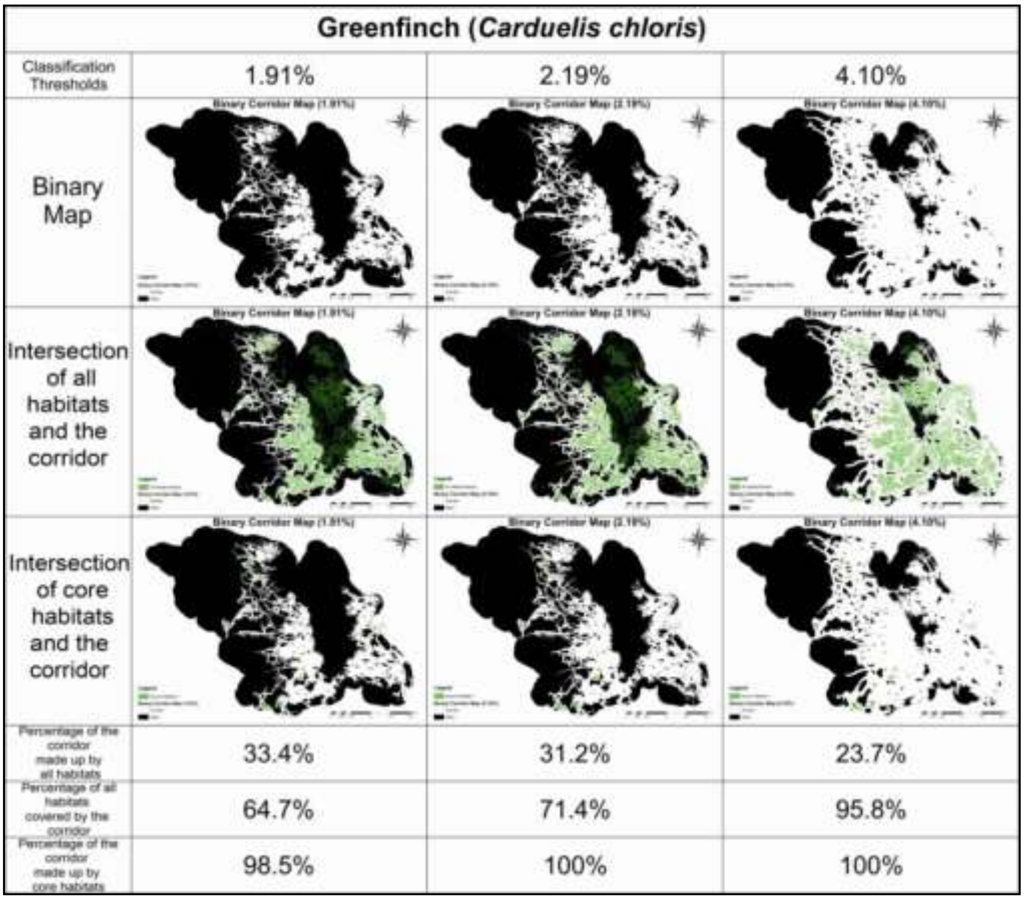
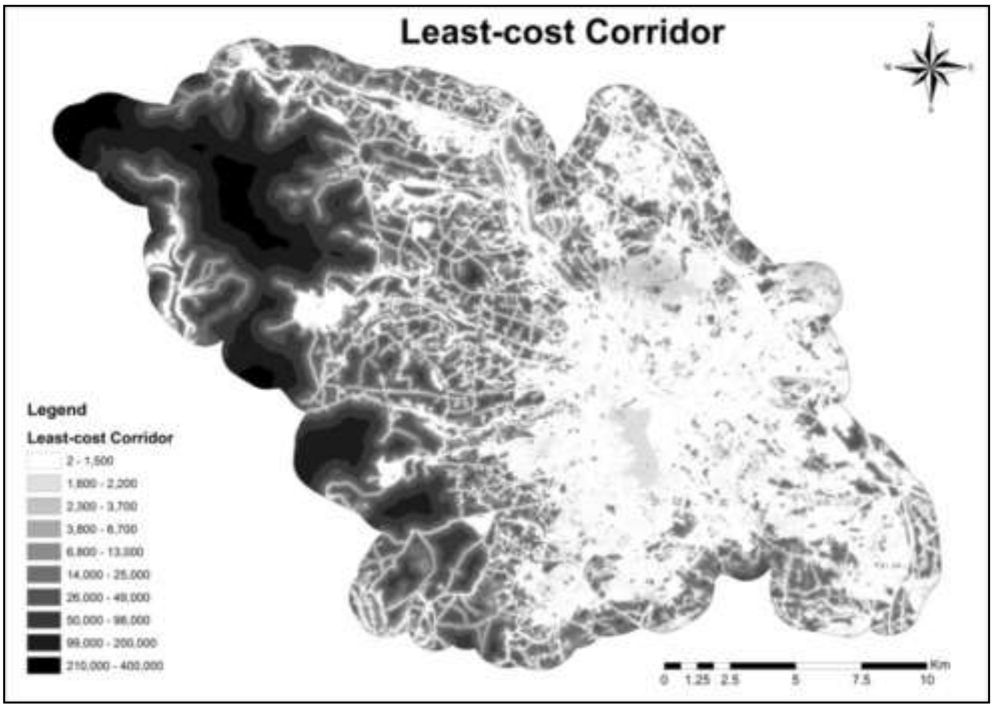


Figure 13: Least-cost binary maps with different thresholds for Greenfinches

With the thresholds of 2.19% and 4.10%, the habitat area covered by the least-cost corridor is increased as a result of expanding the corridor area. Whilst the threshold of 4.10% cover all core habitats as well as 95.8% of the all habitats, the resulting least-cost model covers almost two thirds of the total study area. Therefore, it is obvious that 4.10% does not represent a viable threshold for the determination of the corridor model. Hence, comparing all three thresholds, it was decided that the 2.19% threshold is the most appropriate for the least-cost corridor model for the Greenfinch (see Appendix 18D).

6.4.5 Brown Long-eared Bat (*Plecotus auritus*)

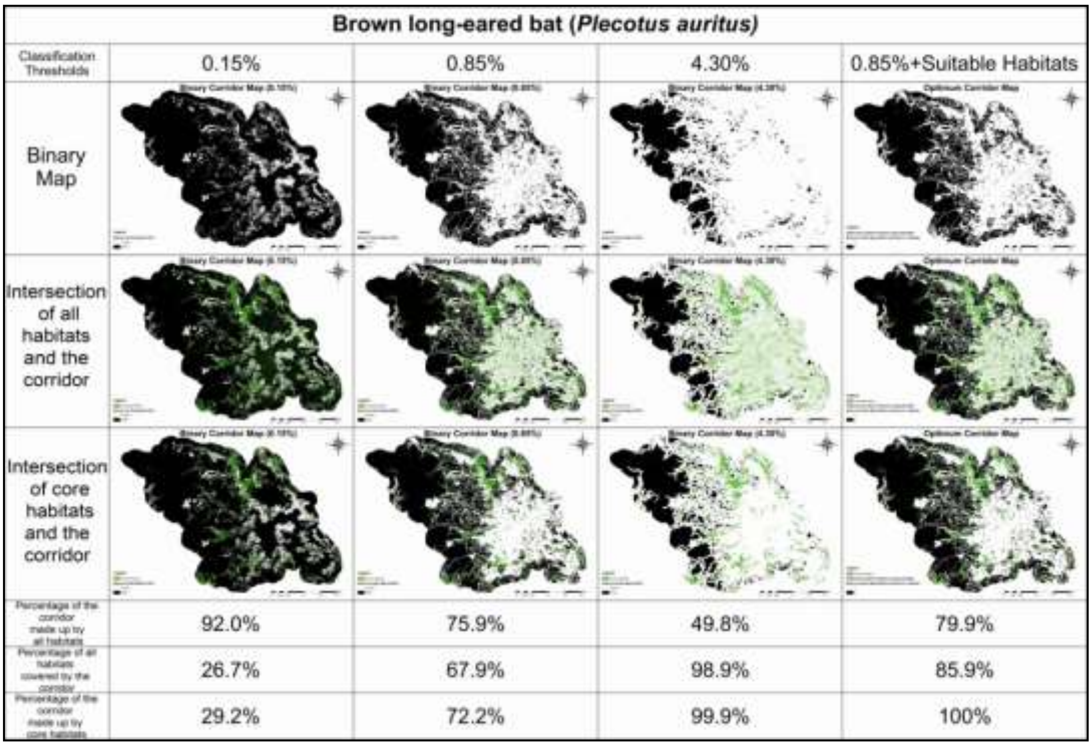
The parameters of least-cost corridor and its input layers for Brown Long-eared bats are given in Appendices 19A and 19B in Volume II. Map 22 shows the generated least-cost corridor model for Brown Long-eared bats (for details see Appendix 19C). As can be seen, the corridor covers an extensive area, particularly around the built-up areas of Sheffield where *Buildings and Structures* offers potential roosting sites for Brown Long-eared bats.



Map 22: Least-cost corridor for Brown long-eared bats

Additionally, most of the suitable habitats are connected to each other by the patches of *Woodlands*, *Roadside Vegetation* and *Private Gardens*. There are no good functional connections around the Peak District National Park, where the patches of *Heathlands* and *Wetlands* constitute the dominate land cover types. However, in general we can claim that the research area provides well-connected movement routes for Brown long-eared bats.

After generating the least-cost model, I attempted to determine a sufficient threshold for the representation of the corridor (Figure 14). The 0.15% threshold resulted in the highest percentage of corridor made up by all habitats. However, the percentage of all habitats covered by the corridor and the percentage of corridor made up by the suitable habitats are the lowest (26.7% and 29.2%, respectively).



Brown long-eared bat (*Plecotus auritus*)

Classification Thresholds	0.15%	0.85%	4.30%	0.85%+Suitable Habitats
Binary Map				
Intersection of all habitats and the corridor				
Intersection of core habitats and the corridor				
Percentage of the corridor made up by all habitats	92.0%	75.9%	49.8%	79.9%
Percentage of all habitats covered by the corridor	26.7%	67.9%	98.9%	85.9%
Percentage of the corridor made up by core habitats	29.2%	72.2%	99.9%	100%

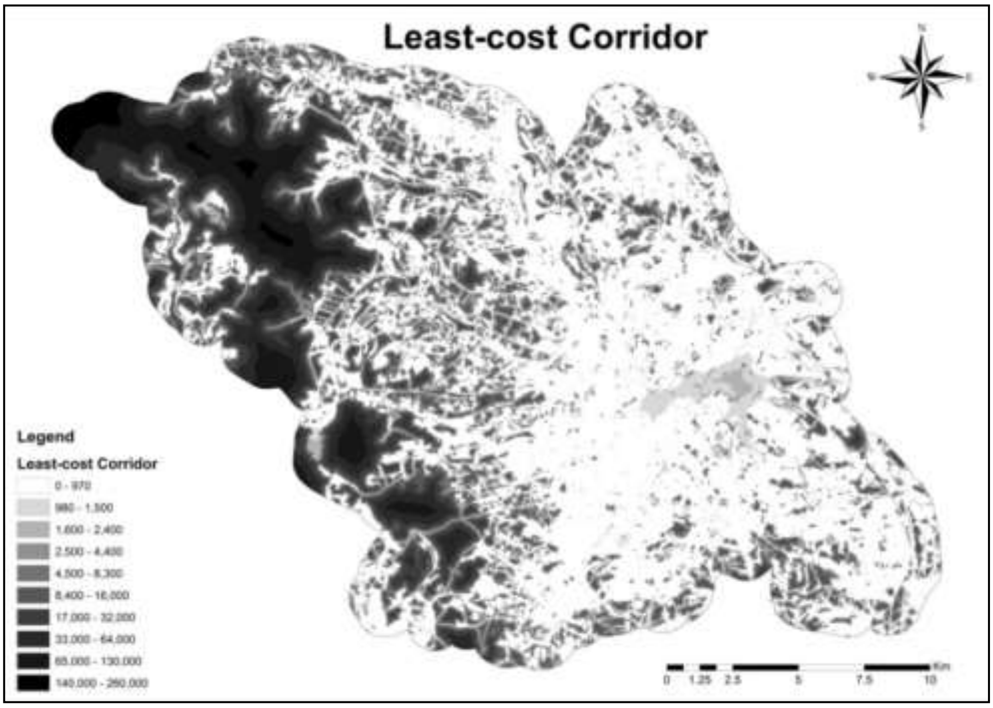
Figure 14: Least-cost binary maps with different thresholds for Brown long-eared bats

With the 4.30% threshold, the corridor covers most of the study area, but all core habitats are not covered by the corridor. On the other hand, the percentage of all habitats covered by the corridor is the highest (75.9%) with the threshold of 0.85%. However, all core habitats are still not included in the corridor. Taking into consideration of the spatial coverage of the corridor and percentage of core habitats in the corridor, I decided to use the threshold of 0.85% whilst adding all core habitat patches to the corridor (see Appendix 19D).

6.4.6 Pipistrelle Bat (*Pipistrellus pipistrellus*)

After creating all the necessary layers based on the expert's opinion, I modelled the least-cost corridor for Pipistrelle bats (for details see Appendices 20A and 20B). As with Brown Long-eared bats, the ecological connectivity routes for the Pipistrelle bat cover an extensive area, which is mainly concentrated in the urban part of the study area in which the built-up areas and river corridors play an important role in providing habitat connectivity for Pipistrelle bats (Map 23, for details see Appendix

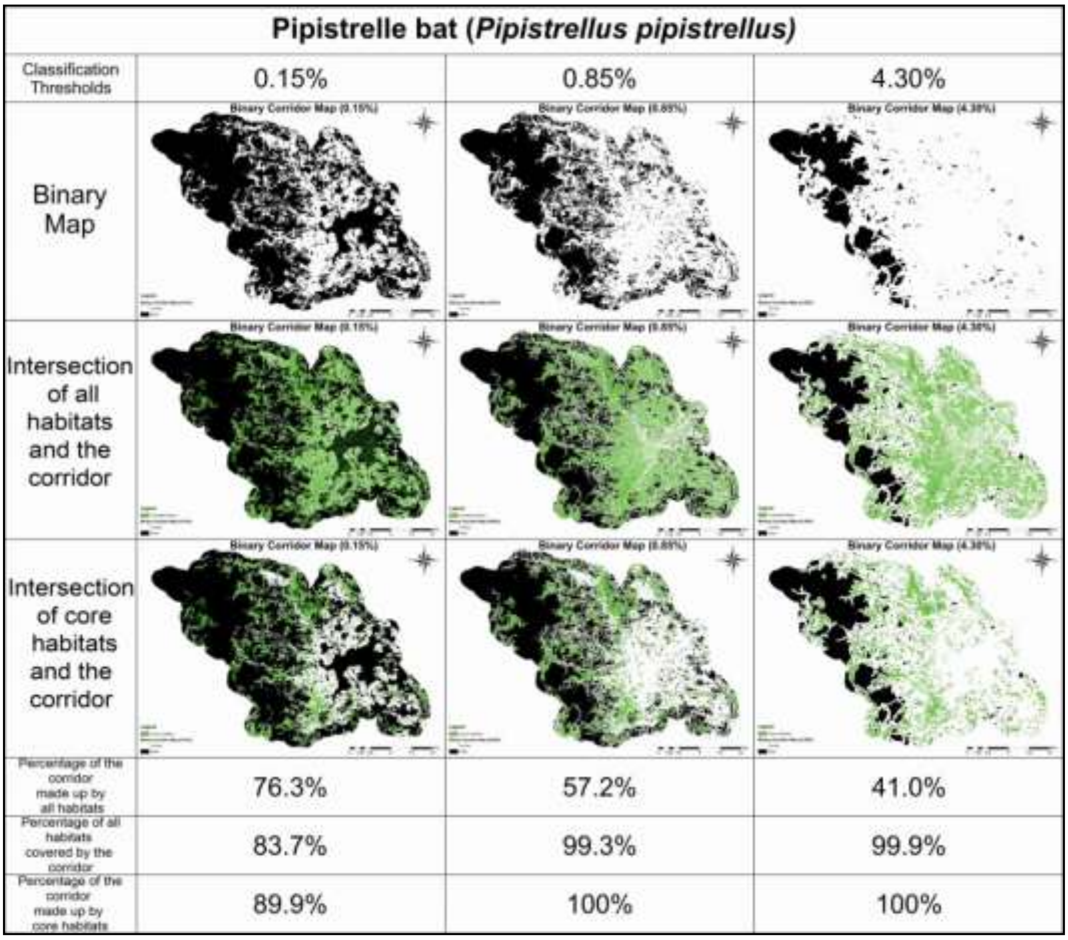
20C). Additionally, it is clear that the potential ecological corridor extends towards to the Peak District National Park where the connections are mostly provided by the areas of *Woodlands*, *Roadside Vegetation* and *Unimproved Grassland*. However, the areas covered by *Heathlands* and *Wetlands* in the Peak District National Park do not provide habitat connectivity for the movement of Pipistrelle bats.



Map 23: Least-cost corridor for Pipistrelle bats

I used the thresholds of 0.15%, 0.85% and 4.30% to determine a suitable cost value threshold for the representation of the least-cost corridor for the Pipistrelle bat (Figure 15). The first threshold of 0.15% permitted the inclusion of the highest percentage of all habitats within the corridor. However, this threshold resulted in the lowest amount of core habitats in the corridor (89.9%).

On the other hand, the threshold of 4.30% resulted in a corridor where all core habitat patches were covered with the highest percentage of all habitats in the corridor. However, with this threshold the corridor expands to the whole of the study area which means that most of the study area is covered by the corridor.



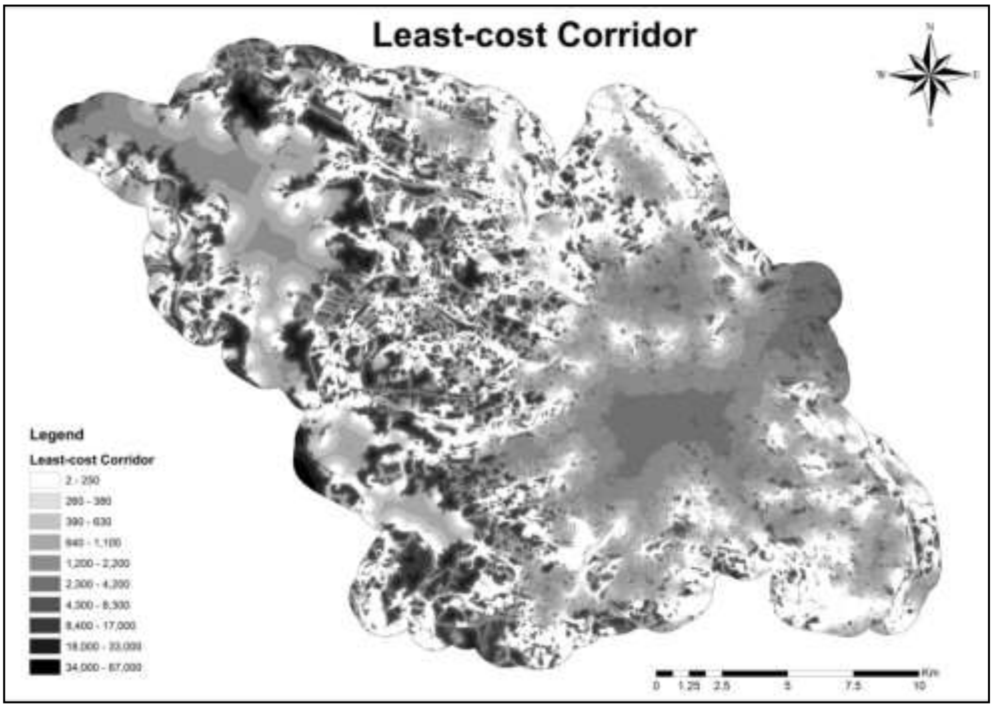
Pipistrelle bat (*Pipistrellus pipistrellus*)			
Classification Thresholds	0.15%	0.85%	4.30%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	76.3%	57.2%	41.0%
Percentage of all habitats covered by the corridor	83.7%	99.3%	99.9%
Percentage of the corridor made up by core habitats	89.9%	100%	100%

Figure 15: Least-cost binary maps with different thresholds for Pipistrelle bats

In this context, it is obvious that 4.30% does not represent a viable threshold for the determination of the corridor width from planning perspective. The threshold of 0.85% provided a corridor in which all core habitats are included with a high percentage of all habitats covered by the corridor (99.3%). Therefore, when I examined the percentage of all habitats, suitable habitats (Source 1 habitats) and the proportion of corridor to these, I decided to use the threshold of 0.85% for the Pipistrelle Bat (see Appendix 20D).

6.4.7 Leisler's Bat (*Nyctalus leisleri*)

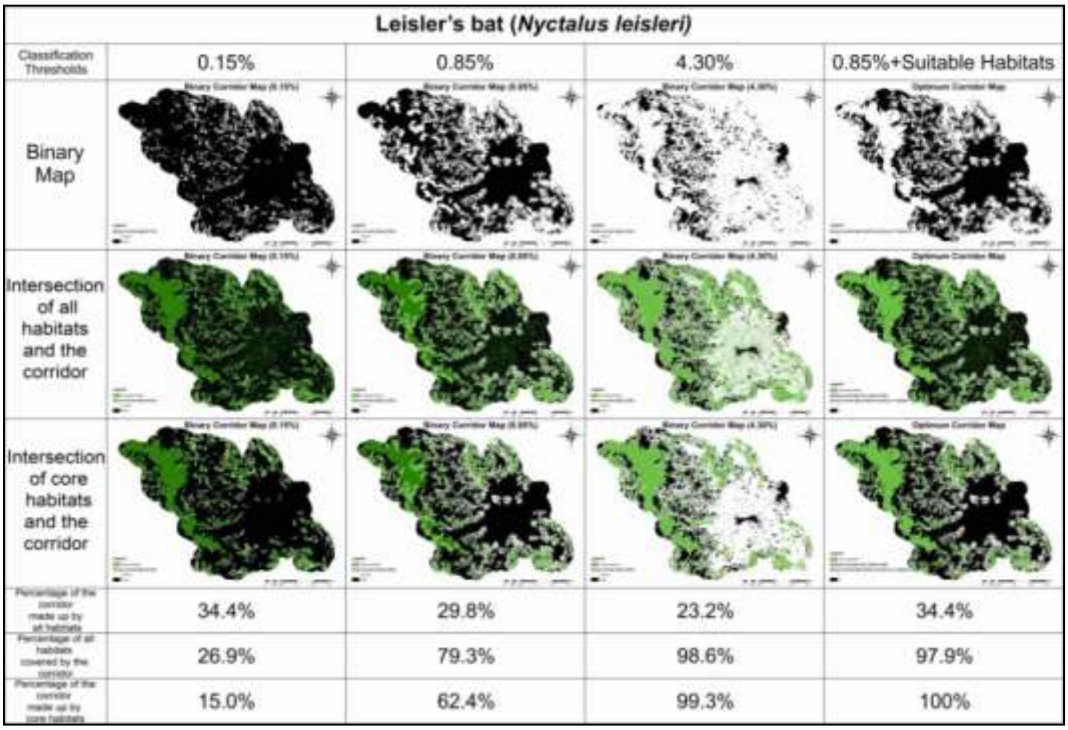
The parameters of least-cost corridor and its input layers for Leisler's bats are given in Appendices 21A and 21B in Volume II. Map 24 represents the resulting least-cost corridor for Leisler’s bats.



Map 24: Least-cost corridor for Leisler's bats

The most suitable areas for potential connectivity routes for Leisler’s Bat are too narrow and concentrated around the Green Belt and suburban area following the river corridors where *Unimproved Grassland* and *Broadleaved Woodland* are the dominant land cover types (for details see Appendix 21C). We can clearly see that the most suitable areas for the corridor are located between the built-up area of Sheffield and the Peak District National Park. Additionally, the areas located in the western and around the urban periphery provide moderate connectivity and enhance the movement corridors for Leisler's bats. However, the movement corridors are confined within areas which do not provide ecological connectivity for Leisler's bats.

After generating the least-cost corridor, I attempted to determine the optimum threshold for the width and representation of the corridor for the Leisler's Bat (Figure 16). Here, the 0.15% threshold resulted in the highest percentage of corridor that is made by up all habitats. However, with this threshold the percentage of core habitats covered by the corridor is the smallest compared to the thresholds of 0.85% and 4.30%.



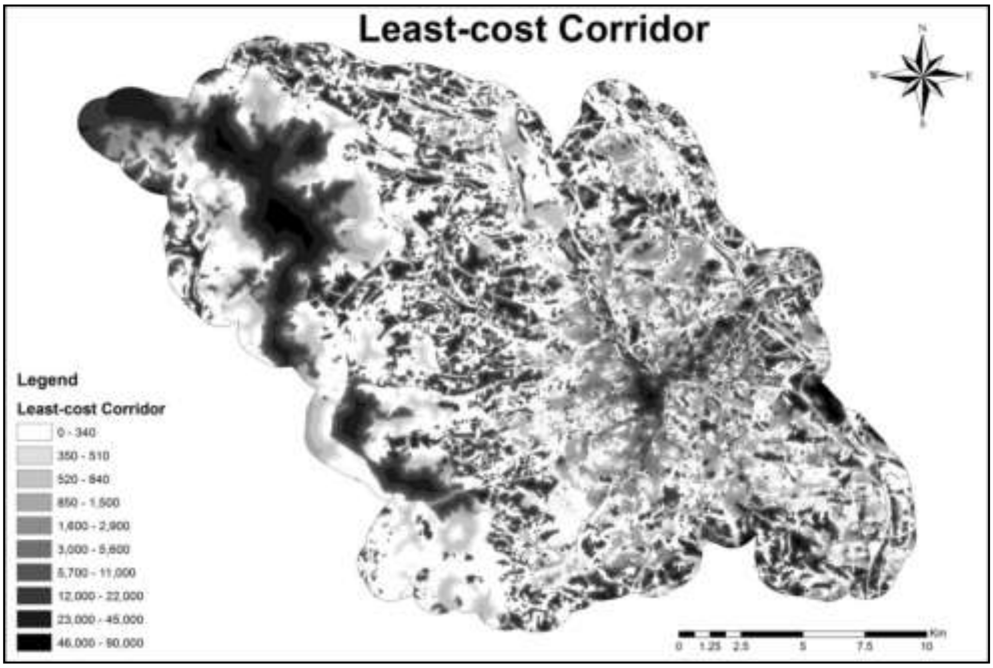
Classification Thresholds	0.15%	0.85%	4.30%	0.85%+Suitable Habitats
Percentage of the corridor made up by all habitats	34.4%	29.8%	23.2%	34.4%
Percentage of all habitats covered by the corridor	26.9%	79.3%	98.6%	97.9%
Percentage of the corridor made up by core habitats	15.0%	62.4%	99.3%	100%

Figure 16: Least-cost Binary Maps with Different Thresholds for Leisler's bats

On the other hand, the threshold 4.30% covers most of the study area and the proportion of all habitats in the corridor is the smallest (23.2%). Hence, this threshold does not give a usable option in a planning context. The threshold of 0.85% provides a corridor with a high percentage of all habitat areas relative to the 0.15% threshold. But, all the core habitats are not included in the corridor (62.45). Therefore, in order to determine the width of the least-cost corridor for the Leisler's bat, I used the 0.85% threshold by forcing it to include all core habitats in the network (see Appendix 21D).

6.4.8 Common lizard (*Lacerta vivipera*)

After creating all the necessary layers based on the expert's opinion, I modelled the least-cost corridor for Common lizards (for details see Appendices 22A and 22B). The least-cost corridor for Common lizards is distributed all around the study area with a very well-connected spatial configuration from city centre towards the Peak District National Park (Map 25, for details see Appendix 22C).

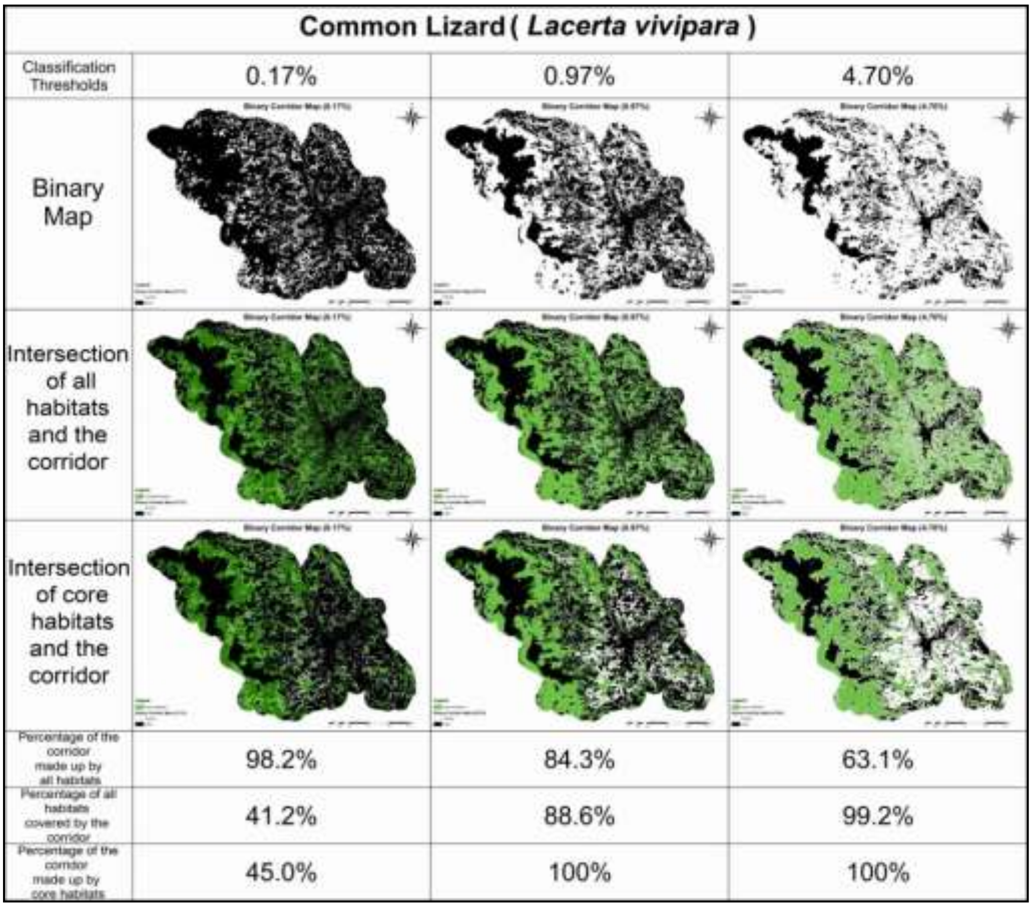


Map 25: Least-cost corridor for Common lizards

The least favourable areas for the potential connectivity routes are generally located around agricultural land, around the built-up areas, and the highest parts of the Peak District National Park. When we consider the disturbances from agricultural activities (agricultural equipment and lack of sheltering cover) and *Buildings and Structures* as barriers to movement, we can confirm the potential contribution of the patches of *Roadside Vegetation* to the movement of Common lizards. Even though the areas of *Wetlands* are generally thought to be good for the movement of Common lizards, this was not reflected by the created networks based on the habitat suitability and permeability estimates made by experts.

After examining the least-cost corridor model I attempted to determine the optimum threshold value (Figure 17). Similar to the previous models, the lowest threshold 0.17% resulted in the highest percentage of corridor that is made up by all habitats (98.2%). However, the percentage of the all habitats and particularly the core habitats in the corridor are the lowest with this threshold (41.2 % and 45.0%, respectively).

On the other hand, with the threshold of 4.70% all core habitats are covered by the corridor. However, with this threshold the area of the corridor becomes too large and almost all of the study area is covered by the corridor.



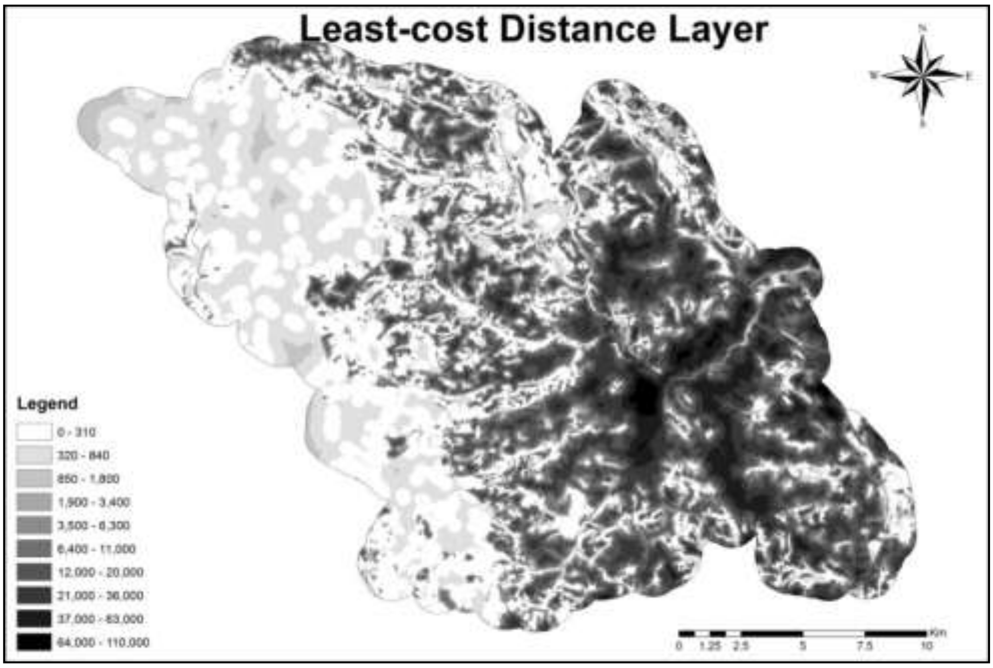
Common Lizard (*Lacerta vivipara*)			
Classification Thresholds	0.17%	0.97%	4.70%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	98.2%	84.3%	63.1%
Percentage of all habitats covered by the corridor	41.2%	88.6%	99.2%
Percentage of the corridor made up by core habitats	45.0%	100%	100%

Figure 17: Least-cost binary maps with different thresholds for Common lizards

Hence, it is obvious that 4.70% does not represent a viable threshold for the determination of the corridor width. When I plotted the corridor with 0.97%, it covers all core habitat patches with a high percentage of all habitat areas (88.6%). Therefore, I decided to use the threshold of 0.97% to represent the least-cost corridor for Common lizards (see Appendix 22D).

6.4.9 Grass Snake (*Natrix natrix*)

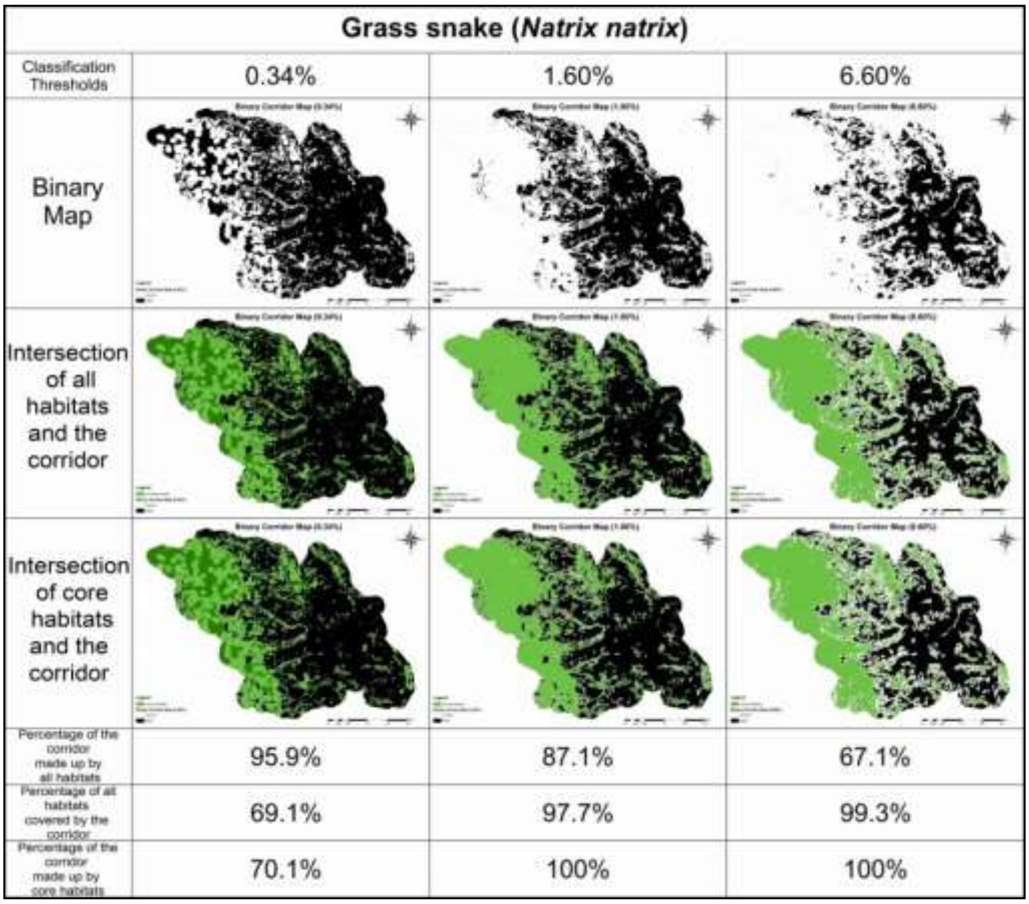
The parameters of least-cost corridor and its input layers for Grass snakes are given in Appendices 23A and 23B in Volume II. The least-cost corridor for Grass snakes is shown in Map 26. The least-cost corridor for Grass snakes is mainly located in the Peak District National Park where the land is covered by *Wetlands* and *Heathlands* (for details see Appendix 23C).



Map 26: Least-cost corridor for Grass snakes

In general, the potential ecological connectivity routes extend across the city centre from the western part of the study area, through the river corridors where the patches of *Woodlands*, *Unimproved Grassland* and *Water* dominate the land. The corridors from the Peak District National Park towards to the city centre are surrounded by agricultural land, which cause disturbance for Grass snakes (vehicles and lack of cover against predators). Additionally, even though there are some weak connections in the built-up area of Sheffield, the connectivity is the lowest in the city centre where *Buildings / Structures and Constructed Surfaces* dominate the area and affect the movement of Grass snakes as suggested by experts.

Figure 18 represents the corridor plotted with different thresholds for Grass snakes. With the threshold of 0.34%, I obtained the highest percentage of corridor made up by all habitats (95.9%). However, this corridor does not include all core habitats (70.1%) and the percentage of all habitats covered by the corridor is the lowest (69.1%) compared to the other thresholds. Using the threshold of 6.60%, I obtained a very large corridor in which all core habitats are included. However, because of covering an extensive area in the whole study area, this threshold does not provide a feasible corridor from planning perspective. On the other hand, with the threshold of 1.60%, the corridor includes all core habitats with a high percentage of all habitat areas in the corridor (97.7%). Therefore, I decided to use the threshold of 1.60% to determine the width of the corridor for Grass snakes (see Appendix 23D).

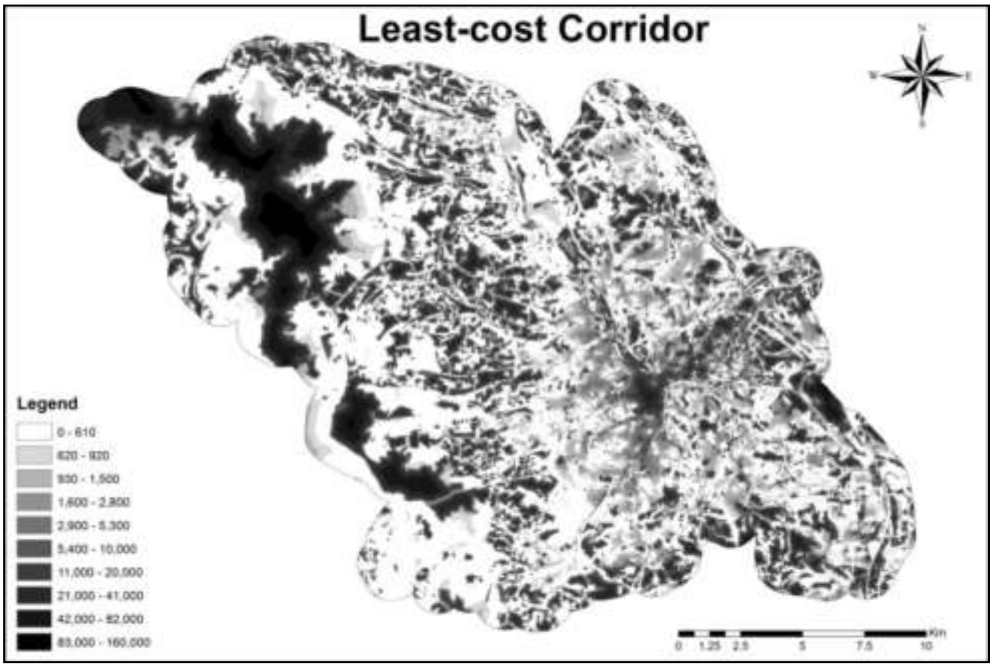


Grass snake (*Natrix natrix*)			
Classification Thresholds	0.34%	1.60%	6.60%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	95.9%	87.1%	67.1%
Percentage of all habitats covered by the corridor	69.1%	97.7%	99.3%
Percentage of the corridor made up by core habitats	70.1%	100%	100%

Figure 18: Least-cost binary maps with different thresholds for Grass Snakes

6.4.10 Slow-worm (*Anguis fragilis*)

After creating all the necessary layers based on the expert's opinion, I modelled the least-cost corridor for Slow-worms (for details see Appendices 24A and 24B). The connectivity corridor is distributed throughout the city and it is well-connected (Map 27, for details see Appendix 24C). Similar to previously mentioned reptile species, agricultural activities were considered to act as disturbances by experts, due to the effects of vehicles and lack of cover from predators. However, among agricultural lands, the presence of areas of *Woodlands, Unimproved Grassland* and *Roadside Vegetation* make an important contribution to the potential connectivity routes between the Peak District National Park and the city centre of Sheffield. On the other hand, the areas of *Wetlands* in the Peak District National Park do not support the connectivity corridor as suggested by experts, because of being too humid for Slow-worms to provide required food resources and refuge areas.

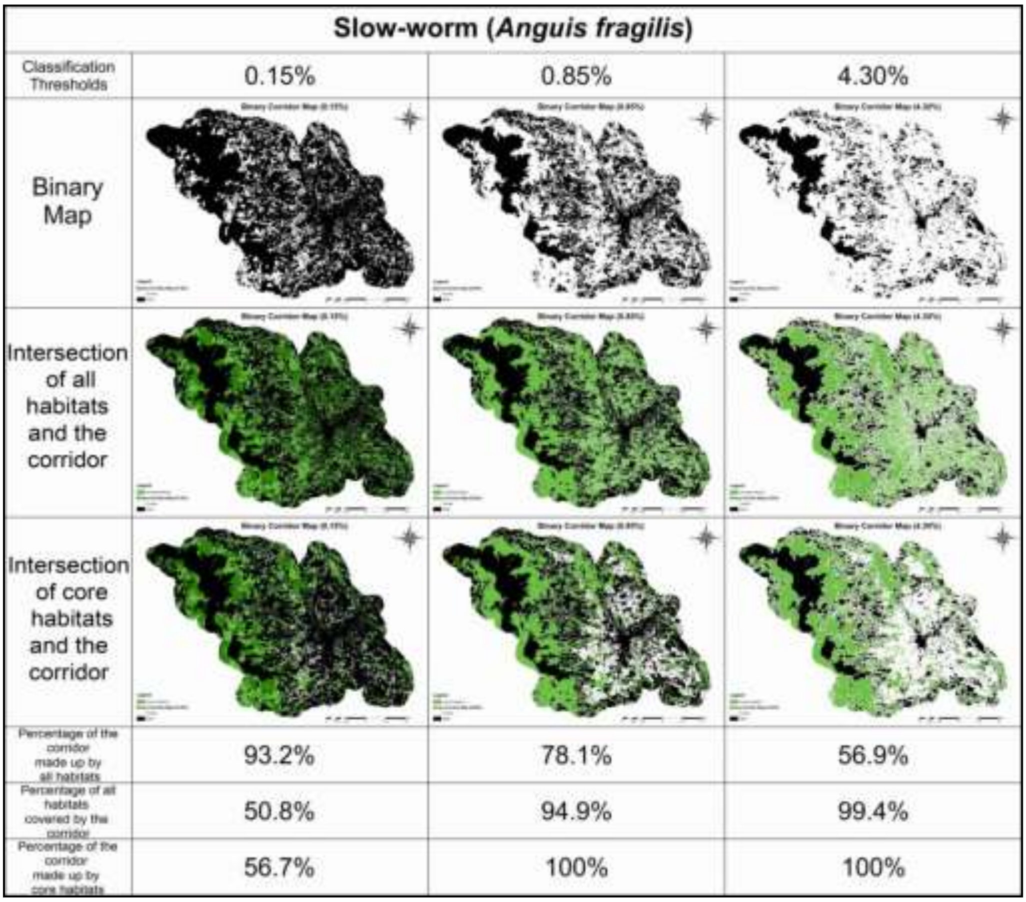


Map 27: Least-cost corridor for Slow-worms

Figure 19 shows least-cost corridor for Slow-worms with different thresholds. When I represented the corridor using different thresholds, the lowest threshold (0.15%) resulted in the highest percentage of the corridor covered by all habitat areas (93.2%).

However, using this threshold resulted in the lowest percentage of core habitats and the lowest percentage of all habitats being covered by the corridor (56.7% and 50.8%, respectively).

The 4.30% threshold covers most of the study area, with the highest percentage of all habitats covered by the corridor, but because the resulting corridor is too wide to be realistic for planning purposes, it was assumed that this threshold cannot be used to represent the corridor. On the other hand, the 0.85% threshold covers all core habitats and a high percentage of all habitat areas covered by the corridor. Therefore, it was decided to use the threshold of 0.85% for the representation of the least-cost corridor for Slow-worms (see Appendix 24D).



Slow-worm (*Anguis fragilis*)			
Classification Thresholds	0.15%	0.85%	4.30%
Binary Map			
Intersection of all habitats and the corridor			
Intersection of core habitats and the corridor			
Percentage of the corridor made up by all habitats	93.2%	78.1%	56.9%
Percentage of all habitats covered by the corridor	50.8%	94.9%	99.4%
Percentage of the corridor made up by core habitats	56.7%	100%	100%

Figure 19: Least-cost binary maps with different thresholds for Slow-worms

6.4.11 Validation of Parameters Gathered from Experts

As indicated previously, the information for the parameters of the functional least-cost connectivity models for the chosen species are based on very limited input from experts. Therefore, I aimed to validate the input dataset and the output models by applying the following approaches data availability allowing.

- I assessed the internal consistency between the 3 estimations of experts who provided guidance on habitat requirements with regard to reptiles,
- I tested the sensitivity of the outputs from the least-cost corridor analysis by varying the input expert opinion values by 5% and 20% for one species from each taxon.
- I overlaid the species occurrence data onto my binary maps of least-cost corridors in order to validate expert opinion data with real data.

- Finally, I compared the responses of experts as the input parameters for bird species with the published data on relative population densities in different habitats from the British Trust for Ornithology (BTO) to validate expert estimations on the habitat suitability.

6.4.11.1 The Cronbach's Alpha Internal Consistency Analysis

The internal consistency between the 3 experts' reports on the habitat suitability of different land cover types for a group of selected species and the cost values for landscape permeability were assessed using Cronbach's alpha. Cronbach's alpha measures the mutual correlation of the different variables, in other words the internal consistency of the variables in a multivariable scale (Vogt, 1999). The values of Cronbach's alpha ranges from 0 to 1 and the closer the value of Cronbach's alpha is to 1 the higher the degree of internal consistency between variables (Tavakol & Dennick, 2011). Essentially this means that experts who are likely to select high scores for one variable also likely to select high scores for the other variables, and vice versa.

Whilst there is not a clear-cut standard on the minimum threshold of Cronbach's alpha value (Clark & Watson, 1995), generally Cronbach's alpha values greater than 0.600 or 0.700 are regarded as representative of the internal consistency for the given variables (Tavakol & Dennick, 2011). However, as noted by Cortina (1993) and Field (2005), the suggested minimum threshold values should be interpreted with caution, since the alpha value is highly dependent on the number of the variables, as well as survey participation (Tavakol & Dennick, 2011), which was limited in this case.

An online survey package, named Survey Gizmo, was used for this research, containing 29 questions and 3 sections designed to elicit opinions on the selected species from experts. The first and second sections were related to the determination of suitable habitat patches for each of the selected species. As explained earlier, the first section includes 14 questions with regard to the suitability of 14 land cover type as habitat for the successful breeding and survival of the selected species, where the estimations were made in a probabilistic way, on a 100 point visual analogue scale from 1 to 100.

On the other hand, the second section includes only one question on the minimum habitat area requirement that is large enough to support at least one successful breeding unit for the selected species, and therefore cannot be used in the consistency analysis.

The last section is related to estimations of the cost values for each land cover type, considering the relative difficulty for the species to move between habitat and non-habitat patches. As in the first section, the estimations for this section were made on a 100 point visual analogue scale. However, the values were reverse scored. Field (2006) states that the result of Cronbach's alpha is affected by reverse scored questions. Hence, the internal consistency analyses of the first and third sections were conducted separately. The Cronbach's alpha analysis was conducted in SPSS (Analyse, Scale and Reliability Analysis). In SPSS, each question within a section in the online survey is regarded as a variable (item) and the details of the survey can be found in Appendix 14. The internal consistency between the 3 estimations of experts for habitat suitability (section 1) and the values for the cost of movement (section 3) were assessed by 14 variables for each reptile species.

Results of the Cronbach's Alpha Analysis

A. Common lizard (*Lacerta vivipara*)

Table 18 displays the Cronbach's alpha values that would result if a given variable were deleted from the habitat suitability and cost value estimations of the three experts for Common lizards, and the overall alpha for both. "Alpha if Item Deleted" is thought be the most important information in Cronbach's alpha analysis, since it "represents the scale's Cronbach's alpha reliability coefficient for internal consistency if the individual item is removed from the scale" (Gliem & Gliem, 2003).

For habitat suitability estimations, while the overall Cronbach's alpha is 0.731, the values of "Cronbach's Alpha if Item Deleted" range from 0.591 to 0.791. For example, if either the variable of "Woodland" or "*Buildings Structures and Constructed Surfaces*" were dropped from the Cronbach's alpha analysis; the overall alpha value would decrease to 0.591 and 0.636, respectively. Since the removal of such variables causes a decrease in the overall alpha value, these variables appear to contribute to the overall reliability of habitat suitability estimations. On the other hand, if the variable of "*Coniferous Woodland*" is excluded from analysis, then the overall alpha would increase slightly from 0.731 to 0.791.

Table 18: Item-total statistics of habitat suitability and cost value estimations for Common lizards

Variables	Cronbach's Alpha if Item Deleted (Habitat Suitability)	Cronbach's Alpha if Item Deleted (Cost Values)
Woodland	0.591	0.799
Coniferous Woodland	0.791	0.807
Shrub	0.745	0.760
Mixed Vegetation 1	0.774	0.767
Mixed Vegetation 2	0.725	0.710
Improved Grassland	0.722	0.726
Amenity Grassland	0.661	0.740
Unimproved Grassland	0.729	0.763
Heathland	0.703	0.784
Arable Land	0.704	0.764
Standing Water	0.723	0.780
Running Water	0.729	0.794
Wetland	0.679	0.746
Buildings Structures and Constructed Surfaces	0.636	0.824

Number of responses, N= 3; Number of Items (Variables) = 14; Cronbach's alpha for Habitat Suitability= 0.731; Cronbach's Alpha for Cost Values = 0.786.

However, as the value of overall alpha does not increase by a large amount, there is not sufficient statistical reason to drop this variable from the analysis. Therefore, all the 14 variables were retained to demonstrate internal consistency of the habitat suitability estimations. The values of the "Cronbach's Alpha if Item Deleted" range from 0.710 to 0.824 for cost value estimations, with an overall alpha value of 0.786. The highest increase in the overall alpha would be 0.038, if the variable "*Buildings Structures and Constructed Surfaces*" was dropped from the analysis. Thus, these 14 variables are considered as internally consistent estimations for the Common lizard's cost value of movement.

B. Grass snakes (*Natrix natrix*)

An examination of the Cronbach's Alpha results for the habitat suitability estimations section reveals that all the "Cronbach's Alpha if Item Deleted" values were greater than 0.750 with an overall alpha value of 0.819. Additionally, the removal of any variable has little or no significant effect on the overall internal consistency between the 3 experts' estimations (Table 19). Similar results were generated by the internal reliability analysis for the cost values. Thus, the cost value estimations of all 14 variables for Grass snakes seem to be consistent.

Table 19: Item-total statistics of habitat suitability and cost value estimations for Grass snakes

Variables	Cronbach's Alpha if Item Deleted (Habitat Suitability)	Cronbach's Alpha if Item Deleted (Cost Values)
Woodland	0.771	0.756
Coniferous Woodland	0.816	0.750
Shrub	0.854	0.693
Mixed Vegetation 1	0.812	0.665
Mixed Vegetation 2	0.850	0.694
Improved Grassland	0.750	0.725
Amenity Grassland	0.759	0.812
Unimproved Grassland	0.777	0.727
Heathland	0.804	0.664
Arable Land	0.749	0.740
Standing Water	0.828	0.827
Running Water	0.812	0.809
Wetland	0.824	0.749
Buildings Structures and Constructed Surfaces	0.771	0.766

Number of responses, N= 3; Number of Items (Variables) = 14; Cronbach's alpha for Habitat Suitability= 0.819; Cronbach's Alpha for Cost Values = 0.763.

C. Slow-worms (*Anguis fragilis*)

Table 20 shows the “Cronbach's Alpha if Item Deleted” for the habitat suitability and cost values of the 3 experts’ estimations for Slow-worms, where the overall alpha values are 0.788 and 0.843, respectively.

Table 20: Item-total statistics of habitat suitability and cost value estimations for Slow-worms

Variables	Cronbach's Alpha if Item Deleted (Habitat Suitability)	Cronbach's Alpha if Item Deleted (Cost Values)
Woodland	0.752	0.840
Coniferous Woodland	0.788	0.783
Shrub	0.820	0.864
Mixed Vegetation 1	0.866	0.840
Mixed Vegetation 2	0.707	0.850
Improved Grassland	0.706	0.798
Amenity Grassland	0.707	0.832
Unimproved Grassland	0.752	0.843
Heathland	0.734	0.840
Arable Land	0.805	0.820
Standing Water	0.785	0.826
Running Water	0.782	0.786
Wetland	0.762	0.783
Buildings Structures and Constructed Surfaces	0.760	0.882

Number of responses, N= 3; Number of Items (Variables) = 14; Cronbach's alpha for Habitat Suitability= 0.788; Cronbach's Alpha for Cost Values = 0.843.

Additionally, the “Cronbach's Alpha if Item Deleted” values for the habitat suitability and cost value estimations were examined, all were greater than 0.700. Hence, all the estimations of habitat suitability and cost value variables were interpreted as internally consistent variables for Slow-worms.

The purpose of the Cronbach's alpha analyses was to provide an analysis of the internal consistency between the 3 estimations of experts who provided guidance on habitat requirements for three selected reptile species. In general, the overall Cronbach’s alpha values are greater than 0.700, and the values for the “Cronbach's Alpha if Item Deleted” were very close to the overall Cronbach’s alpha value for both the habitat suitability and cost values for each of the selected reptile species. Therefore, the results of the reliability analysis for each of the selected reptile species confirm that the estimations for the habitat suitability and cost values gathered from the three experts have high degrees of internal consistency.

6.4.11.2 The Sensitivity Analysis of Input Parameters of the Least-cost Models

The sensitivity analyses were performed to evaluate the change in the least-cost corridor modelling outputs, when the original expert opinion values are varied over a range of different values. According to Sawyer et al. (2011) and Beier et al. (2009) sensitivity analyses are prerequisite for landscape planning where the landscape connectivity is modelled as part of the planning process. Beier et al. (2009) also emphasise the requirement for a sensitivity analysis, given its ability to quantify and determine the possible uncertainties in the input parameters.

As noted earlier expert opinion values for each species include 29 estimations for 3 different sections in the survey, where the first and second sections were related to the habitat suitability of different land cover types and the minimum habitat area for the targeted species respectively, and the last section was related to the difficulty of the targeted species’ movement across different land cover types (cost values). In order to test the sensitivity of the least-cost corridor models, I varied the expert estimations for the habitat suitability and cost values by both increases and decreases of 5% and 20%, as the input parameters of the least-cost connectivity models.

The Skylark, Leisler's bat and Common lizard were used as the examples of each taxon for sensitivity analyses. I created 4 least-cost corridors for each of these species by varying the original expert values by ±5% and ±20%. The least-cost corridors were created in the same way as the least-cost corridors I constructed on the basis of the original expert opinion values.

For the suitable habitats I assigned a cost value of 1, in accordance with the requirement of the least-cost corridor models. As a result, I created 12 additional least-cost corridors in total and compared them with the least-cost corridors based on the original expert opinion values for each of these species. The comparisons were made in ArcGIS, by overlapping each of the newly created least-cost corridors with the original least-cost corridors based on expert opinion values (EOVs).

Results of the Sensitivity Analyses

A. Skylark (*Alauda arvensis*)

The least-cost corridor for Skylarks, based on the original EOVs, covers 39.58% of the whole study area. In general, the percentage of the study area occupied by the least-cost corridors based on the original EOVs and its variations are almost the same, where the original EOVs and + 20% of the EOVs resulted in the largest and smallest corridor area, respectively (Table 21).

Table 21: Percentage of the landscape occupied by the least-cost corridors for Skylark

% of the landscape occupied by the least-cost corridors	
The original EOVs	39.58
- 5% of the EOVs	39.45
+ 5% of the EOVs	39.34
- 20% of the EOVs	39.37
+ 20% of the EOVs	39.23

On the other hand, the resulting least-cost corridors overlapped by 99.68% to 98.14%, with an average overlap of 99.14%, as seen in Table 22.

Table 22: Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Skylark

Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Skylark	
EOVs and - 5% of the EOVs	99.68
EOVs and + 5% of the EOVs	99.27
EOVs and - 20% of the EOVs	99.47
EOVs and + 20% of the EOVs	98.14
Average Overlap (%)	99.14

Since there is only a small amount of difference in the total area of the least-cost corridors, I also compared the location of overlap between each corridor based on the original EOVs and its variations by ±5% and ±20%.

Figure 20 illustrates the overlap between the corridor based on the EOVs and their variations by ±5% and ±20%. Here, while the areas of white colour represent the overlap between the corridors, the green areas show the loss and red increase in the corridor area when I varied EOVs by the given percentages. The black areas, on the other hand, illustrate the areas that are not included in the output corridors either for the original EOVs or its variations.

As seen in this figure the location and the configuration of the least-cost corridor remained almost the same with some small changes when I varied the original habitat suitability and cost values estimated by the experts.

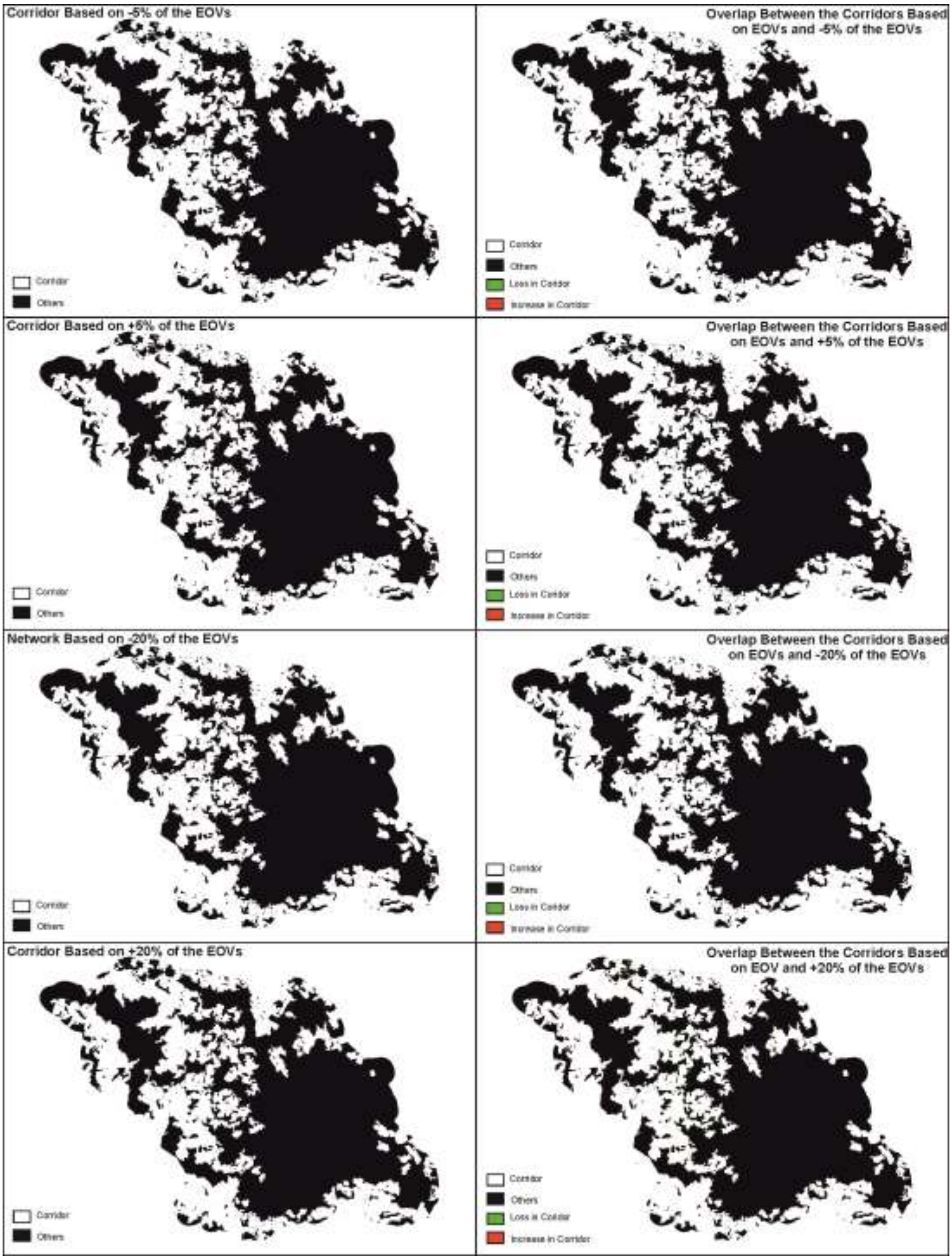


Figure 20: Least-cost corridors for Skylarks based on the original EOVs and its variations by ±5% and ±20%

B. Leisler’s bat (*Nyctalus leisleri*)

The least-cost corridor based on the original EOVs covers 42.58% of the whole study area. On the other hand, all the 4 least-cost corridors based on varying the original EOVs reported higher coverage compared to the original least-cost corridor. However the differences in the total area of the least-cost corridors are the lowest for the positive variations in the original EOVs, -5% and -20% variation in the EOVs resulted in 6% and 9.46% increases in the area of the least-cost corridors, respectively (Table 23).

Table 23: Percentage of the landscape occupied by the least-cost corridors for Leisler’s bat

% of the landscape for the least-cost corridors	
The original EOVs	42.58
- 5% of the EOVs	48.58
+ 5% of the EOVs	43.04
- 20% of the EOVs	52.04
+ 20% of the EOVs	44.49

In spite of this, the percentage of overlap between the original and newly generated least-cost corridors is very high, with an average percentage overlap of 99.56% (Table 24).

Table 24: Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Leisler’s bat

Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Leisler's bat	
EOVs and - 5% of the EOVs	99.59
EOVs and + 5% of the EOVs	99.50
EOVs and - 20% of the EOVs	99.63
EOVs and + 20% of the EOVs	99.52
Average Overlap (%)	99.56

The location and configuration of least-cost corridors based on the variation in the original EOVs are represented in Figure 21. As seen, while the main location of corridors remained almost the same, the changes in corridor area are found around their edges.

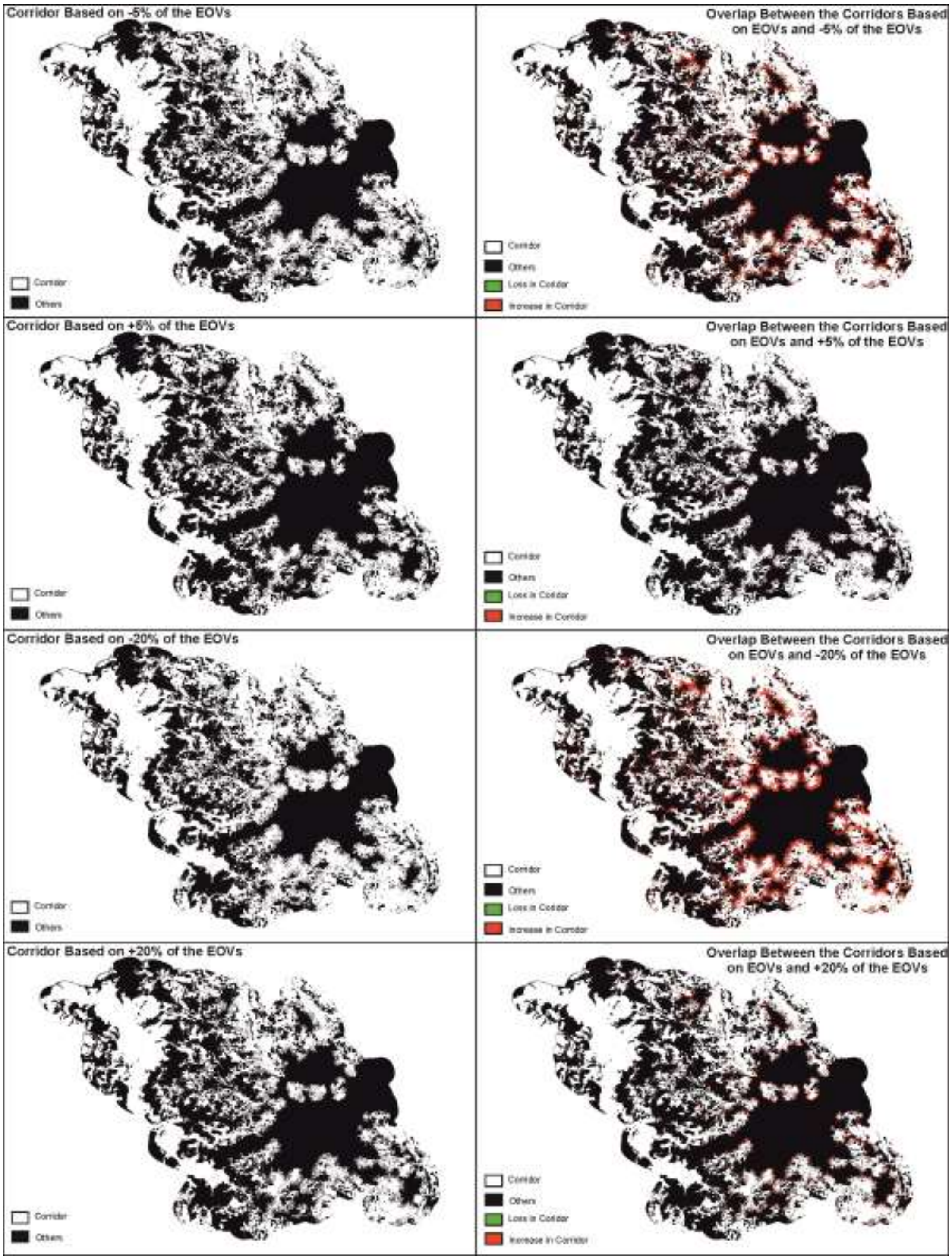


Figure 21: Least-cost corridors for Leisler's bats based on the original EOVs and its variations by ±5% and ±20%

A further examination of the corridors generated by the negative variations revealed that the area of least-cost corridors for Leisler's bats are sensitive to differences in the relative cost values assigned to each land cover type, as well as differences in the values of the minimum habitat area requirement. For example, while a decrease of 20% in the cost values produces a notional increase in the permeability of the landscape for Leisler’s bats, a decrease in the minimum habitat area requirement causes an increase in the core habitat patches, and correspondingly in the total corridor area. However, the main location and configuration of the least-cost corridors based on the variation in the original EOVs did not show major differences compared to the original least-cost corridor, with an average overlap of 99.56%.

Based on these findings, a decrease in the corridor area was expected for the corridors generated by the positive variations, due to the increase in the cost values and the minimum habitat requirement. However, the discrepancy in the resulting least-cost corridors for the positive variations was attributed to the use of the *Geometrical Interval* classification method for the representation of optimum binary corridor widths. As explained earlier, this classification method minimises the differences in the cost values for each group (class) and determines the cost value thresholds (see section 6.3.3). In the case of increased cost values, by varying the original expert opinion cost values by +5% and +20%, the pixels with lower cost values were grouped together to minimise the differences in each group, and this caused an increase in the number of pixels with similar cost values. For example, the least-cost corridor based on the original EOVs included 51717827 pixels (out of 121317495) for the corridor due to the use of the first two break values as thresholds for binary map classification.

However, the positive variations of the original EOVs resulted in least-cost corridors with 53832734 (for +5%) and 54747715 (+20%) pixels, using the same classification methods. As a result, the increase in the number of pixel values falling into the corridor area for positive variations of the original EOVs was increased and resulted an expansion in the total area of the these corridors, particularly where the least suitable habitat patches are mostly located.

C. Common lizard (*Lacerta vivipara*)

For the Common lizard, under each model least cost corridors occupied at least of the landscape. The differences in the total area of the original and generated least-cost corridors ranged from -0.41% to 2.50% (Table 25).

Table 25: Percentage of the landscape occupied by the least-cost corridors for Common lizard

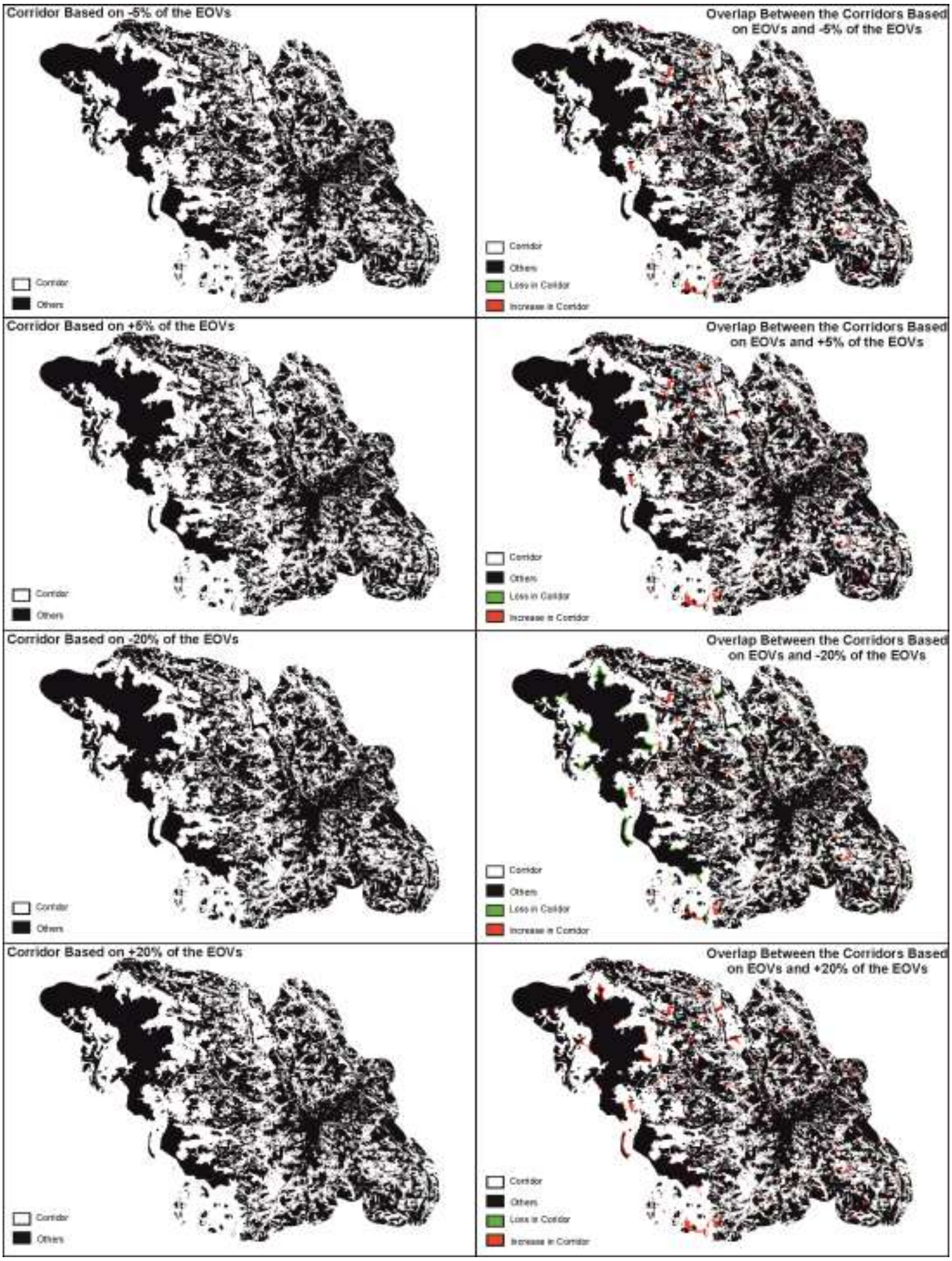
% of the landscape for the least-cost corridors	
The original EOVs	42.63
- 5% of the EOVs	43.69
+ 5% of the EOVs	44.37
- 20% of the EOVs	42.22
+ 20% of the EOVs	45.13

The average percentage of overlap between corridors based on EOVs and their positive and negative variations for Common lizards was 98.55%, with a minimum and maximum percentage overlap of 95.66% and 99.87%, respectively (Table 26).

Table 26: Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Common lizard

Percentage of overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for Common lizard	
EOVs and - 5% of the EOVs	98.86
EOVs and + 5% of the EOVs	99.80
EOVs and - 20% of the EOVs	95.66
EOVs and + 20% of the EOVs	99.87
Average Overlap (%)	98.55

Similar to the generated least-cost corridors for Leisler’s bats, all the least-cost corridor variations have both increases and losses in their total corridor areas. However, as seen in Figure 22, apart from the least-cost corridor based on EOVs varied by -20%, the increases in the total area of all other least-cost corridor variations are larger than the decreases. The least-cost corridor based on the EOVs with the lowest total corridor area, varied by -20% for Common lizards has the highest loss in the total corridor area compared to the other newly generated least-cost corridors.



Corridor Based on -5% of the EOVs

Overlap Between the Corridors Based on EOVs and -5% of the EOVs

Corridor Based on +5% of the EOVs

Overlap Between the Corridors Based on EOVs and +5% of the EOVs

Corridor Based on -20% of the EOVs

Overlap Between the Corridors Based on EOVs and -20% of the EOVs

Corridor Based on +20% of the EOVs

Overlap Between the Corridors Based on EOVs and +20% of the EOVs

Figure 22: Least-cost corridors for Common lizards based on the original EOVs and its variations by ±5% and ±20%

In this section, the main aim was to test the least-cost model behaviours by varying the input parameters by ±5% and ±20% of expert opinions using an example from each taxon. After conducting a sensitivity analysis for each of the selected species, I determined the extent of output corridor variations both in terms of their their size and spatial configuration. I found that the spatial location and configuration of the least-cost corridors were not overly sensitive to differences in relative habitat suitability and cost values assigned to different land cover types, since the percentage overlap between corridors based on EOVs and EOVs varied by ±5% and ±20% for each of the selected species was greater than 95%. This suggests that there was fairly low variability in the output least-cost corridors for each of the selected species, where the degree of sensitivity was largely depended on the relative cost values assigned to land cover types.

I also assessed the extent of changes in location and configuration of the output least-cost corridors. These assessments have quite important consequences for landscape planning as well as the prioritisation of biodiversity conservation interventions, when we interpret the output corridors for landscape planning (Briers, undated). There were only a few spatial changes in the output models consequent on the different variations and these changes generally occurred at the edges of the least-cost corridors in the form of expansions (and also fairly small contractions) of the corridor based on the original expert opinion values.

However, there were no significant shifts in the extent to which habitat patches are functionally connected to each other. Essentially all the least cost corridors occupy the same locations and each species' corridor is more or less robust to minor variations in input parameters elicited from expert opinion.

Also, as found in the examples of species from each taxon, the classification system that we use for the representation of optimum corridor width is also sensitive to relative cost values assigned to land cover types. I varied all the cost values by ±5% and ±20% and expected that the positive variations would result in a less permeable landscape compared to the negative variations.

However, contrary to what was expected, when I increased the cost values assigned to each land cover type by +5 and +20, the total area of the resulting least-cost corridors for Leisler's bats and Common lizards became larger than when the cost values were lowered. As noted earlier, further consideration revealed that the area of these corridors became larger as a result of using the Geometrical Interval classification method to determine the cost value thresholds for the optimum corridor representations. Thus, we should also be aware of the influences of the selected classification method that we use to determine the optimum corridor width and representation on the least-cost model behaviours when we vary the input parameters.

6.4.11.3 Plotting Species Occurrence Data onto the Binary Maps of Least-cost Corridors

In order to validate experts' opinions on habitat suitability and the relative difficulty for the species to move between habitat and non-habitat patches, I overlaid the species occurrence data onto my binary maps of least-cost corridors using species records with an appropriately fine resolution grid size (1 km grid squares and smaller). The species occurrence dataset was obtained from the Sheffield City Council Ecology Unit, Recorder 6 species database. Out of ten selected species, I only had occurrence records at sufficient grid size for Song thrushes, Skylarks and Pipistrelle bats.

For each species, the species occurrence data and the least-cost corridors were overlaid in ArcGIS 10.1. I only used species occurrence data with resolutions of 1km, 100m and 10m grid squares, and excluded other records with bigger grid squares.

When calculating the percentage overlap between species records and the binary maps of the least-cost corridors, each species was considered to be present in each grid, regardless of the extent of the actual overlap between the grids and the least-cost corridors. Table 27 represents the summary of the occurrence records of Song thrushes, Skylarks and Pipistrelle bats as well as the percentage overlap between species records and the binary maps of the least-cost corridors for these species.

Table 27: Summary table of species records and the percentage overlap between species records and the binary maps of least-cost corridors

Song thrush		1 km grid	100 m grid	10 m grid
No. of Records	226	73	148	5
No. of Records with Multiple Observations	789	522	259	8
Observation Time Interval		1968-2011	1991-1996	1997-2013
The Percentage of Records Overlap with the Corridors		95.89%	83.78%	80.00%
The Percentage of Records Overlap with the Corridors (with multiple observations)		97.32%	94.60%	75.00%
Skylark		1 km grid	100 m grid	10 m grid
No. of Records	70	34	36	No records
No. of Records with Multiple Observations	117	75	42	No records
Observation Time Interval		1939 - 2011	1997 - 2009	
The Percentage of Records Overlap with the Corridors		73.33%	85.71%	
The Percentage of Records Overlap with the Corridors (with multiple observations)		76.47%	72.22%	
Pipistrelle Bat		1 km grid	100 m grid	10 m grid
No. of Records	45	20	25	No records
No. of Records with Multiple Observations	54	22	32	No records
Observation Time Interval		1980 - 2011	1978 - 2011	
The Percentage of Records Overlap with the Corridors		100%	100%	
The Percentage of Records Overlap with the Corridors (with multiple observations)		100%	100%	

Percentage coverage of least-cost corridors for each species in the total study area

Song thrush = 33.89%	**Skylark = 39.47%**	**Pipistrelle Bat = 57.57%**

The total number of occurrence records for Song thrushes between the years of 1968 - 2013 is 226, when each grid square was regarded as one record (regardless of how many records were located within it). When multiple records were taken into account within each grid, then the total number of records was 789. Out of 226 records, there are 73, 148 and 5 records for the grid resolutions of 1km, 100m and 10m, respectively. Figure 23 illustrates the overlap between occurrence data and the binary least-cost corridor for Song thrushes. As seen, the spatial pattern of the species occurrence and the binary least-cost corridor for Song thrushes are very similar to each other for 1km grid squares.

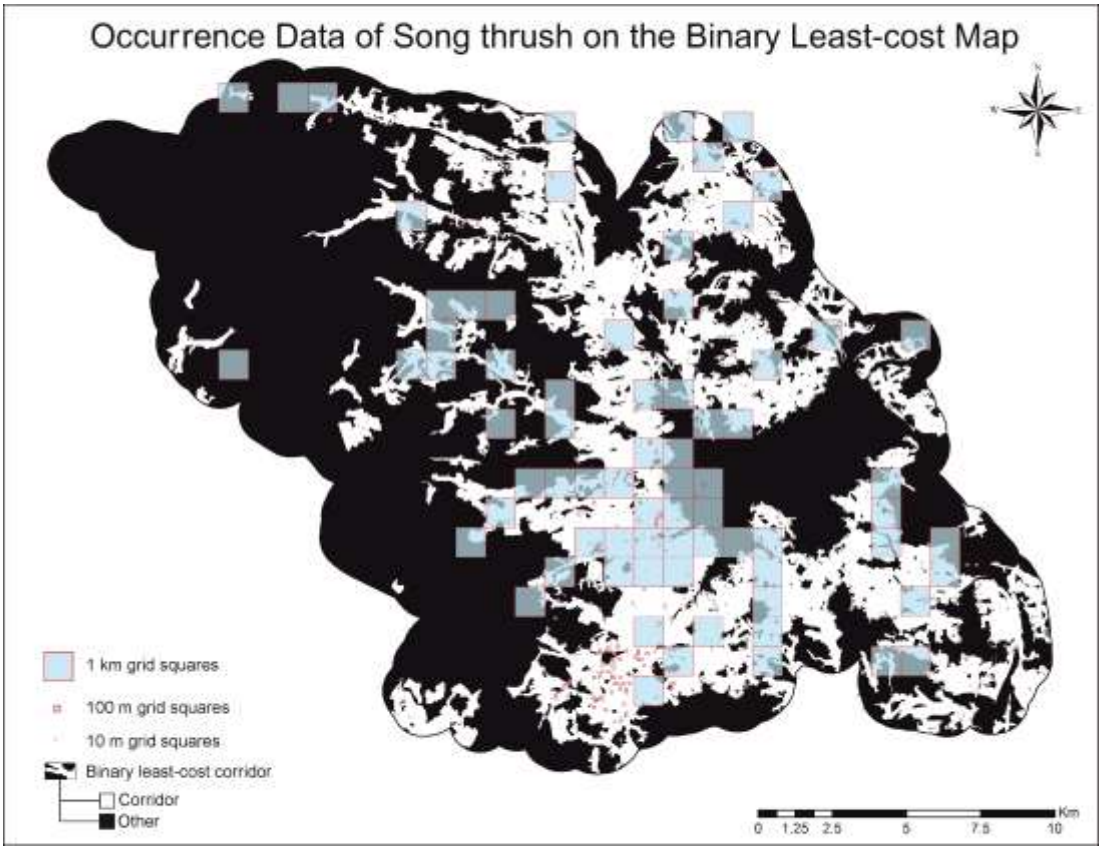


Figure 23: Spatial overlap between species records and the binary map of least-cost corridors for Song thrushes

The difference between the percentage of single record grids that overlap with the binary corridor and that of multiple record grids overlapping with the binary corridor suggests that 1km and 0.01km grid squares include more multiple records for one grid square which overlap with the least-cost binary map. The 10m grid squares include only 1 grid square with multiple records that overlaps with the binary least-cost corridor. Hence, even though the percentage overlap between the least-cost corridor and the occurrence of Song thrushes decreases in the case of the smaller grid squares, when considered together with the locations and numbers of records included these grid squares, these figures might not mean that the binary corridor does not match with the real data on the occurrence of Song thrushes. Also, I found that the percentage of records that overlap with the corridor is higher than 75% for each grid resolution regardless of whether each grid represents an individual record or multiple records. When compared with the total corridor coverage of 33.89% in the study area, this suggests a strong affinity between the binary least-cost corridor and the real data on the occurrence of Song thrushes.

With regard to Skylarks, the occurrence records are found in 1km and 100m grid squares between the years of 1939- 2011. When grid represented one record, the total number of records was 70, and with multiple records it was 117. Figure 24 shows the spatial overlap between the occurrence records of Skylarks and the binary map of the least-cost corridor.

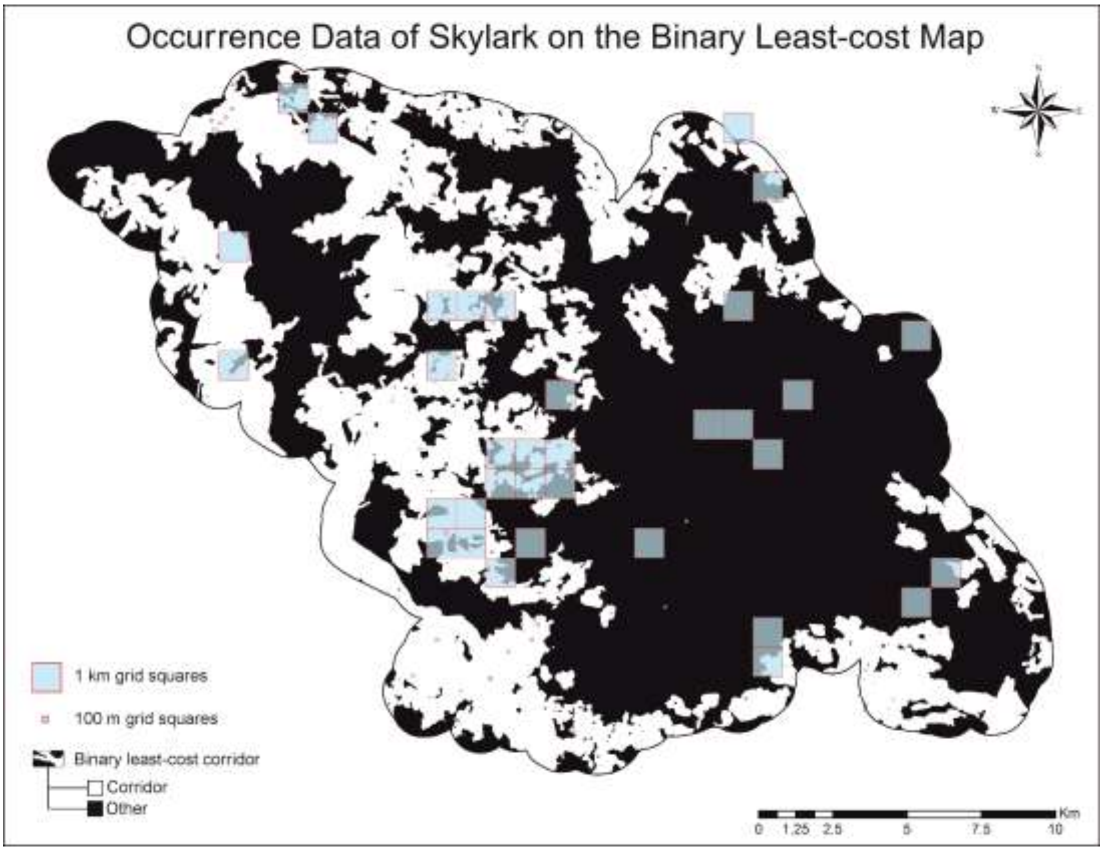


Figure 24: Spatial overlap between species records and the binary map of least-cost corridors for Skylarks

As seen, the spatial pattern of the binary least-cost corridor and the occurrence data for Skylarks are quite similar to each other, excluding the areas that lie in the built-up area of Sheffield. When each grid is counted as one record 26 out of 34 1km grid squares overlap with the least-cost corridor, and 55 out of 75 overlap in the case of multiple records, with an average percentage overlap of 74.90%.

On the other hand, the percentage overlap for 100m grids for single and multiple records was 85.71% and 72.71%, respectively. Hence when each 100m grid was treated as an equally weighted record the affinity of the binary least-cost corridor to the Skylark's occurrence is higher at a finer resolution, compared to the 1km grids. However as seen in Table 27, there is a reverse situation when multiple records within 1km and 100m grid squares are taken into account, where there is a high affinity between the corridor and the Skylarks' occurrence dataset. Taken together, the percentage overlaps between the binary map and the species occurrence datasets are greater than 70%, and this confirms the relevance of the least-cost corridor to the habitats of Skylarks.

Finally, the total number of occurrence records for Pipistrelle bats are 45 and 54 respectively, with single and multiple records for 1km and 100m grid squares between the years of 1978 and 2011 (Table 27). The spatial overlap between the binary map of the least-cost corridor for Pipistrelle bats and their occurrence dataset is also given in Figure 25.

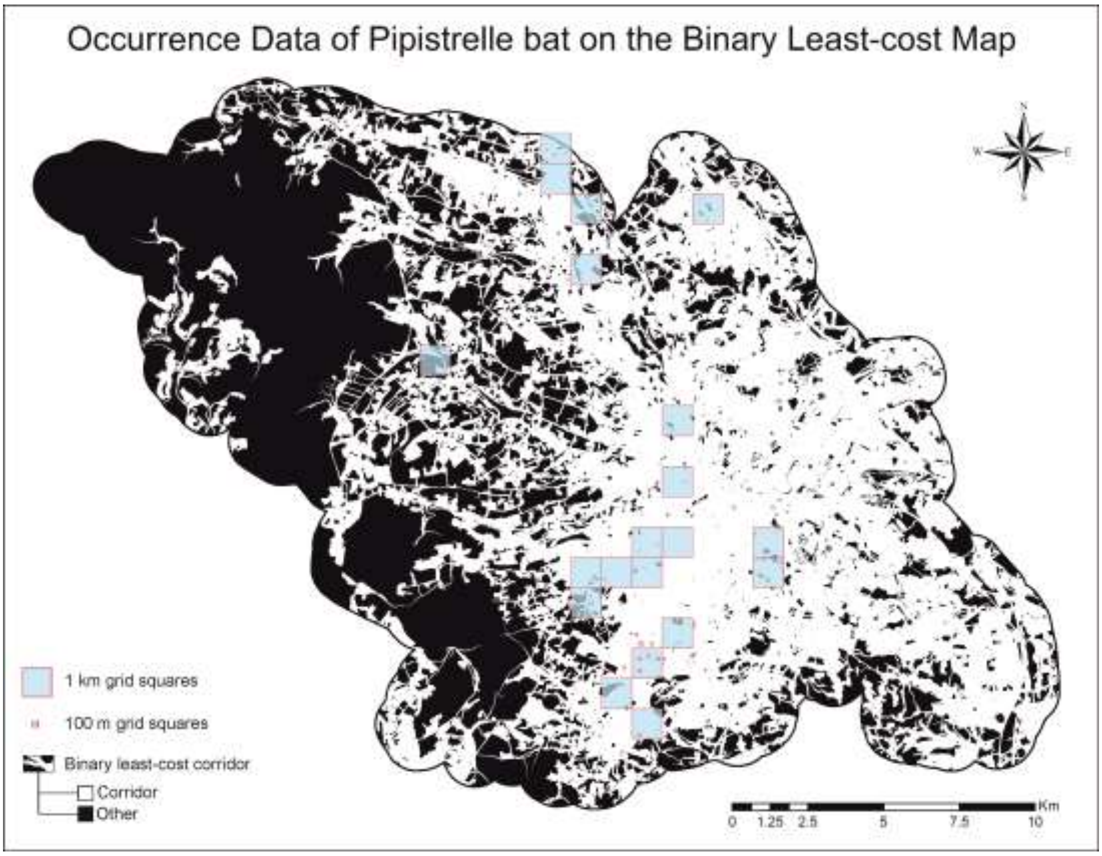


Figure 25: Spatial overlap between species records and the binary map of least-cost corridors for Pipistrelle bats

For each grid size, the percentage overlap between the least-cost binary corridor and the grid records of Pipistrelle bats are 100%, since each grid intersects with the corridor to some extent. This result can be attributed the small number of records and also the largest spatial coverage of the least-cost binary corridor for Pipistrelle bats (57.57%). However, the absence of occurrence data in the Peak District National

Park can be evaluated as a confirmation of the affinity between the least-cost corridor and habitats of Pipistrelle bats.

Overall, we can claim that a percentage overlap greater than 70% between the least-cost corridor binary maps and the available occurrence data for each species supports the accuracy of expert opinions on the habitat sutability and the relative difficulty for the species to move between habitat and non-habitat patches. Accordingly, these results also confirm the affinity of the least-cost binary maps and the actual presence of the selected species in the study area.

6.4.11.4 Comparison of the Input Parameters for the Selected Bird Species with BTO Relative Population Densities

In order to compare the expert estimates on the habitat suitability of each land cover type and the BTO habitat categories for the selected species, I initially extracted data on their relative population densities in different habitats from the BTO (BTO, 2015a). Then, I assessed the extent to which the BTO habitat categories match for those habitats that I have identified.

For this purpose, I used Breeding Bird Survey Guidance for Habitat Codes (BTO, 2015b) and BTO / JNCC / RSPB Breeding Bird Survey Habitat Recording Form (BTO, 2015c). Below is a summary table which represents the match between the BTO habitat classification and land cover categories that I used (Table 28).

The BTO classifies the occurrence of bird species in different habitats under three broad categories:

- “Most frequent habitats: scaled proportional occupancy >= 0.95
- Also common in habitats: scaled proportional occupancy >= 0.7
- And found in: scaled proportional occupancy >= 0.5

Thus, for each of the habitats listed a bird is at least half as likely to occur there as it is in the habitat in which it is commonest” (BTO, 2015d).

On the other hand, experts were asked to estimate the suitability of different land cover types as habitats for the selected species in a probabilistic way, on a scale of 1 to 100, where higher scores reflect higher probability of land cover categories to be the habitat for the selected species.

Table 28: Cross match between the BTO habitat categories and my land cover classification

Habitats based on expert estimations for the selected species	**Determined habitats for the selected species**	**BTO Habitat Classification**	
		Level 1	**Level 2**
Woodlands	Broadleaf	Woodland	Broadleaved, Mixed (10% of each), Broadleaved waterlogged, Mixed water-logged
Coniferous Woodland	Conifer	Woodland	Coniferous, Coniferous waterlogged
Shrub	Scrub	Woodland Scrubland Human Sites	Dense, Moderate, Sparse Shrub at level 4 (each habitat class at level 1)
Improved Grassland	Pasture Farmland	Farmland	Improved, Unimproved, Mixed Grass, Tilled land, Orchard, Other Farming
Unimproved Grassland	Pasture Farmland	Farmland	
Arable Land	Arable	Farmland	
Heathlands	Heathland / Moorland	Heathlands and Bog Scrubland Semi-natural Grassland	All types of heath categories at level 2, and also Bog Heath Scrub Grass moor mixed with heather
Buildings/Structures and Constructed Surfaces	Villages Towns	Human Sites	Urban, Suburban, Rural (Building, Gardens, Municipal parks / grass / golf courses / recreational areas, Sewage works ”urban” gardens, Near road (within 50m) gardens, Near active railway line (within 50m) gardens, Other, Rubbish tip at level 3)
Mixed Vegetation 1 (roadside and railway vegetation)	Villages Towns	Human Sites	
Mixed Vegetation 2 (private gardens and other landscaped areas)	Villages Towns	Human Sites	
Amenity Grassland	Villages Towns	Human Sites	
Wetlands	Marsh, Reedbed, Bog	Semi-natural Grassland / Marsh Heathlands and Bog	Reed swamp, Other open marsh, Saltmarsh / All types of Bogs at level 2
Standing Water	No information for the selected bird species	Water bodies	All types of freshwater bodies at level 3
Running Water	No information for the selected bird species	Water bodies	All types of freshwater bodies at level 3

Table 29 shows the occurrence of the selected bird species in different habitats which was derived from the BTO and habitats that I identified on the basis of expert opinions as input parameters of the least-cost corridors. As seen, the habitats in which the selected bird species occur most frequently match with the habitats that I identified on the basis of expert estimations.

Table 29: BTO habitat categories and habitats based on expert estimates for the selected birds and

	Song thrushes	**Skylarks**	**Blackbirds**	**Greenfinches**
BTO Habitats				
Most frequent in	Deciduous Wood	Moorland	Villages, Towns	Villages
Also common in	Scrub, Villages, Coniferous Wood	Arable Farmland, Bog	Scrub, Deciduous Wood, Arable and Pasture Farmland	Towns
And found in	Towns, Pasture Farmland	Grass / Heath, Marsh	Coniferous Wood	Arable and Pasture Farmland
Habitats Based on Expert Estimates				
	Woodland, Shrub, Mixed Vegetation 2 (Private Gardens and Other Landscaped Areas)	Unimproved Grassland, Heathland, Arable Land	Woodland, Coniferous Woodland, Shrub, Mixed Vegetation 1 (Roadside and Railway vegetation), Mixed Vegetation 2 (Private Gardens and Other Landscaped Areas)	Shrub, Mixed Vegetation 1 (Roadside and Railway vegetation), Mixed Vegetation 2 (Private Gardens and Other Landscaped Areas)

According to the BTO, the most frequent habitat type for Song thrushes, *Deciduous Wood*, corresponds to the *Woodland* land cover category in my classification system (BTO, 2015e). Additionally, the less common habitat types (*Towns, Scrub and Villages*) correspond to *Shrub, Mixed Vegetation 1* and *Mixed Vegetation 2* land cover categories. However, *Arable Farmland* and *Pasture Farmland* were not mentioned as suitable habitats according to the results of expert estimations. In spite of this, habitats which I identified on the basis of expert estimations are in agreement with the BTO habitat categories to a large extent as well as more general references, where *Woodlands, Hedgerows* and *Parks and Gardens* are reported as the main habitats for Song thrushes (Hornbuckle and Herringshaw, 1985; SRWT, 2014b; RSPB, 2014a).

The suitable habitat types for Skylarks are composed of *Moorland, Arable Farmland, Bog, Grass / Heath* and *Marsh* the BTO habitat categories (BTO, 2015f). These habitat categories largely match with *Heathland, Arable Land* and *Unimproved Grassland* land cover categories in my classification system. On the basis of expert estimates, only Bog habitat category was not taken into account as habitat for Skylarks in the least-cost modelling process. Apart from this, habitat categories which I identified according to expert estimates are broadly compatible with the BTO habitat categories.

With regard to Blackbirds, most of habitat categories based on expert estimates match with the BTO habitat categories, except from *Arable and Pasture Farmland* (BTO, 2015g).

Finally, the BTO habitat categories for Greenfinches are matched well with the habitats that I identified, except from *Arable and Pasture Farmland* and *Shrub* (BTO, 2015h). In spite of that habitats based on expert estimates are in agreement with more general references where the mentioned habitats include Woods and Hedges, Bushes, *Parks* and *Gardens* (Hornbuckle and Herringshaw, 1985; SRWT, 2014d; RSPB, 2014j).

To conclude, habitat categories which were identified on the basis of expert estimations match well with the BTO habitat categories for the selected bird species and confirm the validity of least-cost models.

6.4.12 Summary

The spatial arrangement and components of the potential connectivity routes for Song thrushes, Blackbirds and Greenfinches are very similar to each other and largely distributed across the research area, except for the areas in the Peak District National Park western and built-up areas of Sheffield. The difference in their spatial extent can be attributed to their habitat preferences, minimum habitat requirements and also the cost values assigned to the land cover types to represent how easily they traverse non-habitat patches. For example, amongst the potential connectivity routes for all selected species, the spatial extent of the connectivity corridors for Greenfinch is the smallest. The potential connectivity routes for Brown long-eared bats and Pipistrelle bats are mainly concentrated around the built-up areas of the Sheffield with very extensive spatial coverage. On the other hand, the potential connectivity routes for Common lizards and Slow-worms are evenly distributed in the study area, excluding the areas covered with *Wetlands* in the Peak District National Park and *Buildings and Structures*. The connectivity routes for Skylarks, Leisler's bats and Grass snakes are mainly located in dense clusters in the Peak District National Park, where the potential connectivity routes for Grass snakes have the largest spatial extent.

Part 2 Modelling the Networks of Green and Open Spaces for People

In Chapter 5, the potential connectivity routes for people were modelled on the basis of the structural connectivity of different land use types. In this chapter, I used a least-cost corridor modelling approach to develop alternative networks of green and open spaces for people.

This part of Chapter 6 aims to develop different ways of deriving a functionally connected network of green and open spaces for people in an urban environment, which would contribute to the movement of people across different land use types in urban areas. This aim is achieved by addressing the following research questions:

1. Can criteria be derived to identify the potential routes of connectivity?
2. What forms do the potential routes of connectivity constructed using these criteria take?

6.5 Methods

In order to model the potential connectivity routes for people, the areas within the boundaries of the Peak District National Park were excluded. The underlying reasons for the exclusion of the Peak District National Park are to focus on the urban part of Sheffield in order to obtain a functional network of green and open spaces, which contributes to the movement of people by walking, and to avoid bias consequent upon including the Peak District National Park in the modelling process, as it covers a large area (almost 30% of the whole of the study area).

To delineate different multifunctional networks of green and open spaces, I used the *least-cost corridor* modelling approach with different parameters. In an urban environment, people may utilise green and open spaces for recreational and practical purposes, such walking, exercising, or going to workplaces, shops, and schools (Moseley et al., 2013). Therefore, I modelled different connectivity routes which would support the movement of people by walking from their homes (*Residential Buildings*) to:

- *Publicly Accessible Green and Open Spaces,*
- *Industrial and Commercial Units,*
- *Public Buildings.*

When modelling different movement routes between these areas, I took into account the following criteria to identify green and open spaces for inclusion in the potential routes of connectivity:

- the physical / legal access to green and open spaces,
- the effects of gradient on the movement of people in combination with the physical / legal access.

Here, it is also important to note that even though some land use types are legally accessible they constitute barriers to movement of people since they are not physically accessible (such as rivers, lakes and buildings). On the other hand, even though some land use types are physically accessible, they are not legally accessible because of the private ownership (such as agricultural land). Therefore, as the first criteria for the identification of green and open spaces for inclusion in the potential routes of connectivity, the term of the “physical / legal” accessibility has been used.

In addition to this, all pedestrians are affected by the changes in the topography of the ground they are walking across and gradient constitutes a constraint for pedestrians. For some pedestrians, e.g. people with limited mobility, or families with children in pushchairs gradient is particularly crucial, and is therefore a significant factor in the modelling the way people might use green networks.

6.5.1 Preparation of Input Datasets for Least-cost Corridor Analysis

The following datasets were used for the preparation of the input data layers:

- The previously created land use map at level 3, which includes 49 land use categories,
- Sheffield City Council’s Accessible Green and Open Spaces layer, and
- Ordnance Survey Terrain 50 layer.

6.5.1.1 Study Area Preparation

The previously created land use map covers the whole of Sheffield. Hence, the first step was cutting out the areas included in the Peak District National Park to generate a land use map which includes only the urban part of Sheffield.

6.5.1.2 Land Use Map Manipulation

The potential components of the green and open spaces network were derived from the previously created land use map at level 3, which includes 49 land use classes. The land use categories which represent the existing green and open spaces were proposed as the potential components of the network:

- Allotments
- Cemeteries and Churchyards
- Parks and Gardens
- Provision for Children and Young People
- Amenity Green Spaces
- Natural and Semi-natural Greenspaces
- Outdoor Sport Facilities
- Roadside Vegetation
- Railway Vegetation
- Inland Water

As seen above, the potential components of the network include both private and public green and open spaces as well as water features. As my first criterion for inclusion of green and open spaces in the network was legal accessibility I attempted to identify the publicly accessible green and open spaces. Out of the potential network components "*Railway Vegetation*" and "*Allotments*" are not publicly accessible. In addition, some "Outdoor Sport Facilities" are not publicly accessible. In order to distinguish publicly accessible "*Outdoor Sport Facilities*", I split these spaces into four subclasses as follows:

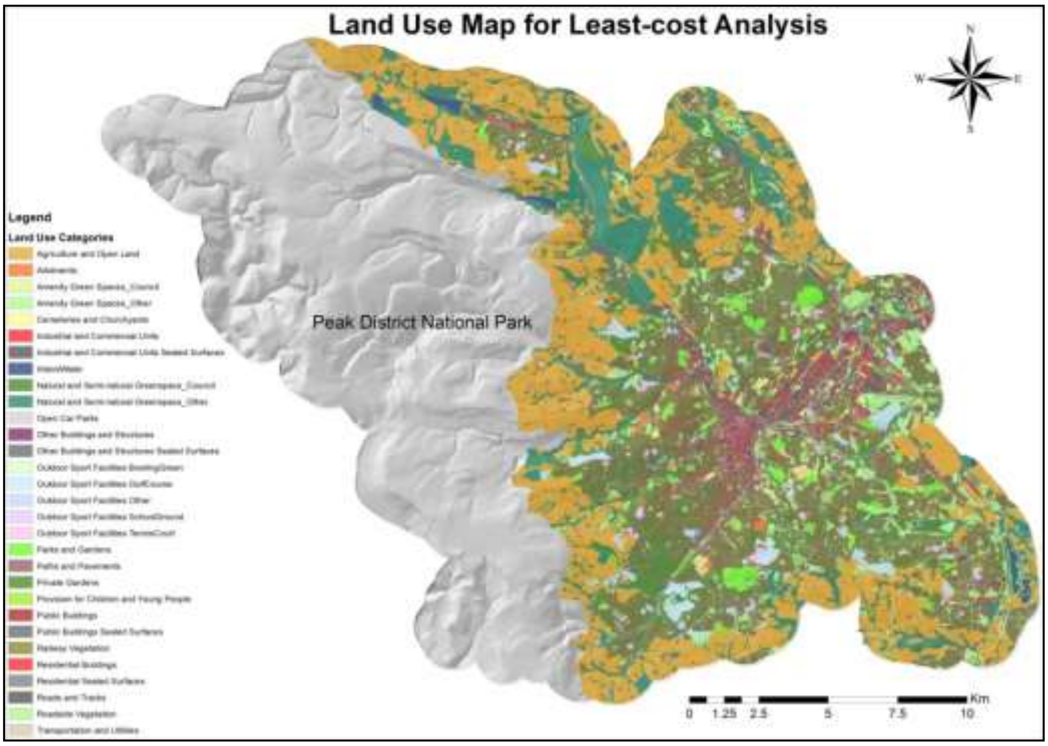
- *Outdoor Sport Facilities* - *School Grounds* -Not publicly accessible,
- *Outdoor Sport Facilities* - *Golf Courses* - Not publicly accessible,

- *Outdoor Sport Facilities - Bowling Green* - Not publicly accessible, and
- Publicly accessible *Outdoor Sport Facilities*.

Also, as mentioned earlier in Chapter 3 Part 2, some "*Amenity Greenspaces*" and "*Natural and Semi-natural Greenspaces*" in private ownership are not included in the Sheffield City Council (SCC) Accessible Green and Open Spaces layer. Therefore, I intersected these land use categories in my land use map with the Sheffield City Council green and open spaces layer. The "Amenity Greenspaces" and "Natural and Semi-natural Greenspaces" patches that coincide with SCC Accessible Green and Open Spaces Layer, are publicly accessible. However, the remaining patches of these can be either public or private accessible. Thus, "Amenity Greenspaces" and "Natural and Semi-natural Greenspaces" were split into four subclasses:

- Sheffield City Council *Amenity Greenspaces* (included in SCC Accessible Green and Open Spaces Layer),
- Other *Amenity Greenspaces* (additional patches which are not owned by SCC),
- Sheffield City Council *Natural and Semi-natural Greenspaces* (included in SCC Accessible Green and Open Spaces Layer),
- Other *Natural and Semi-natural Greenspaces* (additional patches which are not owned by SCC),

After identifying all publicly accessible green and open spaces, I aggregated the remaining land uses into more generalized categories according to their common characteristics to reduce unnecessary time consumption for the modelling process. For example, all of the institutional, educational, religious, leisure and recreational, medical, and community buildings and structures were aggregated under Public Buildings. The final land use map, excluding the Peak District National Park, composed of 30 land use categories, was used as the base dataset for the least-cost analysis (Map 28, and for details see Appendix 25).



Map 28: Final land use dataset for analysis

The final land use map represents those green and open spaces that are definitely accessible to the public. According to this map, *Publicly Accessible Green and Open Spaces* are composed of the following land use categories:

- Cemeteries and Churchyards
- Parks and Gardens
- Provision for Children and Young People
- Sheffield City Council Amenity Greenspaces,
- Sheffield City Council Natural and Semi-natural Greenspaces,
- Publicly Accessible Outdoor Sport Facilities, and
- Roadside Vegetation.

6.5.1.3 Preparation of Source, Cost and Cost Distance Layers

Source Layers

I aimed at modelling different connectivity routes for people, which can support the movement by walking from their homes (*Residential Buildings*) to (1) *Publicly Accessible Green and Open Spaces* (2) *Industrial and Commercial Units* and (3)

Public Buildings using the least-cost modelling approach. I extracted the following source layers from the final land use map for each of the least-cost analysis:

- "*Residential Buildings*" and "*Publicly Accessible Green and Open Spaces*",
- "*Residential Buildings*" and "*Industrial and Commercial Units",*
- "*Residential Buildings*" and "*Public Buildings*".

Cost Layers

The required cost layers were prepared on the basis of land use map. A cost layer is a single raster dataset, but it can be used to represent several variables influencing the cost of movement. I prepared two cost layers:

- first cost layer: the effect of each land use type in terms of their permeability to pedestrian movement, and
- second cost layer: the effect of each land use type in terms of their permeability to pedestrian movement in combination with the effects of gradient.

A. First cost layer: I set rules for the scoring of each land use type in terms of its permeability to pedestrian movement between different land use types. Here, low cost values correspond to high permeability (or low resistance) for movement. For example, a cost value of 1 indicates that the particular land use category allows unrestricted pedestrian movement (publicly accessible), 50 indicates land use categories which may be either publicly or privately accessible, and 100 indicates land use categories which are not publicly accessible, and / or may not allow the movement between places despite they are public accessibility. When creating rules for the scoring of each land use type, I therefore took into account public and *de facto* accessibility.

Rule 1. "*Paths and Pavements*" allow pedestrians to travel to other destinations and they are entirely accessible. Therefore, I assigned a cost value of 1 to "*Paths and Pavements"*

Rule 2. All "*Publicly Accessible Green and Open Spaces*" allow pedestrians to move through the landscape, and so they got a cost value of 1,

Rule 3. The "*Amenity Greenspaces*" and "*Natural and Semi-natural Greenspaces*" patches that are not included in the Sheffield City Council accessible green and open spaces layer, may be either publicly or privately accessible. So, I gave them a cost value of 50.

Rule 4. Apart from these, "Outdoor car parks", "*Residential and Public Sealed Surfaces*" are similar to "*Publicly Accessible Green and Open Spaces*" and allow the movement in and between places. Therefore, I assigned a cost value of 1 to these land use categories.

Rule 5. All the remaining land use categories are not publicly accessible, or do not allow pedestrian movement, or are composed of buildings and structures. Therefore, they got a cost value of 100.

The first cost layer was used to delineate least-cost corridors for people with high mobility – i.e. for whom the gradient is not a constraint (Figure 26).

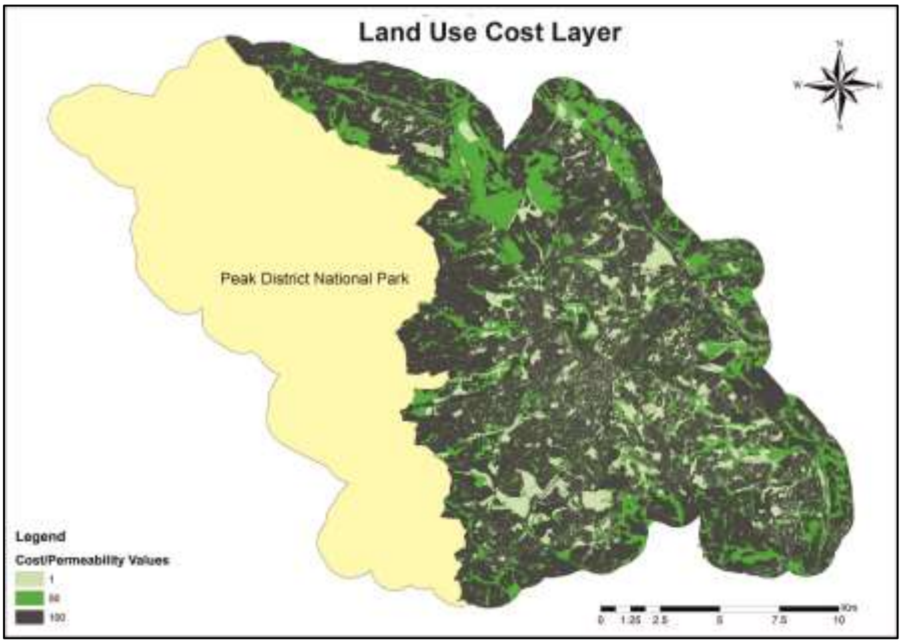


Figure 26: Land use cost layer

B. Second cost layer: For the second cost layer, in I added a slope cost layer to the land use cost layer and combined these two variables into one cost layer. Firstly, I created a slope map, using Ordnance Survey Terrain 50m dataset (Figure 27a) which is composed of contour lines and spot heights. Initially, I created a Digital Elevation

Model (DEM) with a resolution of 2m using the *3D Analyst, Raster Interpolation, Topo to Raster* tool in ArcGIS 10 (Figure 27b).

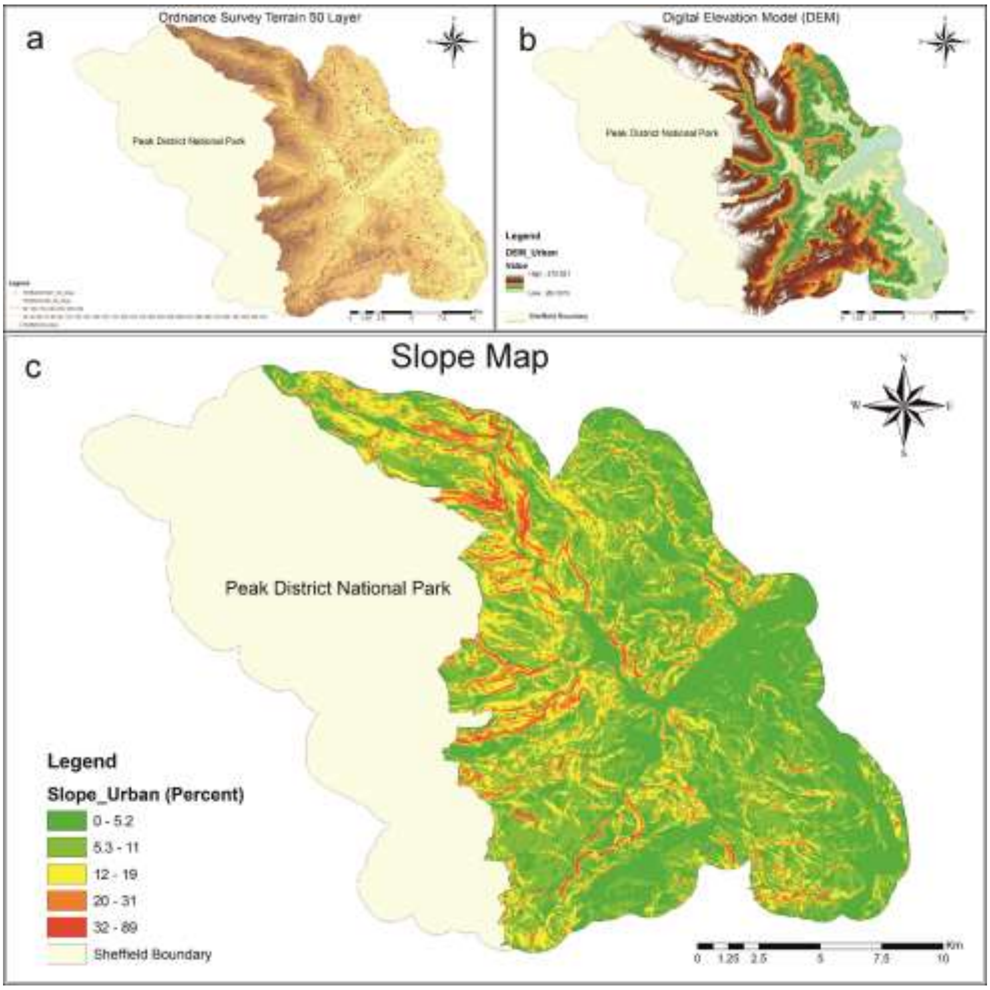


Figure 27: Ordnance Survey terrain 50 layer (a), DEM (b) and slope map in percent rise (c)

I created the slope map using the *Spatial Analyst, Surface, Slope* tool. In order to analyse the slope in the study area, I changed its symbology. I selected 4 classes and *Natural Breaks (Jenks)* as the classification method. *Natural Breaks* uses natural groupings inherent in the data to define the classes (Figure 27c). Then the slope map was reclassified into a range of values that would be tolerated by pedestrians when they are walking. Slopes ranged from 0-89.2% but most of the land lies within the range 0-18.9% and most of the publicly accessible green and open spaces are found within the slope gradients of 0-31.5%.

I manipulated the first three slope classes according to the slope standards for the benefit of people with limited mobility. The accepted standards were extracted from the "Inclusive Mobility" document published by the Department for Transport in

2005. This report constitutes the guidelines for pedestrians and transport infrastructure with the aim of achieving a good standard of inclusive design for people, including those with limited mobility. According to this document, the maximum slope for wheelchair users should be 1 in 12 (8.33%). Based on this document, the slope map was reclassified into four classes to generate the slope cost layer (Figure 22a):

- 0 -8.33%- can be managed by the most people including those with limited mobility. Therefore, I assigned a cost value of 1,
- 8.34-18.90 %- can be managed by many people. So, I gave this class a cost value of 25,
- 19.00-31.50% - can be managed by some people with some difficulty and so this class got a cost value of 50,
- 31.51-89.20% - cannot be managed by the most of people. Therefore, this gradient class got a cost value of 100.

C. Combining the cost layers into a single cost layer: This is an essential stage when there is more than one environmental variable to be included in the least-cost analysis. Each generated raster cost layer is weighted according to their influence.

In the present study, public access to green and open spaces is our primary concern. Therefore, the land use cost layer was given a higher weight (66%) compared with slope (34%). Using the *Spatial Analyst, Overlay* and *Weighted Overlay* tools in ArcGIS 10, I overlaid the land use and slope cost layers to generate the final cost layer with a resolution of 2 m (Figure 28c).

The weighted overlay cost layer represents the ease of movement for people through the landscape. The areas with lighter colours indicate that the movement of people is easiest in terms of public accessibility and slope, whereas darker colours mean that the pedestrian movement is hardest within these areas due to lack of public accessibility and the effects of steep slopes. This weighted overlay cost layer was used particularly for the delineation of movement routes for people with limited mobility.

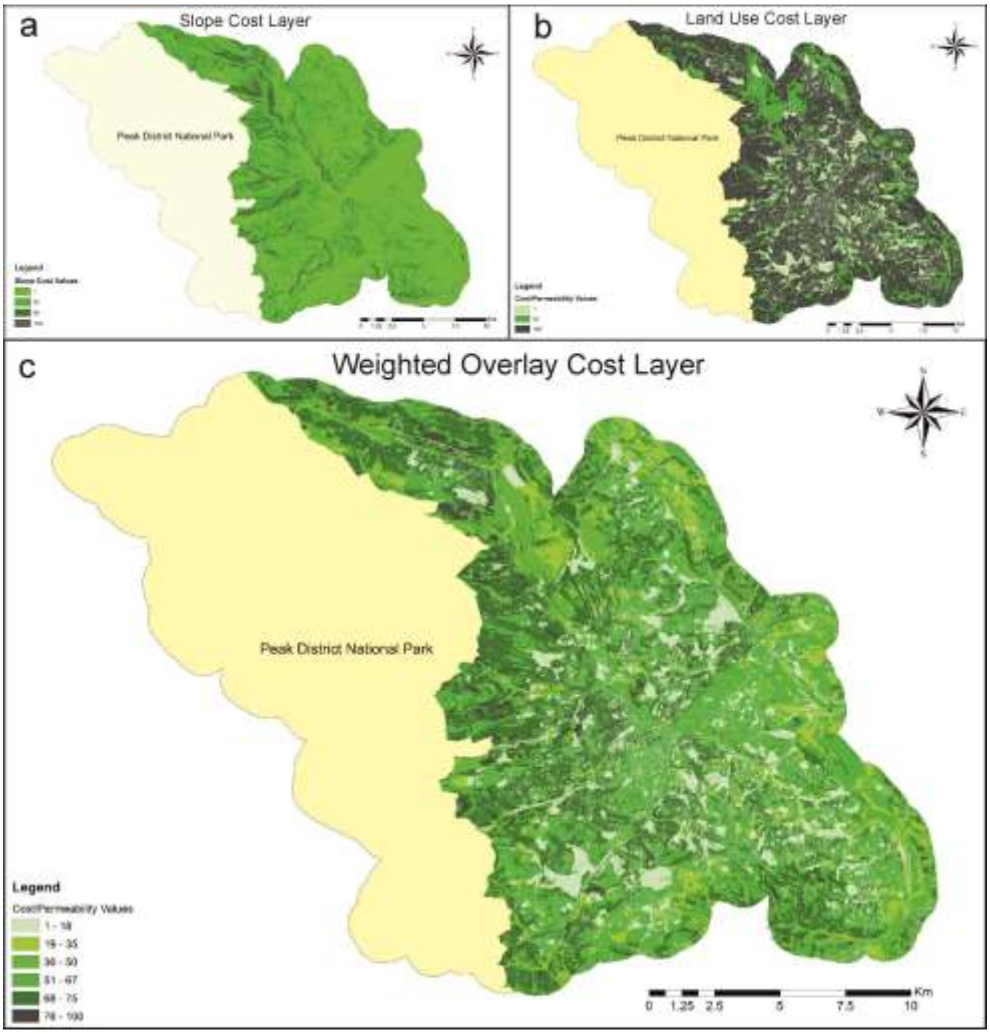


Figure 28: Slope cost layer (a), land use cost layer (b) and weighted overlay cost layer (c)

Cost Distance Layers

Prior to modelling the least-cost corridors I generated two cost distance layers for each least-cost corridor analysis using the *Spatial Analyst, Distance, and Cost Distance* tools in ArcGIS 10.1. The two analyses represent two different types of movement that people might wish to make. The first is movement between residential areas and green and open spaces (e.g. from home to a recreational area), the second is between residential areas and industrial, commercial and public building (e.g. from home to work).

In order to model the networks from residential buildings to publicly accessible green and open spaces, I used the following parameters:

- *Residential Buildings* (source layer 1) and *Publicly Accessible Green and Open Spaces* (source layer 2),
- The land use cost layer representing the permeability of each land use type to pedestrian movement,
- For the second pair of cost distance layers I used the same source layers plus the weighted overlay cost layer in which the effects of land use permeability and slope were taken into account to support pedestrian movement.

In order to model networks between *Residential Buildings* and *Industrial / Commercial Units*, and between *Residential Buildings* and *Public Buildings* I used the first and second cost layers with the following source layers to create a pair of cost distance layers for each analysis:

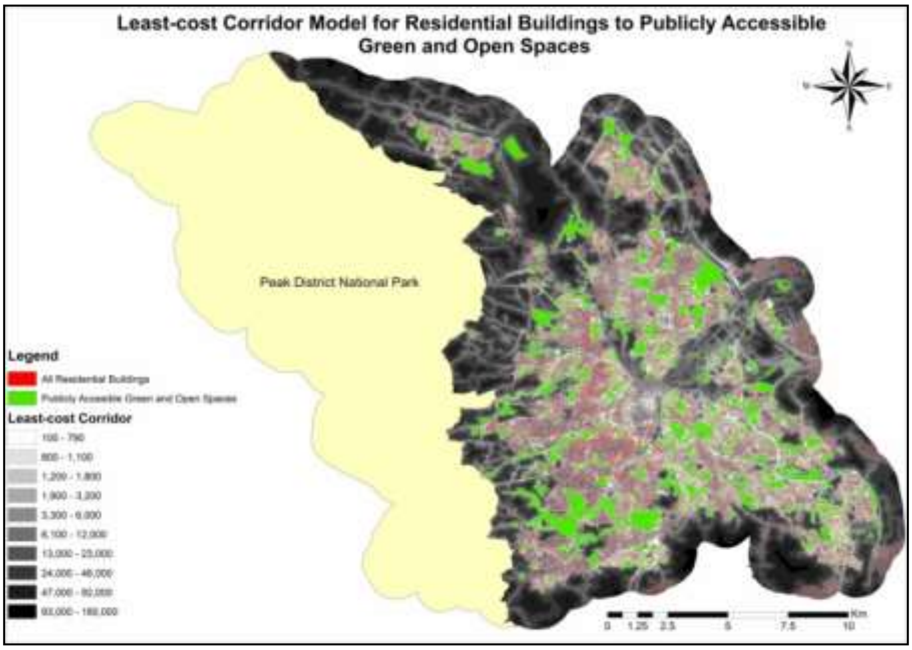
- *Residential Buildings* (source layer 1) and *Industrial / Commercial Units* (source layer 2),
- *Residential Buildings* (source layer 1) and *Public Buildings* (source layer 2).

The source, cost and cost distance input layers can be seen in Appendices 26A, 27A, 28B, 29B, 30B and 31B.

6.6 Results of the Least-cost Corridor Analysis

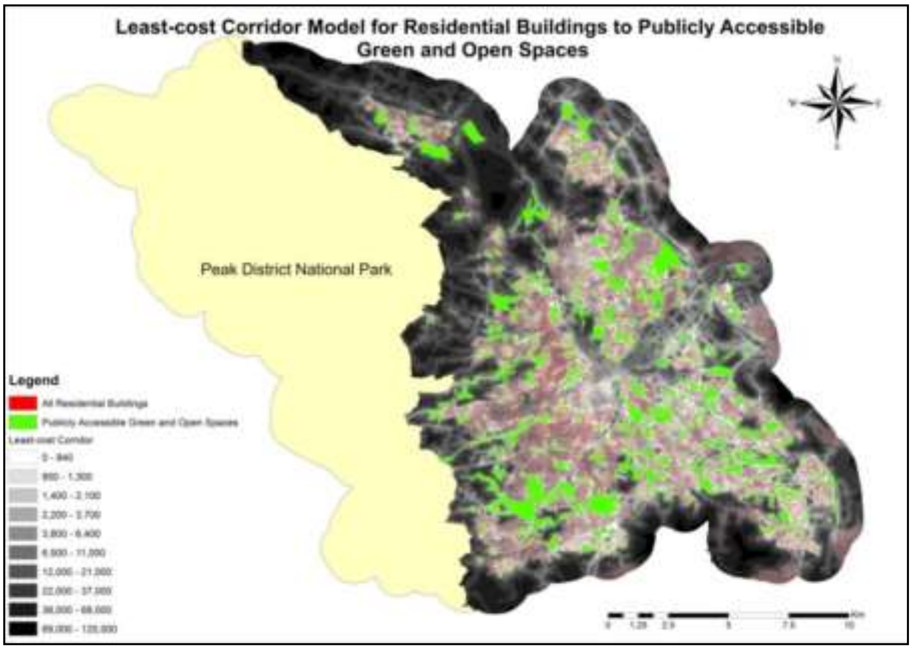
6.6.1 Networks from Residential Buildings to Publicly Accessible Green and Open Spaces

The first least-cost corridor aims at providing networks for the movement of people from *Residential Buildings* to *Publicly Accessible Green and Open Spaces*, and from *Publicly Accessible Green and Open Spaces* to *Residential Buildings* (Map 29, see Appendix 26B for details). The areas in white represent the most suitable areas for inclusion in the potential green and open space network, whereas the areas in black are not suitable for inclusion in the network.



Map 29: First least-cost model for the network between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*

As stated earlier slope is an important constraint to movement, particularly for people with limited mobility. Therefore, taking into consideration both public accessibility and slope, I modelled the second least-cost corridor in which both public accesibility and the effects of slope on movement were taken into account (Map 30, see Appendix 27B for details).



Map 30: Second least-cost model for the network between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*

In order to obtain the optimum corridor width and representation, I used the same approach as I did for species in Part 1 using thresholds to obtain binary maps of 0.52%, 2.20% and 7.90% respectively. Initially, I plotted the least-cost corridor in which only public accessibility is taken into account (Figure 29). When I used the threshold of 0.52%, I obtained a network with some connectivity in the city centre and the south east parts of the study area. However, the connectivity of the corridor is quite weak in the western and northern parts, where there are large patches of green and open space that people need to access. Additionally, even though the Publicly Accessible Green and Open Spaces are sometimes connected there are almost no connections between Residential Buildings and these spaces. Therefore, from the perspective of landscape planning, this threshold does not meet the requirements of public accessibility.

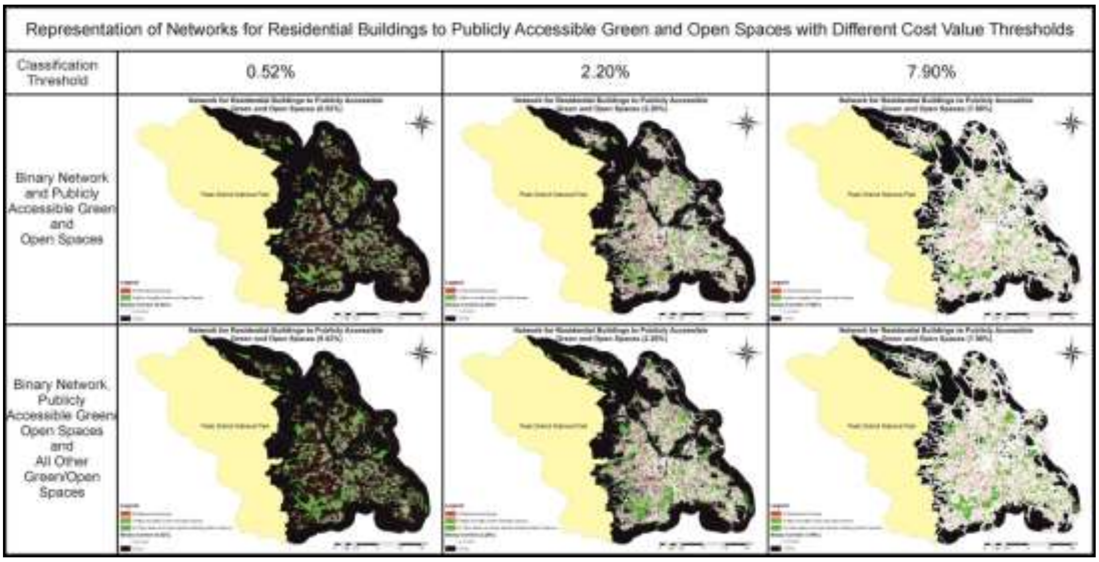


Figure 29: First least-cost corridor with different thresholds

With the threshold of 2.20%, the obtained corridor provides a much better level of public accessibility between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*. In general, most of the network is well connected apart from the areas surrounding the River Don, which are mainly used for industrial purposes. When we use this threshold, we can clearly see that the *Paths and Pavements* make an important contribution to the accessibility of the network. Additionally, *Paths and Pavements* are adjacent to *Roadside Vegetation*, which may provide shelter, shade and visual amenity to pedestrians. I obtained the most connected network, which covers most of the research area, when I plotted the first corridor with the threshold of 7.90%. However, this network does not offer a realistic network for pedestrian movement, as it also covers inaccessible areas, such as *Private Gardens*, *Buildings and Structures* and *Roads.* Likewise, even though the threshold of 2.20% shows the most convenient width and representation of this least-cost corridor, when examined in detail it also includes some inaccessible land uses, such as *Private Gardens*, *Buildings and Structures* and *Roads.* Therefore, I excluded all of the publicly inaccessible land uses from the binary map with this threshold to optimise the network between *Residential Buildings* and *Publicly Accessible Green and Open Spaces* (see Appendices 26C and 26D).

The second least-cost corridor was plotted with thresholds of 0.88%, 3.50% and 11.0% (Figure 30). Because the areas with the steepest slopes increase the difficulty of movement (with increasing cost to movement), the threshold values for each binary map are higher than the first least-cost corridor. However, the resulting binary corridor maps represent a very similar spatial pattern, except in areas of steeper slopes. As with to the first least-cost corridor, the *Paths and Pavements* constitute the backbone of the network. When I examined each threshold for the second least-cost corridor, 3.50% provides the most suitable width and representation. However, the network with this threhold also includes some publicly inaccessible land uses. Hence, this network was optimised by excluding these areas, as in the case of the first least-cost corridor (see Appendices 27C and 27D).

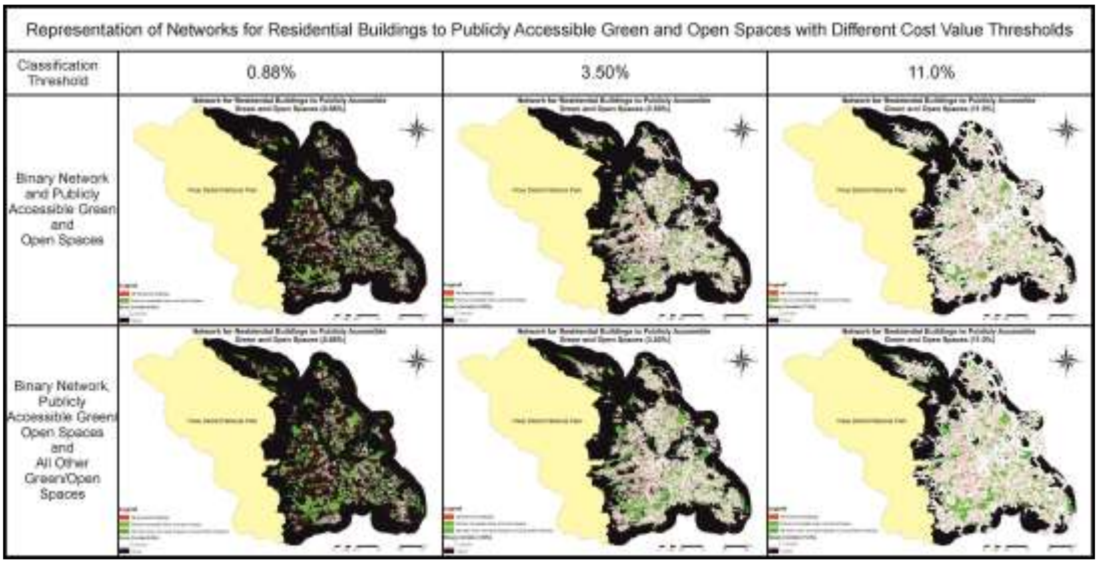
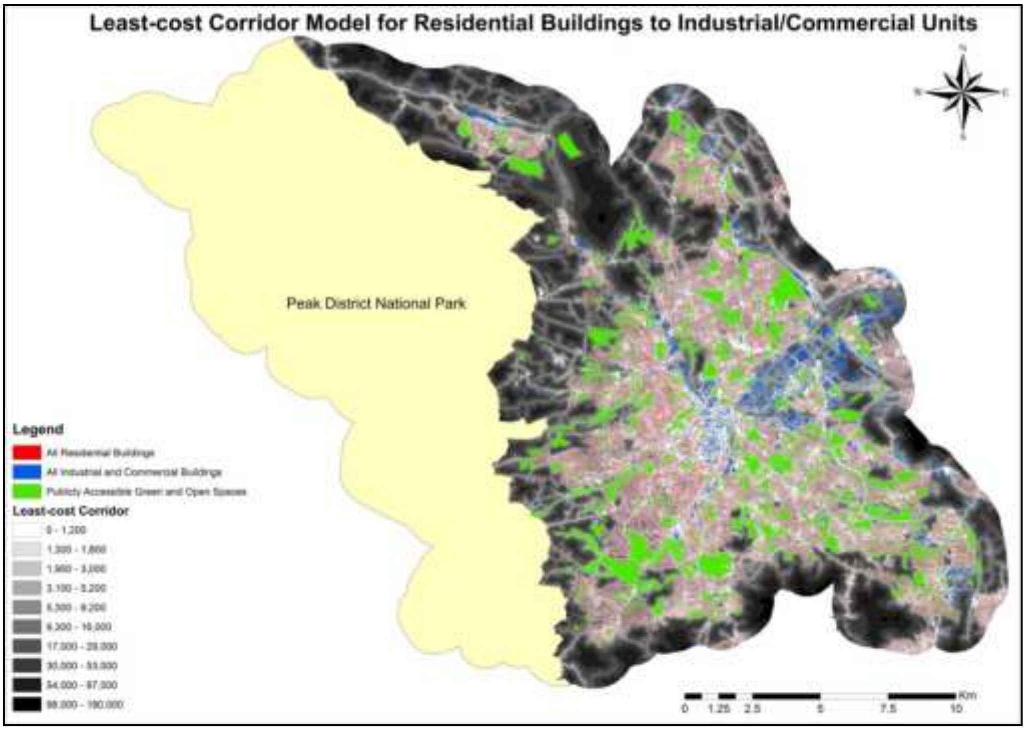


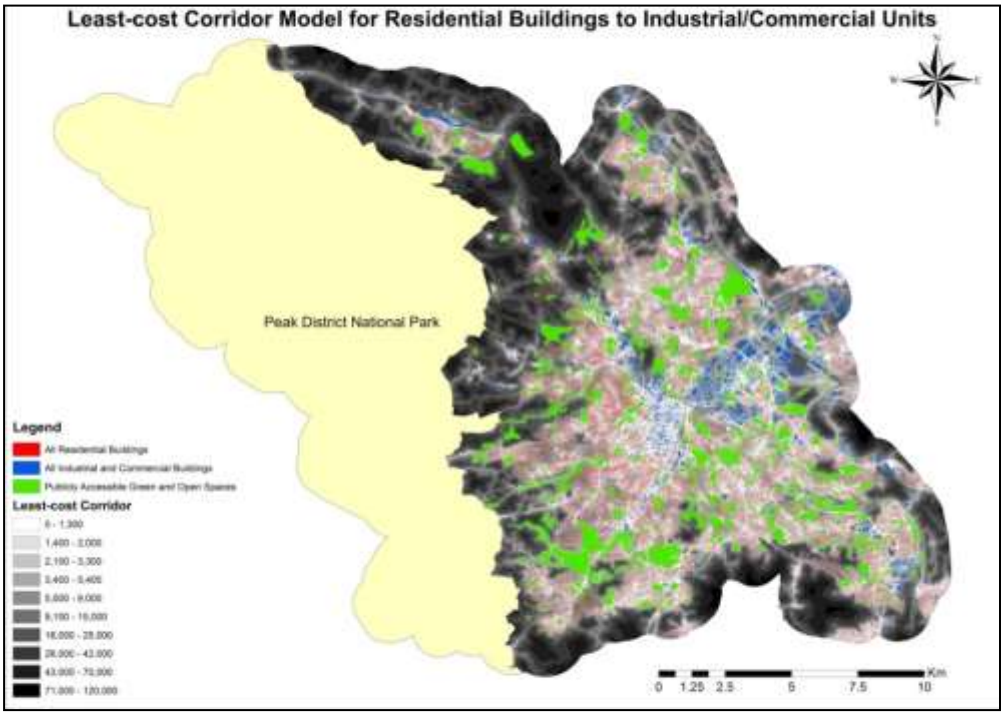
Figure 30: Second least-cost corridor with different thresholds

6.6.2 Networks from Residential Buildings to Industrial and Commercial Units

Networks between *Residential Buildings* and *Industrial and Commercial Units* were developed in the same way outlined with respect to the previous analysis. Map 31 and 32 represent the first and second least-cost corridors, respectively. Afterwards, I plotted both of these networks with different thresholds using the geometric interval classification method with 5 classes. Based on the first three thresholds, the resulting binary maps of the first and second least cost corridors are shown in Figure 31 and 32, respectively (see Appendices 28B and 29B for details)



Map 31: First least-cost model for the network between *Residential Buildings* and *Industrial / Commercial Units*



Map 32: First least-cost model for the network between *Residential Buildings* and *Industrial / Commercial Units*

The first least-cost corridor was plotted with thresholds of 1.20%, 1.30% and 2.50%. The first two thresholds resulted in almost the same corridors (Figure 28).

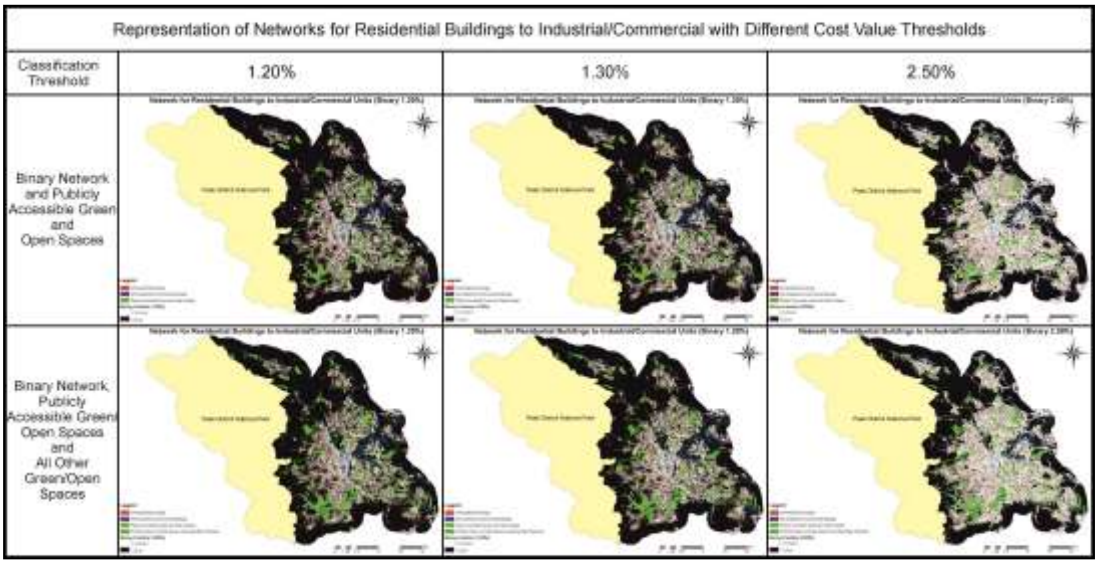


Figure 31: First least-cost corridor with different thresholds

With the threshold of 1.30%, the network between *Residential Buildings* and *Industrial and Commercial Units* is slightly better connected compare to the first threshold. Most commercial units are located in the city centre, and well-connected by *Paths and Pavements*. However, some of the publicly inaccessible land uses are included in the network with this threshold. With the threshold of 2.50%, the resulting network includes inaccessible land uses with an extensive coverage in the research area. Because of this, the optimum spatial arrangement and extent for the network between *Residential Buildings* and *Industrial and Commercial Units* was obtained by removing the publicly inaccessible land uses from the network with the threshold of 1.30% (see Appendices 28C and 28D).

Regarding the second least-cost corridor, I used thresholds of 1.20%, 4.50% and 13.0% (Figure 32). The potential corridor with the threshold of 1.20% resulted in a less connected network. On the other hand, the threshold of 13.0% resulted in the highest connectivity with the largest spatial extent. Hence, from the planning point of view, this threshold does not reflect a realistic network, as it covers almost all the study area and most publicly inaccessible areas are included as part of the network. The threshold of 4.50% provided a well-connected network in which *Pavements and Paths* play an important role in linking *Residential Buildings* and *Industrial and Commercial Units*. This threshold seems to provide the optimum corridor width compared with the other two thresholds. However, the network was further improved by determining its publicly inaccessible components and excluding these areas (see Appendices 29C and 29D).

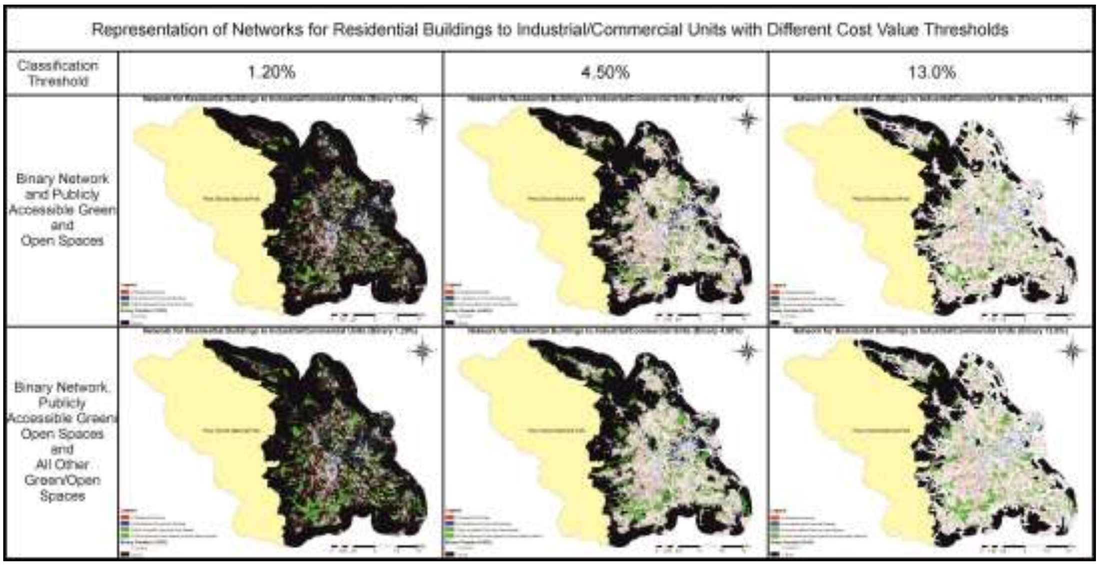
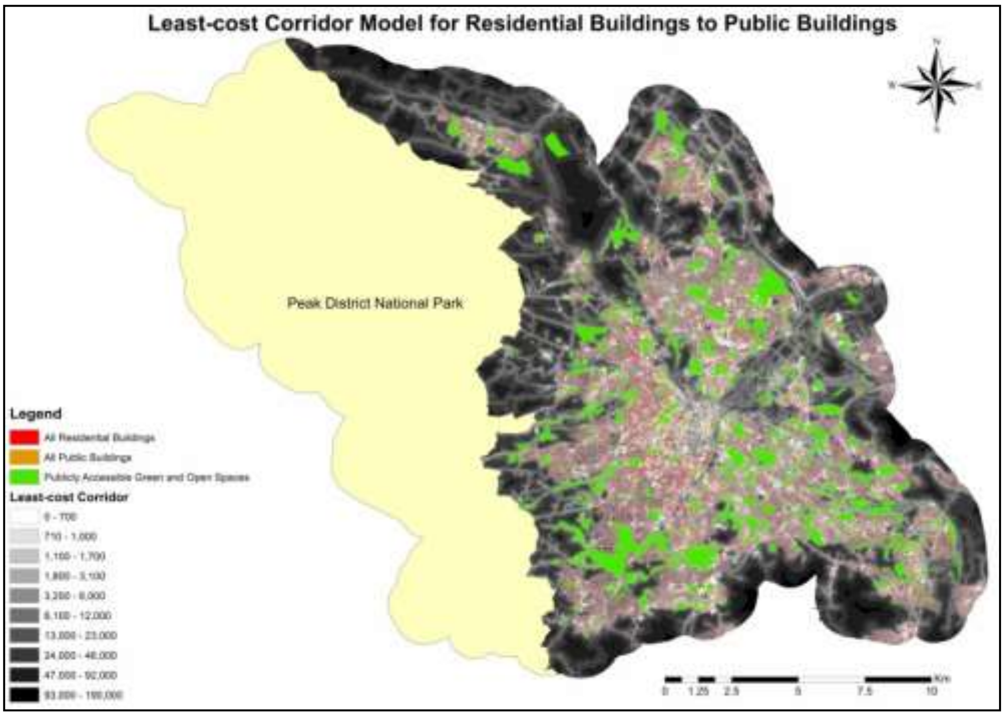


Figure 32: Second least-cost corridor with different thresholds

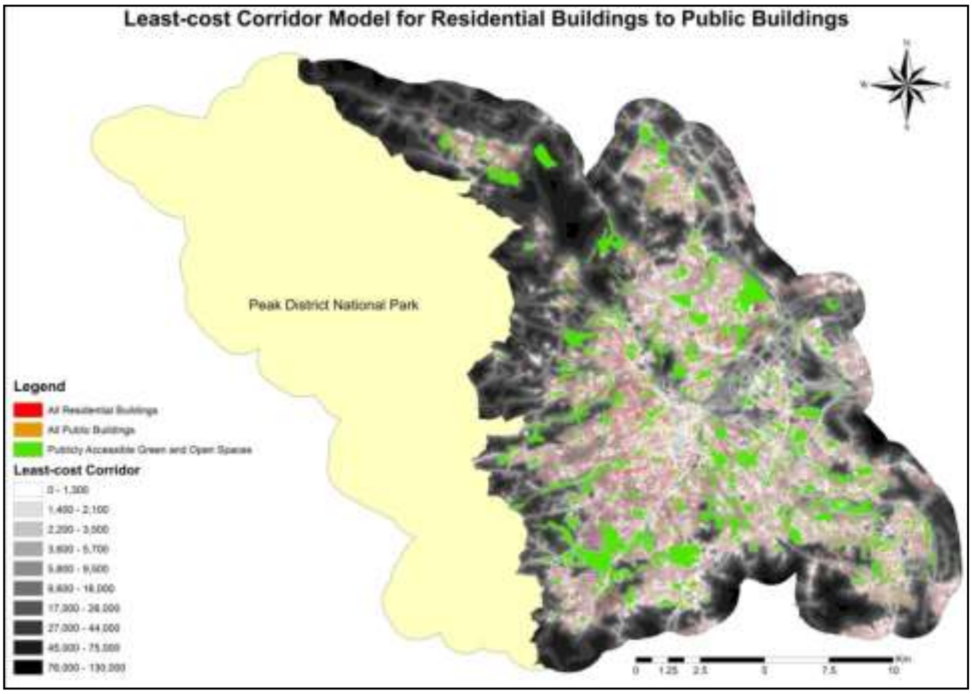
6.6.3 Networks from Residential to Public Buildings

I applied the same methods for the delineation of networks between *Residential Buildings* and *Public Buildings.* Map 33 represent the least-cost corridor model networks between *Residential Buildings* and *Public Buildings* based on physical / legal accessibility.



Map 33: First least-cost model for the network between *Residential Buildings* and *Public Buildings*

The least-cost corridor between *Residential Buildings* and *Public Buildings* incorporates the effects of slope into physical / legal accessibility. Map 34 represents the binary map for the network between *Residential Buildings* and *Public Buildings* (see Appendices 30B and 31B for details).



Map 34: First least-cost model for the network between *Residential Buildings* and *Public Buildings*

After obtaining the least-cost corridors, I attempted to determine the most suitable thresholds for the width and representation of the networks. For the first least-cost corridor, I used thresholds of 0.40%, 1.90% and 7.20% (Figure 33).

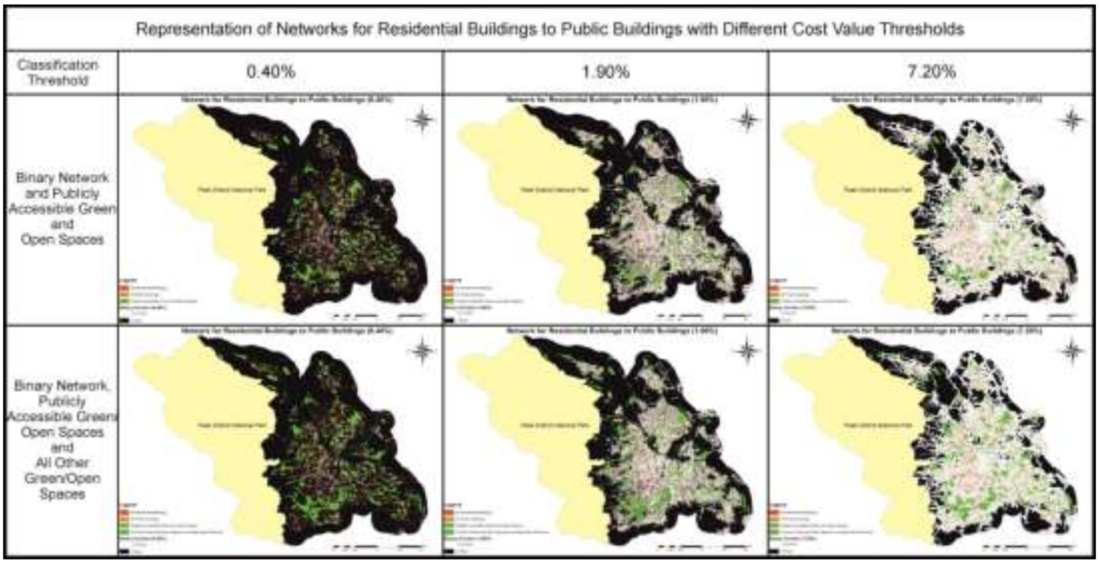


Figure 33: First least-cost corridor with different thresholds

With the threshold of 0.40%, even though *Residential Buildings* and *Public Buildings* with a close proximity to each other are connected, there are a number of significant gaps in the resulting corridor. Additionally, despite some *Publicly Green and Open Spaces* being included in the delineated network, they do not make an important contribution to the network. The threshold of 7.20% did not result in a sufficient network for pedestrians as it includes publicly inaccessible areas, such as roads and private gardens. Moreover, the most obvious problem related to this network is its extensive coverage in the research area. With the threshold of 1.90%, the potential corridor is both well-connected and the land use type of *Paths and Pavements* plays a vital role in linking the desired destinations, as with the previous networks for other destinations. However, some of the publicly inaccessible land uses are still contained in the model. Therefore, all of these areas are excluded from the network with this threshold to achieve a realistic representation (see Appendices 30C and 30D).

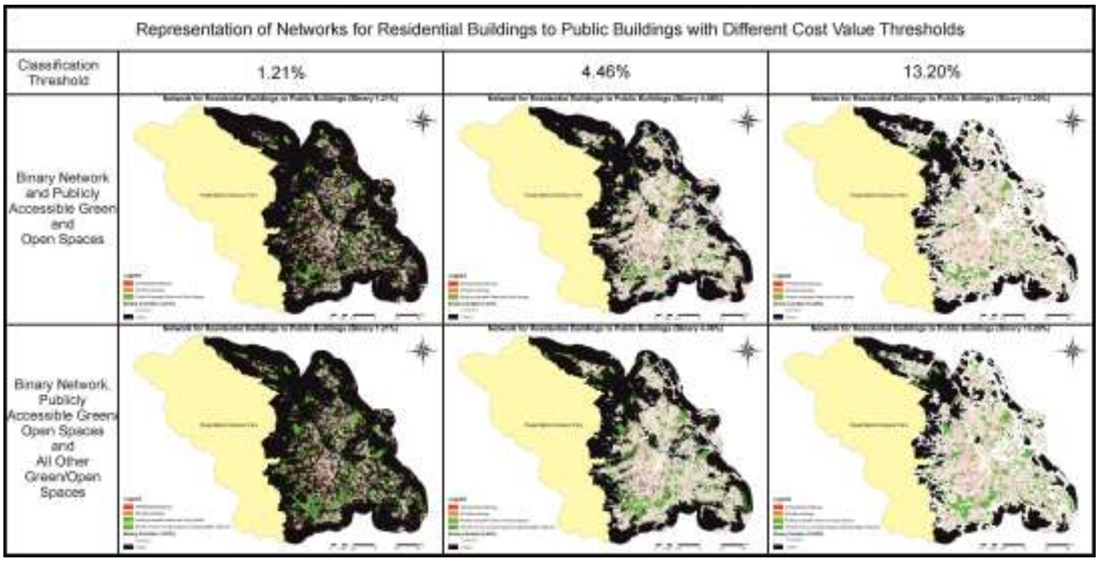


Figure 34: Second least-cost corridor with different thresholds

The thresholds applied to the second least-cost corridor are 1.21%, 4.46% and 13.20% (Figure 34). With the threshold of 1.21%, I obtained a potential network which is mainly concentrated around the city centre. While *Paths and Pavements* constitute the main parts of the network, there are some areas with weak connections between the desired areas. When I plotted the least-cost corridor with the highest threshold value (13.20%), it covers an extensive area including too many publicly inaccessible land uses. In this context, this threshold cannot be a suitable option for planning applications. On the other hand, when the least-cost corridor was plotted with the threshold of 4.46%, the potential network extends over the research area with a well-connected spatial pattern. However, again some of the publicly inaccessible areas are included in the network with this threshold. Therefore, all of the inaccessible land uses are excluded from the network with this threshold similar to the first network (see Appendices 31C and 31D).

In general, all the functional connectivity models for public access are located around built-up areas, surrounding *Residential Buildings*, and in particular *Dwellings*. According to these models, whilst the availability of *Publicly Accessible Green and Open Spaces* support and enhance public accessibility, *Paths and Pavements* and *Roadside Vegetation* also play an important role in linking green and open spaces as the main routes of pedestrian movement.

On the other hand, the distribution of the different types of *Publicly Accessible Green and Open Spaces* is also related to levels of urbanisation throughout the study area. When these models are examined in detail with regard to the quantity of different *Publicly Accessible Green and Open Spaces* types, it was found that rural areas are richer in *Natural and Semi-natural Greenspaces* compared to densely built-up areas. For example, whilst *Natural and Semi-natural Greenspaces* occupy the 34.80% of the total amount of existing *Publicly Accessible Green and Open Spaces,* they constitute the key components of the functionally connected networks of green and open spaces in the urban periphery. Additionally, whilst *Paths* provide the public access throughout *Natural and Semi-natural Greenspaces*, they also allow the public to pass through to other destinations, such as their homes or workplaces. However, as emphasised in Chapter 5, the availability of green and open spaces within a walking distance may be more beneficial for people to support their physical and mental health as well as their well-being (Takano et al., 2002; Groenewegen et al., 2006). Moreover, *Natural and Semi-natural Greenspaces* may not provide a high-standard of facilities compared to the urban parts of the study area, such as the availability of suitable lighting or paths.

On the other hand, *Parks and Gardens* and publicly accessible *Outdoor Sport Facilities* occupy 23.03% and 12.97% of the whole of *Publicly Accessible Green and Open Spaces*, respectively. *Parks and Gardens* and publicly accessible *Outdoor Sport Facilities* are distributed across Sheffield, in particular, around dense urban settings. Hence, similar to *Natural and Semi-natural Greenspaces*, *Paths* provide the public access throughout these green and open spaces as well as passing through other destinations. *Amenity Green Spaces, Cemeteries and Churchyards,* and *Provision for Children and Young People* cover only 11.57% of *Publicly Accessible Green and Open Spaces,* with a scattered distribution in the built-up areas.

Occupying 17.62% of *Publicly Accessible Green and Open Spaces*, *Roadside Vegetation* patches are generally distributed alongside *Pavements* and *Roads*. Therefore, it is clear that *Paths and Pavements* lined with *Roadside Vegetation* enhance the public access to green and open spaces. However, it is also important to note that the availability of *Roadside Vegetation* around the inner parts of the study area is not as much as the outer parts of the built-up areas. Hence, even though there are lots of *Paths and Pavements* in dense urban settings, these areas suffer from the lack of sufficiently vegetated roadsides, which is particularly important in providing a sheltered and attractive walking experience for pedestrians. Consequently, based on these models, we can claim that the availability of areas with different types of *Publicly Accessible Green and Open Spaces* as well as *Paths and Pavements* and *Roadside Vegetation* enhance public accessibility to green and open spaces.

The areas of apparent deficiency in access to *Publicly Accessible Green and Open Spaces* are mainly located in areas where the functional connectivity networks expand through the outskirts of Sheffield as well as in the lower parts of the River Don. Whilst these areas in the least-cost corridor models are highlighted in most need of improvement for public access to *Publicly Accessible Green and Open Spaces*, some of these are the inevitable consequence of the lack of information on their actual accessibility (e.g. *Natural and Semi-natural Greenspaces*). Despite all of these, the least-cost corridor models do provide us with the following information.

The functional connectivity routes for people seem to be very poor in the lower parts of the River Don. Both sides of the lower River Don are mainly covered by *Industrial Buildings* and *Sealed Surfaces*, where the main access routes for pedestrian movement to the surrounding green and open spaces is largely provided by *Paths and Pavements*. In addition, the existing *Amenity Greenspaces* support cross-links between the River Don and the Sheffield and Tinsley Canal. Despite the availability of *Paths and Pavements* and a few *Amenity Greenspaces*, there is an obvious lack of vegetation cover in these areas. Also, it is clear that the existence of *Industrial Buildings* and surrounding *Sealed Surfaces* detract from providing functional connections for people in the lower sections of the River Don. Whilst these areas create less favourable conditions than the areas where people have opportunities to access different types of green and open spaces, it is also important to take into account their proximity to the city centre as well as their high potential to provide recreational activities and amenities to people.

Another example of areas deficient in accessibility to green and open spaces are areas located around the outskirts of Sheffield, where there are only few *Residential Buildings* surrounded by *Paths and Pavements*. The most important factor of public access deficiency is dependent on the lack of *Publicly Accessible Green and Open Spaces*. For example, there are large *Natural and Semi-natural Greenspaces* in the areas between Oughtibridge and Stocksbridge (e.g. Wharncliffe Woods). Because of the lack of information on their actual public accessibility, these areas were assigned a relatively high cost value in the least-cost modelling process, as a constraining factor to pedestrian movement. Also, another reason for this area to be one of the least favourable areas in terms of public access to green and open spaces was the absence of *Paths and Pavements* and the other types of *Publicly Accessible Green and Open Spaces*. Additionally, its distance from residential areas was another reason to be one of the least favourable areas.

A comparison of the most and least favourable areas of public accessibility reveals that the existence of *Publicly Accessible Green and Open Spaces*, *Paths and Pavements*, and *Roadside Vegetation* as well as the proximity of these land uses to residential areas are important to enhance public access to green and open spaces.

The purpose of using the least-cost corridor modelling approach was to develop different ways of deriving a functionally connected network of green and open spaces for people in an urban environment. Therefore, whilst these models can be used to highlight the areas of apparent deficiency in public access, they can also be used to develop targeted interventions with the aim of increasing public access to green and open spaces.

For example, the detrimental effects of *Industrial Buildings* and the surrounding *Sealed Surfaces* to the public accessibility cannot be ruled out. However, there are different ways of increasing public access to green and open spaces in these areas as well as making them more user friendly and attractive. One option is to create new areas of green and open spaces as well as improving the quality of existing ones (e.g. sufficient lighting and safety). However, it is known that there is a high demand for different land use options and it may not be feasible to allocate more land for the *Publicly Accessible Green and Open Spaces*. A reasonable approach to tackle the lack of public access in these areas could be to improve the existing *Paths and Pavements*. A key planning priority should therefore be to plan for the long-term care of *Paths and Pavements* and also *Roadside Vegetation*. Moreover, the vegetation cover of this area can be further enhanced by creating green roofs and green walls on and around *Industrial Buildings*.

6.6.4 Summary

In terms of people, a pair of connectivity routes have been modelled for 3 main destinations. Basically, all the modelled connectivity routes for the movement of people are evenly distributed across the study area. The main spatial components of the potential connectivity routes are mainly composed of *Publicly Accessible Green and Open Spaces, Paths and Pavements, Outdoor Car Parks,* and *Residential and Public Sealed Surfaces*.

Even though, the resulting connectivity routes for people have similarities in their spatial extent and components; they also represent differences in their spatial patterns and coverage, depending on which destinations we intended to connect, and the parameters that we set as the constraints to pedestrian movement (physical / legal accessibility and slope). For example, when I incorporated the effects of slope into physical / legal accessibility, the spatial pattern (and consequently the coverage) of the potential connectivity routes for the same destinations (e.g. from *Residential Buildings* to *Publicly Accessible Green and Open Spaces*) differ from each other, particularly in the western parts of the study area.

6.7 Conclusions

The main research objective dealt with in this chapter is to derive functionally connected networks for biodiversity and people using the actual land cover and land use data. This chapter was divided into two parts, the first explored the potential connectivity routes for a group of selected species, and the second investigated the areas of potential accessibility routes for pedestrians. Both parts provide a prototype modelling approach with regard to connectivity routes in the study area using the least-cost modelling approach.

In order to model the ecological connectivity routes, I selected 10 local species and sought expert opinion to obtain information on the ecology and movement behaviours of selected species. The experts were asked to estimate the suitability of different land cover types as habitats and the relative difficulty for the species to move across habitat and non-habitat patches. As the main parameters of the least-cost models, this information constitutes the selection criteria for different land cover types to be included in the potential connectivity routes. Each species was selected with the aim of highlighting the differences in the spatial configuration of connectivity routes. In accordance with this aim, the connectivity routes for species with different ecological requirements and movement behaviours resulted in connectivity routes with different spatial structures and extents.

The spatial extent of ecological connectivity routes for bird species ranges from 32% to 47% coverage of the whole study area. In general, the ecological connectivity routes for Song thrushes and Blackbirds have a very similar spatial pattern and are mainly distributed throughout the study area, apart from the areas of *Heathlands* and *Wetlands* in the Peak District National Park and where the river corridors confluence in the city centre. On the other hand, the ecological connectivity routes for Song thrushes and Blackbirds cover 35.48% and 47.30% of the whole study area, respectively. The ecological connectivity routes for Blackbirds, particularly gets larger towards to the city centre and the Peak District National Park, where the land is dominated by *Roadside Vegetation, Railway Vegetation* and *Coniferous Woodland*. The difference in their spatial extent is dependent on the minimum habitat requirements of Song thrushes and Blackbirds, and the differences in the cost values assigned to the different types of land cover as an indication of the difficulty of their movement through those land covers. To some extent, the ecological connectivity routes for Greenfinches represent a similar spatial pattern to Song thrushes and Blackbirds. However, the differences in Greenfinches' habitat requirements and movement behaviours across the landscape resulted in the smallest spatial extent of all the birds. The most obvious difference in the spatial pattern of connectivity routes for Greenfinches was found in the areas between the River Don and the borders of

Rotherham, and in the built-up area of Sheffield where there are no ecological connections. The potential connectivity routes for Skylarks, on the other hand, had a completely different pattern to other bird species, based on their habitat requirements. The ecological connectivity routes for Skylarks are mainly concentrated in the suburban parts of the study area and the Peak District National Park where the land is covered by *Heathlands, Unimproved Grassland* and *Arable Land*. However, the areas of *Wetlands* in the Peak District National Park, and the areas of *Mixed Vegetation* and *Buildings and Structures* in the urban parts of the study area do not provide sufficient ecological connections for Skylarks.

The ecological connectivity routes for the Brown long-eared bat and Pipistrelle bat extend across the whole study area but exclude a large proportion of the Peak District National Park where the areas of *Heathlands* and *Wetlands* dominated the land. The urban part of the study area provides ecological connections for both Brown long-eared bat and Pipistrelle bat where the land is mainly covered by *Buildings and Structures* and *Mixed Vegetation*. While the spatial coverage of the ecological connectivity routes for Brown long-eared bats is the largest of all the selected species (57.54%), the ecological connectivity routes for Pipistrelle bats cover 46.07% of the whole study area. Therefore, there is a slight difference in the spatial pattern of ecological connectivity routes for Brown long-eared bats and Pipistrelle bats in the areas of urban periphery where the patches of *Unimproved Grassland* provide ecological connections for Brown long-eared bats. Conversely, Leisler's bats mainly benefit from the habitats included in the western part of the study area, through connections from the Peak District National Park to the urban parts of the study area. The ecological connectivity for Leisler’s bats is mainly provided by the areas of *Wetlands*, *Woodlands*, *Unimproved Grassland* and *Arable Land* in the study area. Also, the spatial extent of the ecological connectivity routes for Leisler’s bats is the smallest of all the bat species (42.57%).

Regarding reptile species, the potential connectivity routes for Common lizards and Slow-worms resulted in very similar spatial patterns with some difference in their spatial coverage. While the ecological connectivity routes for these species are distributed throughout the study area and the suitable land for connectivity routes are mainly covered by *Woodlands, Heathlands, Mixed Vegetation* and *Unimproved*

Grassland. On the other hand, the spatial coverage of the networks for Common lizards and Slow-worms are 42.63% and 51.32%, respectively. On the other hand, the areas of *Wetlands* in the Peak District National Park and built-up areas in the study area do not provide sufficient ecological connectivity for Common lizards and Slow-worms. The third reptile species, Grass snakes, prefer different land cover types as habitats and utilise different land cover types to traverse the landscape. This led to significant differences in the spatial patterns of the connectivity routes for Grass snakes, compared with other reptile species. The ecological connectivity routes for Grass snakes covers 48.63% of the total study area and they are mainly distributed in the Peak District National Park where the land is dominated by *Heathlands and Wetlands.* In addition to this, the ecological connections in the suburban part of the study area are mostly provided by the habitat patches of *Woodlands, Unimproved Grassland* and *Standing Water*.

In principle, these potential connectivity models for each species can be used as base maps to create an ecological connectivity model for Sheffield. However, it is important to note that the scope of this study was limited by issues related to the parameterisation of the least-cost corridor models. Ideally, input datasets and parameters of the least-cost modelling approach should be based on biological / empirical data on selected species (Calabrese and Fagan, 2004; Epps et al., 2007; Sawyer et al., 2011). However, where the empirical data is unavailable / insufficient the next best approach is to use expert opinion to get an estimate of habitat suitability and species dispersal. It was unfortunate that this study did not achieve the intended level of expert participation and it would be premature to make direct use of these maps in planning, without further development and validation. However, the approach does demonstrate the principle, and potential nature of the outputs, from such a procedure. The production of such 'species-eye' views of the urban environment clearly creates the possibility of then identifying the common elements of these species-specific networks, both with each other, and with other, different types of networks, to highlight the areas that may provide high levels of 'multifunctional connectivity' – i.e. where planning attention to conserving such areas may deliver maximum connectivity benefits

With regard to people, the main criteria to identify the potential connectivity routes were physical / legal accessibility and the effects of gradient on movement by walking. Additionally, I identified different destinations to derive potential accessibility routes for people. As a result, 6 different potential connectivity routes were modelled for pedestrians between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*, *Residential Buildings* and *Industrial and Commercial Units*, and *Residential Buildings* and *Public Buildings*. For each of these destinations, a pair of connectivity routes was created. While the first connectivity routes were based on the effects of physical / legal accessibility on movement, the second ones also incorporated the effects of gradient as a constraint to the convenience of pedestrians' movement across the landscape.

In general, all the potential connectivity routes for people resulted in a similar coverage, ranging from 17.43% to 24.22%, of the study area. When the effects of physical / legal accessibility and gradient were taken together, the total area of the potential connectivity routes tended to increase, except in the case of the networks between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*. The spatial pattern and extent of the connectivity routes for these destinations are almost the same for the criteria of physical / legal access and its combination with the effects of gradient on pedestrians. The only difference in the spatial arrangement of these networks is found in the western parts of the study area where the slopes are too steep to accommodate movement by walking.

The spatial coverage of the network between *Residential Buildings* and *Industrial / Commercial Units*, based on physical / legal accessibility, is the smallest compared to all other networks for people (17.43%). On the other hand, when physical / legal accessibility was combined with the effects of gradient on pedestrian movement; the extent of the network increased by around 5%. This was an unexpected result, since gradient was assumed to be a constraint on movement. However, a detailed examination revealed that gradient had a positive effect on the movement of people, particularly where the land is flat and its use provide moderate physical / legal access to the public. This was simply because of the cost layer used to generate this network includes the effects of physical / legal accessibility was combined with the effects of gradient on pedestrian movement. In order to prepare the required cost layer, different land use types were reclassified into a raster layer to represent the cost of pedestrian movement based on physical / legal accessibility (land use cost layer), and gradient was reclassified into a raster layer to indicate the cost of pedestrian movement based on the steepness of the land (slope cost layer). Then, these cost layers were combined into a single cost layer. Therefore, a land use type on flat or gently sloping surfaces resulted in lower cost to movement even though they are not accessible by the public A similar result was determined for the networks between *Residential Buildings* and *Public Buildings*.

As a result, we can claim that the spatial arrangement and extent of all potential connectivity routes for pedestrians is highly dependent on the criteria used to identify them. In spite of this, some land uses appeared to be more compatible with the potential movement routes for people by walking. For each of the potential connectivity routes for people, *Paths and Pavement* and *Roadside Vegetation* play a key role in all potential accessibility models by constituting an extensive linear network throughout the research area. These areas allow people to travel from their residences to other destinations by providing public access both for recreational and practical purposes (e.g. walking, running, going to work or shopping). The patches of *Roadside Vegetation* are of particular importance, since they have potential to provide well-connected, sheltered and pleasing environments for people supporting their movement in between places (Fukahori and Kubota, 2003; Giles-Corti et al., 2005). Moreover, they also provide connectivity across the landscape for a variety of species. Therefore, in a landscape planning context, these areas should be considered as part of a wider network at a landscape scale, taking into consideration their potential to support public accessibility and ecological connectivity for species.

After modelling functional connectivity routes for biodiversity and people, the next chapter moves on to the comparison of derived connectivity routes with each other and with current network approaches in order to explore how differing landscape morphologies support or detract from their ecological connectivity and public accessibility functions.

Chapter 7 Comparisons and General Discussions

7.1 Introduction

This chapter compares and contrasts the derived connectivity routes with each other, and with current network approaches, and also analyses the relationship between their structural properties and the urban morphologies in which they occur, with a view to predicting the implications for ecological connectivity and use by members of the public. This chapter explores how differing landscape morphologies within a wider landscape matrix support or detract from their ecological connectivity and public accessibility functions according to what we define spatially. The main objective of the chapter is to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice. In this context, Chapter 7 addresses the following research questions:

1. Do the derived routes of potential connectivity and accessibility coincide with each other and the actual green and ecological networks?
2. How does the landscape matrix complement or detract from the potential routes of connectivity and what are the best possibilities for improving the functionality of connectivity in urban areas considering potential habitat use by organisms and/or accessibility to the public?
3. Considering the space limitations in urban landscapes, are some types of land uses and morphologies more compatible with the potential routes of connectivity. If so, how can we measure their compatibility?

The comparisons were conducted in ArcGIS 10.1 through spatial and visual assessments of each network, comparing and contrasting their spatial extent, pattern and components. Also, I measured the structural connectivity of different habitats within all of the Priority Landscape Areas (PLAs) and the areas that lie outside the Living Don ecological network using landscape metrics in FRGASTATS 4.1. These analyses helped me to assess how well these PLAs are actually performing.

7.2 Comparison of Structural Connectivity Routes with the Least-cost Corridors

In this section, structural connectivity and functional connectivity routes were compared and contrasted. The structural connectivity routes for biodiversity and people were derived using ArcGIS and FRAGSTATS in combination, where only the physical connectedness of the different land cover and land use types were taken into account. In this context, after determining the most connected land cover types in the study area, I aggregated the subclasses of the broader land cover categories to delineate the potential connectivity routes for biodiversity. Initially, the structural connectivity of individual land cover categories were calculated using FRAGSTATS landscape metrics. Therefore, structural connectivity networks are based on the physical properties of land cover patches such as the area and number of patches, and the average distance to each other (see Chapter 5).

On the other hand, the second criterion for the delineation of alternative connectivity routes was functional connectivity. With regards to biodiversity, 10 species from 3 different taxon groups (birds, mammals and reptiles) were selected. Their habitat requirements and likely movement characteristics across the landscape were used as the measure of functional connectivity. In terms of people, the alternative connectivity routes between residential buildings and (a) green and open spaces, (b) public buildings and (c) industrial / commercial units were generated taking into account the effects of physical / legal accessibility and slope on pedestrian movement. Functional connectivity routes for biodiversity and people were developed using a least-cost corridor approach in ArcGIS (see Chapter 6).

For each comparison, the following sub-sections represent the methodology for comparisons, a summary of methods to derive alternative structural and functional connectivity routes, the results and discussions of comparisons.

7.2.1 Methods

The comparison of the derived and existing networks was conducted in ArcGIS 10.1 by the visual assessment of the overlaps on the maps.

7.2.2 Ecological Connectivity

7.2.2.1 Deriving structural and functional networks

The structural connectivity routes for biodiversity were created by taking into consideration the physical connections / links between the land cover sub-classes (see Chapter 5, Part 1). Then, when delineating the structural connectivity routes for biodiversity, the land cover sub-types were aggregated into the broader categories starting from the most connected land cover category to least connected ones. The resulting structural connectivity networks were *Heathlands, Woodland and Shrub, Grasslands, Cultivated Land, Mixed Vegetation, Wetlands* and *Water*. For example, while the *Wetlands* network consists of the sub-classes of *Heath Dominated Bog, Grass Dominated Bog, Marsh Reeds and Saltmarshes*, the structural *Heathlands* network is formed from the *Heather Grassland* and *Heather* land cover sub-classes.

Out of the structural connectivity networks at level 2, *Wetlands* and *Heathlands* demonstrated the greatest structural connectivity. *Woodland and Shrub* and *Grasslands* also had good physical connectivity. The structural network of Vegetation was delineated by aggregating *Heathlands, Woodland and Shrub, Grasslands, Cultivated Land, Mixed Vegetation* resulting in 71.86% coverage and the highest structural connectivity. The aggregated *Water and Wetlands* occupies 13.55% of the total study area with greater structural connectivity than its individual spatial components.

The least-cost corridors, used to represent functional connectivity routes for biodiversity, were developed using information on the suitability of different land cover types as habitats for the selected species and their likely dispersal characteristics in each type of land cover (see Chapter 6, Part 1).

In total, ten least-cost corridors were generated for 4 bird species, 3 mammal species and 3 reptile species. Regarding bird species, I created least-cost corridors for Song Thrushes, Skylarks, Blackbirds and Greenfinches. As stated by the expert on birds, the selected species are migratory species and may travel across the landscape by crossing over most of the land cover types. However, the estimates of habitat suitability and the relative cost / resistance values for different land cover categories resulted in different spatial patterns for the least-cost corridors for each bird species.

7.2.2.2 Comparing networks

Figure 35 represents the overlap between structural networks and binary least-cost corridors for birds.

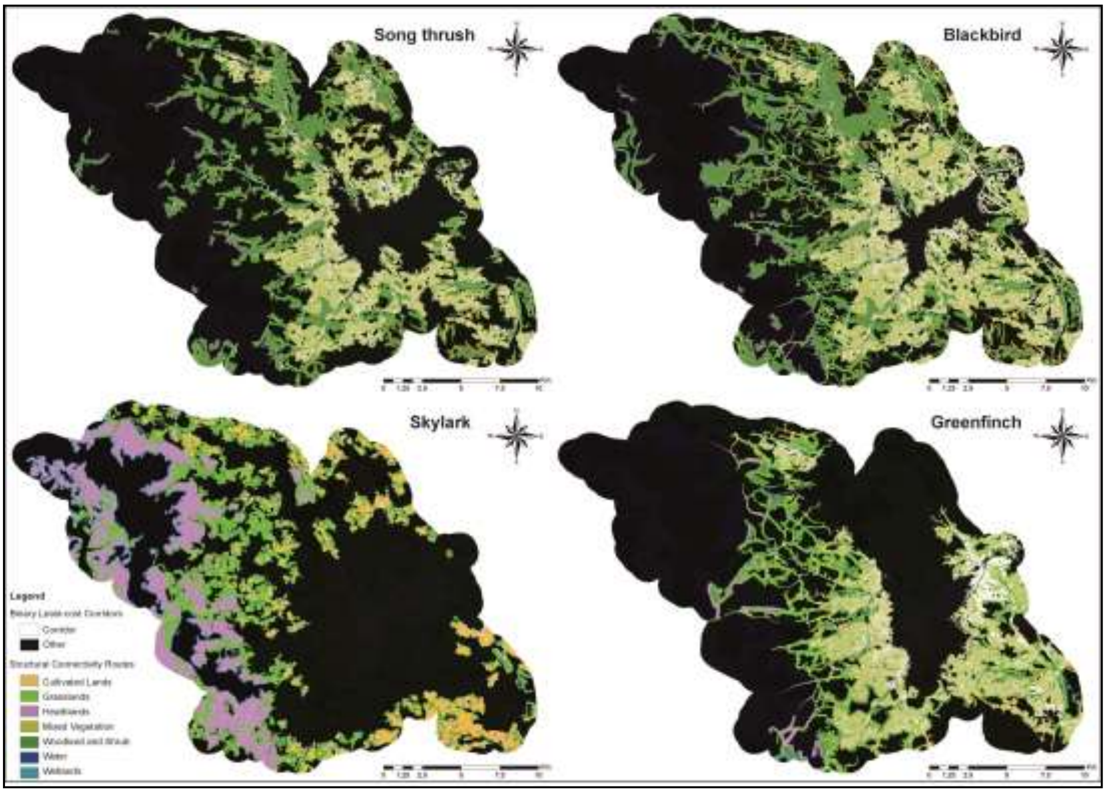


Figure 35: Overlap between structural networks and binary least-cost corridors for birds

The least-cost corridor for Song thrushes is mainly formed from patches of *Woodlands, Shrub*, *Private Gardens* and *Other Landscapes Areas*, and covers around 35% of the study area. Therefore, the least-cost corridor for Song thrushes largely coincides with the structural networks of *Woodland and Shrub* and *Mixed Vegetation*. Also, even though the least-cost corridor for Song thrushes does not coincide with the structural network of *Water* features, there are some intersections where the linear *Water* features are surrounded by the patches of *Woodland and Shrub* structural network.

Additionally, the networks of the most structurally connected broad land cover types, Wetlands and Heathlands, do not overlap with the least-cost corridor for Song thrushes. Therefore, we can deduce that even though these land cover types represent the highest physical connectivity, they do not provide functional connections for the movement of Song thrushes.

As with Song thrushes, the least-cost corridors for Blackbirds and Greenfinches coincide partly with the structural connectivity networks of *Woodland and Shrub* and *Mixed Vegetation,* by covering 47% and 31% of the whole study area respectively. The difference in the spatial extents of their least-cost corridors largely depends on their habitat preferences, the minimum habitat area requirements and the cost values applied to different land cover types. The patches of *Roadside Vegetation* land cover play an important role in providing functional, linear connections for the movement of Blackbirds and Greenfinches.

The spatial arrangement of the least-cost corridor for Skylarks is quite different from the corridors for the other bird species. Furthermore, the spatial extent of the least-cost corridor for Skylarks is slightly larger than that for Song thrushes and Greenfinches, as it covers 39% of the whole study area. The least-cost corridor for Skylarks is mainly concentrated in the western part of the study area and largely coincides with the *Heathland* structural network within the boundaries of the Peak District National Park, as well as the *Cultivated Land* structural network. Additionally, there are some overlaps between the least-cost corridor and the *Grasslands* network, where the patches of *Unimproved Grassland* are present. Here, it is important to note that, despite *Unimproved Grassland* and *Cultivated Land* having low structural connectivity, they did provide important connections for Skylarks towards to the central parts of the study area.

Overlap between structural networks and binary least-cost corridors for bats are shown in Figure 36. The least-cost corridors for Brown long-eared bats and Pipistrelle bats had very similar spatial patterns with some differences towards the Peak District National Park. In general, the least-cost corridors for these species coincide with the structural connectivity networks of *Woodlands and Shrub* and *Mixed Vegetation.* They also include patches of *Buildings / Structures and Constructed Surfaces.*

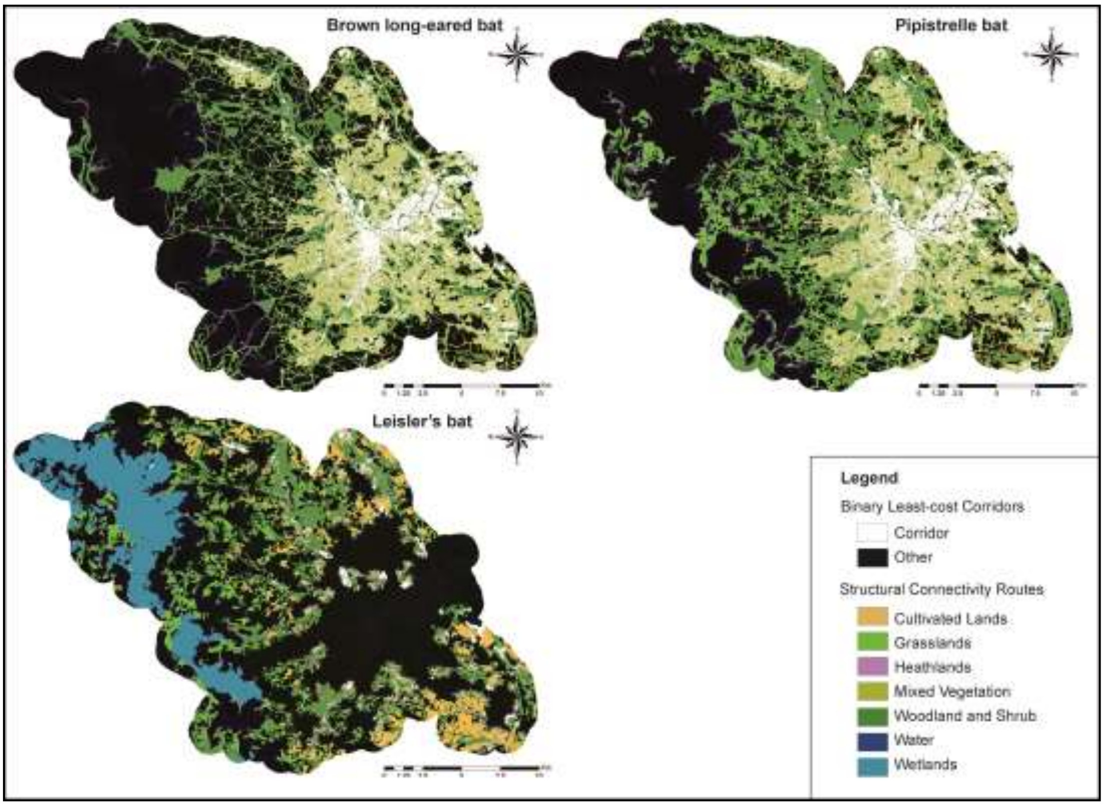


Figure 36: Overlap between structural networks and binary least-cost corridors for bats

Despite the fact that the patches of *Roadside Vegetation* and *Railway Vegetation* do not have strong structural connectivity, as linear habitats for Brown long-eared bats and Pipistrelle bats, their crucial role in supporting ecological connectivity was reflected in the least-cost corridors. Conversely, the spatial extent of the least-cost corridor for Pipistrelle bats is larger than that for Brown long-eared bats as it also contains the patches of *Unimproved Grassland*. Therefore, the least-cost corridor for Pipistrelle bats includes some spatial overlaps with the structural connectivity network of *Grasslands.*

The spatial extent of the least-cost corridor for Leisler's bats is the least of all the bat species, as well as having a quite different spatial pattern. The least-cost corridor is distributed throughout the study area, apart from the central parts where the land is largely covered by small patches of the *Mixed Vegetation* structural network. However, the least-cost corridor partially overlaps with the structural connectivity network of *Mixed Vegetation*, where the patches are large enough to accommodate Leisler's bats. The least-cost corridor overlaps almost completely with the structural connectivity networks of *Wetlands* and *Cultivated Land*, and also partially coincides with the networks of *Woodland and Shrub* and *Grasslands*.

Figure 37 represents the intersection of the structural connectivity routes for biodiversity and the least-cost corridors for the selected reptile species.

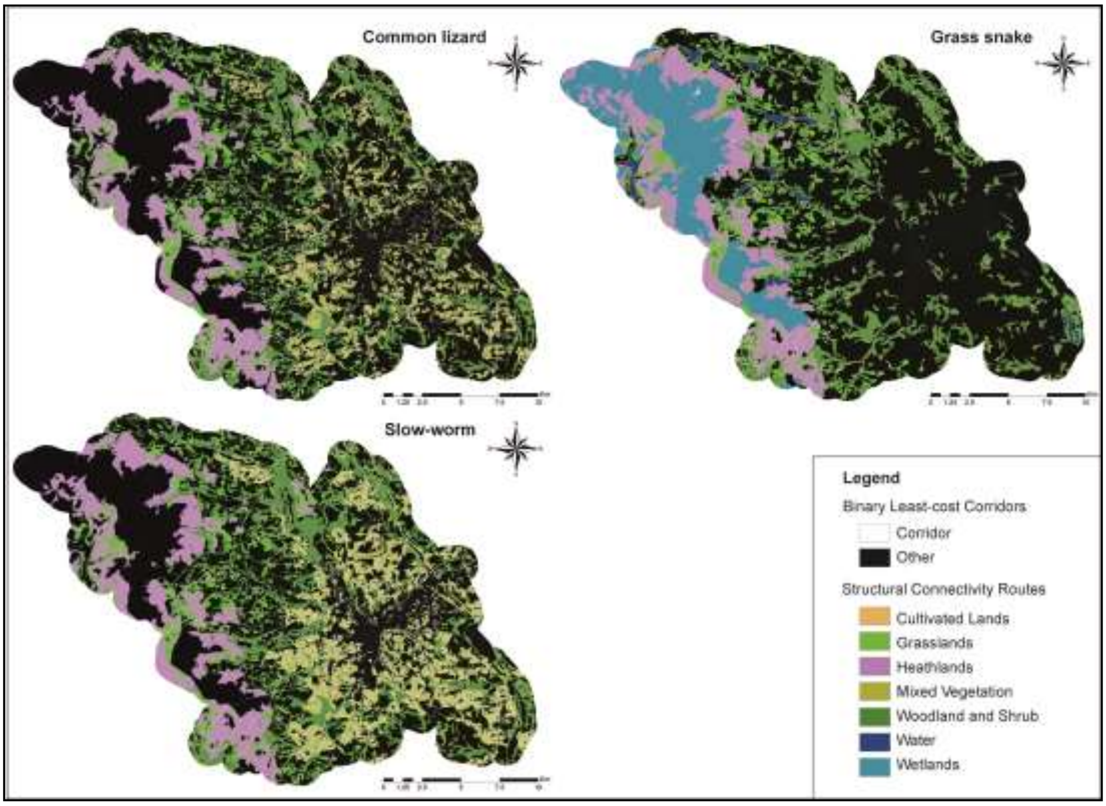


Figure 37: Overlap between structural networks and binary least-cost corridors for reptiles

The spatial pattern of the least-cost corridors for Common lizards and Slow-worms are very similar and evenly distributed across the whole study area (with a difference in their spatial extent, 42.6% and 51.3%, respectively). For both species the least-cost corridors largely coincide with the structural connectivity networks of *Heathlands* and *Mixed Vegetation* and partially overlap with the structural connectivity networks of *Woodland and Shrub* and *Grasslands*. Here, it is worth noting that Common lizards utilise patches of *Shrub* land cover type as well as patches of *Woodlands, Heathlands, Mixed Vegetation and Unimproved Grassland* for their habitat. However, the spatial extent of the least-cost corridor for the Common lizard is slightly smaller than that for Slow-worms.

On the other hand, the least-cost corridor for Grass snakes appears to have quite a different pattern across the study area, with 48.3% coverage, and is mainly distributed throughout the western parts of the landscape. The least-cost corridor completely overlaps with the structural connectivity networks of *Heathlands* and *Wetlands*, which were determined as the most connected land cover types in the study area. In addition partial overlaps are found with the structural connectivity networks of *Woodlands and Shrub, Grasslands* and *Water* features in the central parts of the study area.

7.2.2.3 Summary

The comparison of outputs provides evidence that when behaviour is taken into account, the resulting networks differ between the approaches. The most obvious difference between structural and functional connectivity routes was seen in the Peak District National Park. For example, whilst the structural networks *Heathlands* and *Wetlands* are mainly located in the Peak District National Park, there are little or no functional connections for most of the selected species (e.g. Greenfinches, Brown long-eared bat). In addition, the *Wetlands* network in the Peak District National Park does not coincide with the functional connectivity networks for the selected species, apart from the ones for Leisler’s bats and Grass snakes.

On the other hand, one of the most important similarities between the spatial arrangement of structural and functional connectivity routes was seen in the lower River Don and the upper parts of the River Sheaf corridors. Whilst, these areas only support functional connectivity for Brown long-eared and Pipistrelle bats, there are almost no structural connectivity routes for biodiversity.

Additionally, the derived structural and functional connectivity routes typically coincide in the areas where the areas of habitat patches for the selected species are presented. An obvious example of this pattern was explicitly seen in the large spatial overlap between the structural networks of *Woodland and Shrub* and *Mixed Vegetation* and the functional connectivity routes for Blackbirds. Also, the network of *Woodland and Shrub* and *Mixed Vegetation*, in general, coincides with the functional connectivity routes for most of the species with a greater area compared to the other structural connectivity routes.

The structural landscape measures can be useful to understand the actual spatial characteristics of the landscape and the relationships between its components, such as the overall proportion of different land cover / use types, their proximity to each other and their distribution across the landscape. Therefore, structural connectivity measures can be useful in their own right. However, if the definition and planning of the potential connectivity routes for biodiversity relies only on the physical connectivity of habitats then this may lead to inappropriate planning decisions. We can clearly see that habitat patches do not necessarily need to be structurally / physically connected to be functionally connected for species.

Planning the potential connectivity routes for biodiversity at the structural connectivity level ignores specific requirements of individual species. Therefore, if the definition and planning of the potential connectivity routes for biodiversity relies only on the physical connectivity of habitats then this may lead to inappropriate planning decisions. We can clearly see that habitat patches do not necessarily need to be structurally / physically connected to be functionally connected for species. For example, in the case of Sheffield, *Wetlands* and *Heathlands* are structurally the most connected broad land cover types and provide physically clustered and connected patches. In spite of this, the network of *Wetlands* and *Heathlands* do not provide functional connections for Blackbirds, Greenfinches, Song thrushes and Brown long-eared bats - whereas Skylarks, Pipistrelle bats and Slow-worms can partially benefit from these structural networks.

7.2.3 Public Accessibility

7.2.3.1 Deriving structural and functional networks

The aim of structural connectivity networks was to prioritise the potential contribution of different land use types into a network which would allow people to move through the urban environment with maximum contact, or opportunity for contact, with vegetation and non-built areas. Structural connectivity routes for people were developed on the basis of the spatial composition and configuration of different green spaces as well as *Paths and Pavements* in the landscape. Therefore, when generating the potential connectivity routes for people, I focused on structural connections between the different types of *Natural and Semi-natural Land* uses and *Paths* and *Pavements*. Thus, all patches of the *Natural and Semi-natural Land* uses and *Paths* and *Pavements* were considered as part of the potential connectivity routes within the whole of the study area. The resulting networks are composed of *Recreation and Leisure* and *Mixed Vegetation* with a spatial coverage of 49.35% and 13.17%, respectively.

When developing the functionally connected routes for people, the physical / legal accessibility of different land use types and the effects of slope on the movement of people by walking were taken into account. Additionally, only the urban part of the study area was taken into consideration to obtain a functional network of open and green spaces for people. The exclusion of the areas within the Peak District National Park (almost 30% of the whole study area) led to substantial differences in the spatial components, patterns and extents of structural and functional connectivity routes for people. Therefore, the areas within the Peak District National Park were excluded from the comparisons (see Chapter 6, Part 2).

7.2.3.2 Comparing networks

The *Recreation and Leisure* network has very strong structural connectivity and is well distributed within the urban part of the study area, covering 34.18% of this area (and 49.35% of the total study area). It includes the following *Natural and Semi-natural Land* uses: *Allotments, Amenity Green Spaces, Cemeteries and Churchyards, Outdoor Sport Facilities, Parks and Gardens, Natural and Semi-natural Greenspaces, Provision for Children and Young People* and *Countryside / Urban Fringe*. In addition, the *Recreation and Leisure* network includes *Paths and Pavements* as the main routes of movement for pedestrians. The *Mixed Vegetation* structural network, on the other hand, is mainly distributed around the central parts of the urban area with a 21.03% coverage and is composed of *Roadside Vegetation, Railway Vegetation, Private Gardens* and *Paths and Pavements* with a lower level of structural connectivity compared to the *Recreation and Leisure* network.

The first pair of least-cost corridors for people were generated in order to determine the networks of green and open spaces between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*. Based on the physical / legal accessibility of different land use types, the first least-cost corridor is largely distributed over the central parts of the study area and covers 49% of the whole area. The extent of the second least-cost corridor is slightly smaller than the first and takes into account the effects of physical / legal accessibility and slope on pedestrian movement. The most important difference between the first and second least-cost corridors was found in their spatial pattern in areas of steep slope.

Figure 38a and 38b are examples of the detail of the first and second least-cost corridors, respectively. Because the second corridor incorporates the effects of slope into the ease of movement, some connectivity routes disappeared from the network, even though they are physically / legally accessible to the public. If we intend to obtain a functional network for people with limited mobility, we should consider the gradient as well as physical and legal accessibility.

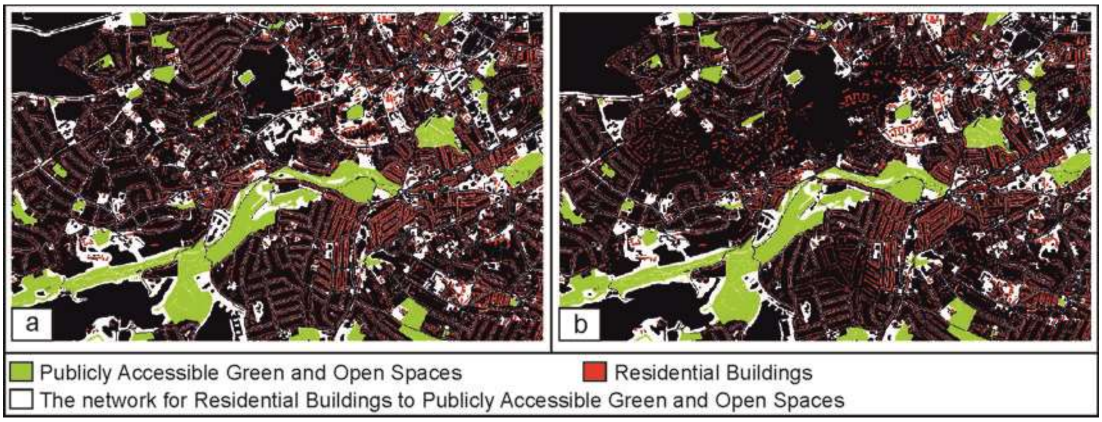


Figure 38: Details of the least-cost corridor between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*

Both of the least-cost corridors between *Residential Buildings* and *Publicly Accessible Green and Open Spaces* have partial overlaps with the networks of *Recreation and Leisure* and *Mixed Vegetation*, where the land provides physical / legal accessibility to the public. The most striking difference between structural and functional connectivity routes lies in their spatial components and pattern. For the least-cost corridors between *Residential Buildings* and *Publicly Accessible Green and Open Spaces,* the functional connections for the movement of people are mainly provided by *Paths and Pavements* and *Roadside Vegetation*.

Similar to the first and second least-cost corridors between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*, both the *Recreation and Leisure* and *Mixed Vegetation* networks include *Paths and Pavements*. Additionally, for structural connectivity networks, high physical connectivity was regarded as the main criteria to construct the potential networks and public accessibility was not taken into account. Therefore, both the *Recreation and Leisure* and *Mixed Vegetation* networks include some of the publicly inaccessible areas, such as *Outdoor Sport Facilities, Allotments* and *Private Gardens*.

The second pair of the least-cost corridors were created to support the movement of people between *Residential Buildings* and *Industrial and Commercial Units*. The second least-cost corridor has a greater spatial extent than the first one, with coverage of 22.61% and 17.43%, respectively. However, the anticipated outcome of the comparison was for the coverage of the second least-cost corridor to be less than the first due to detrimential effects of slope on the movement of people. This surprising result can be explained by the location of destination areas, and the cost values assigned to land uses as an indication of the difficulty in movement (Figure 39).

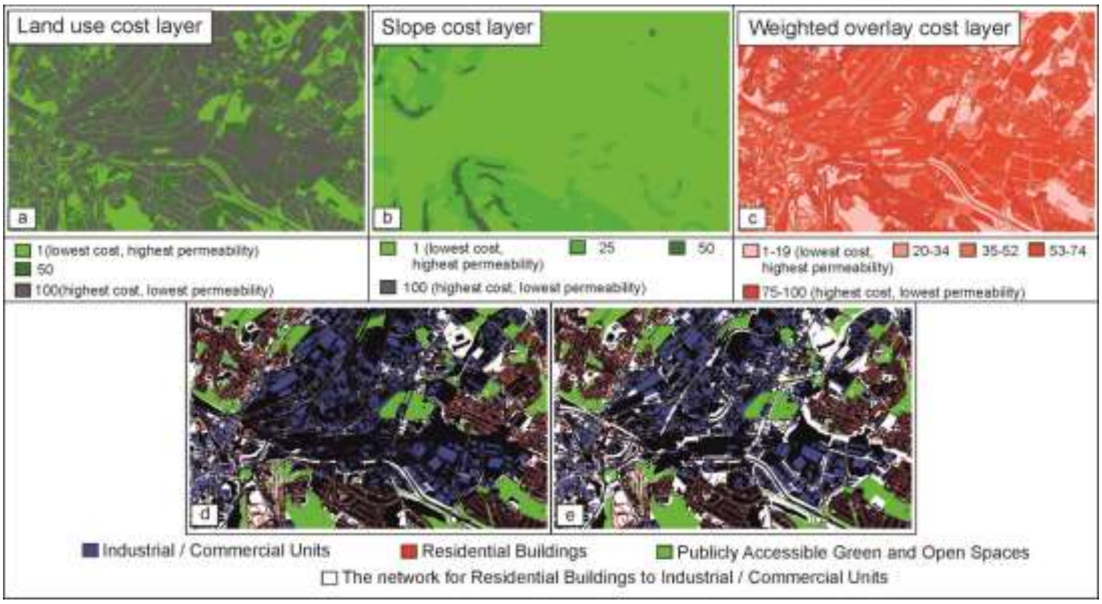


Figure 39: Details of the least-cost corridor between *Residential Buildings* and *Industrial and Commercial Units*

The majority of *Industrial and Commercial Units* are located on flat surfaces where the effect of slope on the movement is the lowest. In addition to this, these areas are generally located near areas of *Amenity Greenspaces* and *Natural and Semi-natural Greenspaces*, which are not included in the Sheffield City Council accessible green and open spaces layer and hence assumed as either publicly or privately accessible with an intermediate cost value of 50. As a result, the positive effect of slope (with low cost values) decreased the accumulated cost of movement around these areas and increased the amount of notionally connected land.

Industrial units are located around the River Don and the Sheffield and Tinsley Canal with almost no accessibility routes around these areas. However, considering the recreational and visual value of water features and their proximity to the city centre, this part of the city should be improved in terms of the public accessibility. This can be achieved by improving the existing *Paths and Pavements* lined with *Roadside Vegetation* and creating more of these areas, where needed. In addition, residential areas in the west and south west part of the research area cannot benefit from the network due to the location of *Industrial and Commercial Units* and the distance between *Residential Buildings* and *Industrial and Commercial Units*.

The third pair of least-cost corridors was created to support the movement of people between *Residential Buildings* and *Public Buildings*. When examined, the first least-cost corridor, based on the physical / legal accessibility, represents a very similar spatial arrangement and extent to the first least-cost corridor between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*. The difference between these networks largely depends on the location of the destinations that we intend to connect to each other for the movement of people.

The first and second least-cost corridors between *Residential Buildings and Public Buildings* occupy 20.74% and 24.22% of the study area without the Peak District National park. Two main differences have been identified in the spatial arrangement and extent of the first and second optimum corridors. To begin with, in the second least-cost corridor there are some areas with weak or no connections caused by the effects of slope (Figure 40). This was an expected outcome and resulted in a lower amount of land allocated for the second network, where the land is too steep to support the movement of people by walking.

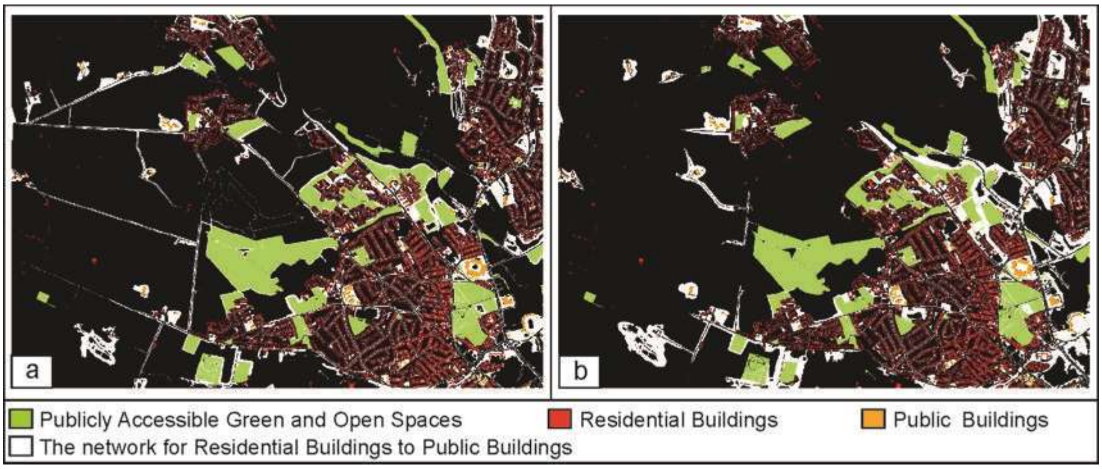


Figure 40: Details of the least-cost corridor between *Residential Buildings* and *Public Buildings* -1

On the other hand, the second difference was found to be the increase in the connectivity and land allocated for the potential network within the areas with lower degrees of slope. Similar to the networks between *Residential Buildings* and *Industrial / Commercial Units*, this difference is due to the accumulated effects of physical / legal accessibility and slope on movement, as well as the location of the *Public Buildings*. Therefore, even though they are not necessarily accessible by the public, the second least-cost corridor expanded over these areas and resulted in a larger accessible area compared to the first least-cost corridor, which only takes into consideration the effects of physical / legal accessibility on the movement of people.

Both of the least-cost corridors between *Residential Buildings* and *Industrial and Commercial Units*, and *Residential Buildings* and *Public Buildings* have spatial overlaps with the structural connectivity routes of *Recreation and Leisure*, and *Mixed Vegetation* (excluding the areas within the Peak District National Park). However, as stated previously, the most significant difference is in their spatial components, where the structural connectivity routes of *Recreation and Leisure* and *Mixed Vegetation* includes some of the publicly inaccessible land uses.

7.2.3.3 Summary

The differences between structural and functional connectivity routes are largely dependent on the criteria used to derive them. The structural connectivity networks for people were derived on the basis of high physical connectedness of different green spaces as an indication of allowing people to move through the urban environment with maximum contact, or opportunity for contact. Therefore, whilst *Natural and Semi-natural Land* uses were considered as the green components of the network, *Paths and Pavements* were considered as the main components of the structural connectivity networks to support pedestrian movement. Also, I did not distinguish land uses as publicly accessible or not, since I was interested in the physical connectivity of different green spaces and *Paths and Pavement*. Accordingly, the resulting structural connectivity routes are composed of both publicly accessible and inaccessible land uses. The reason for the inclusion of *Private Gardens* and *Railway Vegetation* as part of the network was their potential to provide amenity / visual values and resources to people. However, if the main aim in defining potential connectivity routes for people was to support their movement by walking, as is the case with functional connectivity networks, then it is obvious that these land uses would not be suitable to serve this function for the public.

On the other hand, functional connectivity routes were derived taking into account the pedestrian movement as the main criterion to constitute networks. Therefore, all land use types were identified as physically accessible or not. Hence, while including all *Publicly Accessible Green and Open Spaces* in networks, similar to structural connectivity routes, *Paths and Pavements* constitute the backbone of functional connectivity routes for people, as they are the key elements of pedestrian movement in between spaces. The differences in the spatial extent of functional connectivity routes for people further reflect the restricting effects of slope on the movement of mobility limited people. Hence, these differences confirm that it is possible to take such criteria into account, and that it produces a different network.

7.3 Comparison of the Derived Connectivity Routes with the Sheffield Green Network

Sheffield City Council (SCC) Green Network is defined as "*a network of open space that provides the means for wildlife and people to move through the built-up areas and to connect with the surrounding countryside. It consists of existing Green Links, Desired Green Links and all waterways shown on the Proposals Map* (SCC, 2013b)."

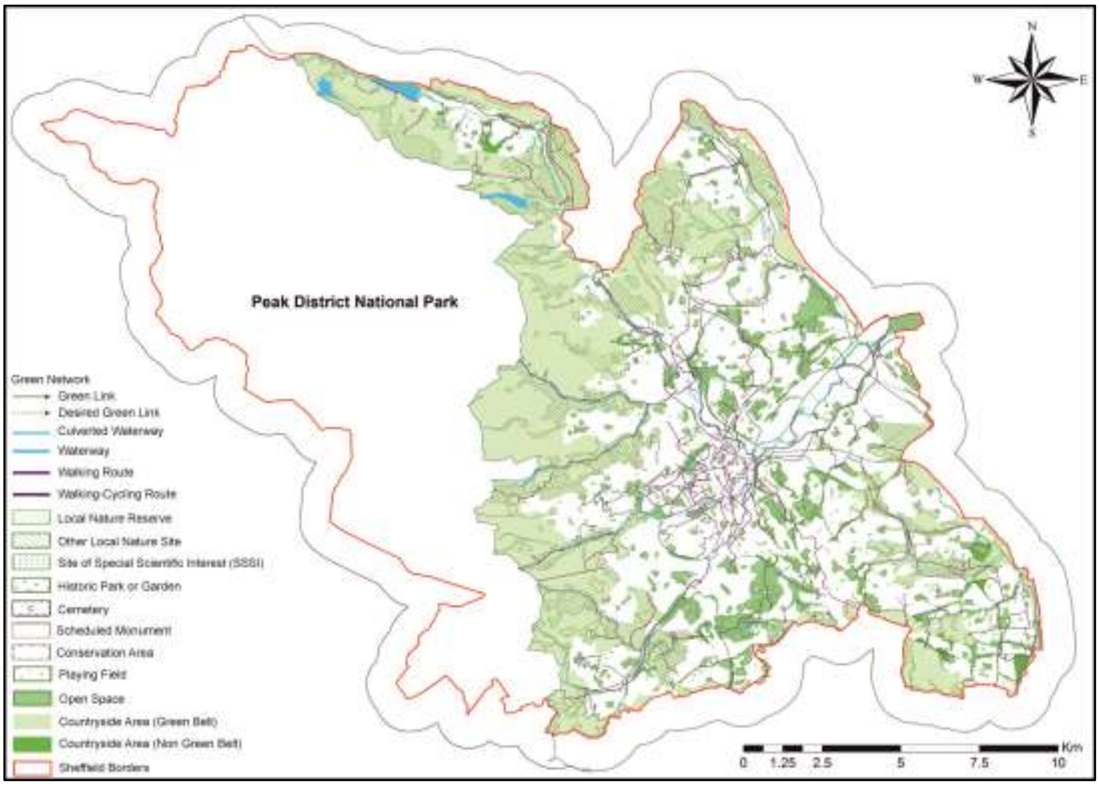
Spatially, the Green Network is composed of:

- The Strategic Green Network which follows the rivers and streams of the main valleys,
- Strategic Green Corridors, largely through other valleys across the city, and
- Green Links and Desired Green Links, which are more local and include linked open spaces, some footpaths, watercourses and corridors of dense vegetation without public access (SCC, 2013a).

As mentioned previously, the Sheffield City Council did not define the width of the Green Network on the Proposals Map, in order to provide an opportunity to allow flexible judgments on a site-by-site basis (see Chapter 4). However, in order to be able to compare and contrast the alternative structural connectivity routes with the Sheffield City Council (SCC) Green Network spatially, I merged the following layers of the Proposals Map since they are included and / or connected by the Green Network:

- Local Nature Reserve (LNR)
- Other Local Nature Site (Ecological Local Nature Site –LNS- and Geological Local Nature Sites -LNS),
- Site of Special Scientific Interest (SSSI) (Ecological and Geological Site of Special Scientific Interest),
- Historic Park or Garden, and
- Cemetery
- Scheduled Monument,
- Conservation Areas,
- Playing Field,
- Open Space,
- Countryside Area (Non Green Belt),
- Countryside Area (Green Belt) (Map 35).

In this way, I attempted to obtain an approximation for the extent of the Green Network assuming that all of the above-mentioned components are included in it. The comparisons between the derived connectivity routes and the Green Network were made by the visual assessment of overlays in ArcGIS.



Map 35: The Green Network

7.3.1 Structural Connectivity Routes and the Sheffield Green Network

In this phase of the research, I compared the alternative structural connectivity routes for biodiversity and people with the Green Network. At this point, it is also important to note that, because the Green Network does not include the areas within the boundaries of the Peak District National Park, these areas were excluded from comparisons.

7.3.1.1 Structural Connectivity Routes for Biodiversity and the Sheffield Green Network

Structurally, the most connected land cover types *Wetlands* and *Heathlands*, and their connectivity routes for biodiversity, are mainly located in the Peak District National Park. Therefore, there is little or no spatial overlap between those and the Green Network.

On the other hand, *Water* features network completely overlaps with the Green Network, since the waterways as a whole form an important part of the Green Network. As indicated in the Green Environment Policy Background Report (SCC, 2013a), there are many elements of the Green Network which are also designated as Green Belt. On the assumption that the Green Network includes all the areas of Green Belt, then the Green Belt largely coincides with the structural connectivity networks of *Woodland and Shrub* and *Grasslands* and (Figure 41).

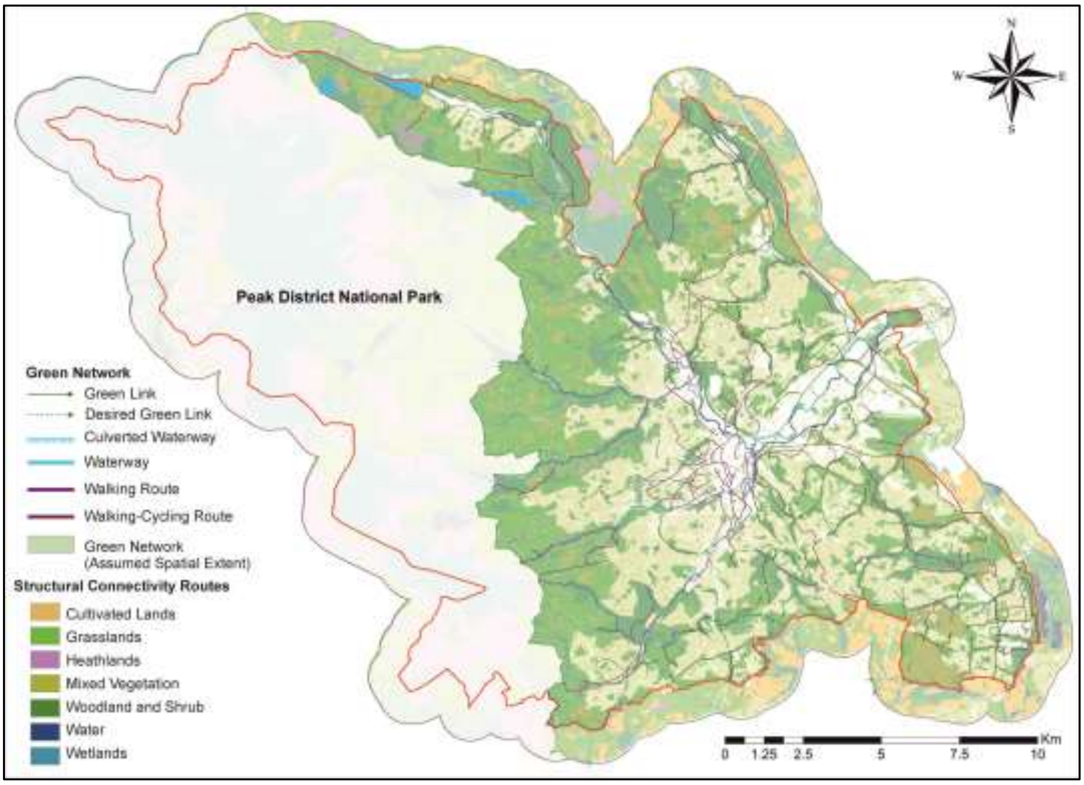


Figure 41: Intersection of the Green Network and structural connectivity routes for biodiversity - 1

Similarly, the other components of the Green Network in the central parts of Sheffield coincide mainly with the structural connectivity networks of *Woodland and Shrub* and *Grasslands*, which are centred on the *Water* features.

Figure 42 shows the details of overlap between the Green Network and the structural connectivity networks for biodiversity in the areas that lie below the lower parts of the River Don and between the River Sheaf and the River Rother. As can be seen, the Green Links mostly pass through the structural networks of *Grasslands* and *Woodlands and Shrub*. It is also important to note that the networks of *Woodlands and Shrub* and *Grasslands* have strong connectivity in the urban part of Sheffield. Considering the spatial relationships between the networks of the *Woodlands and Shrub* and *Grasslands*, it is apparent that the Green Links pass through and link physically connected land cover types. Hence, they represent the potential of the Green Network to support structural connectivity for biodiversity.

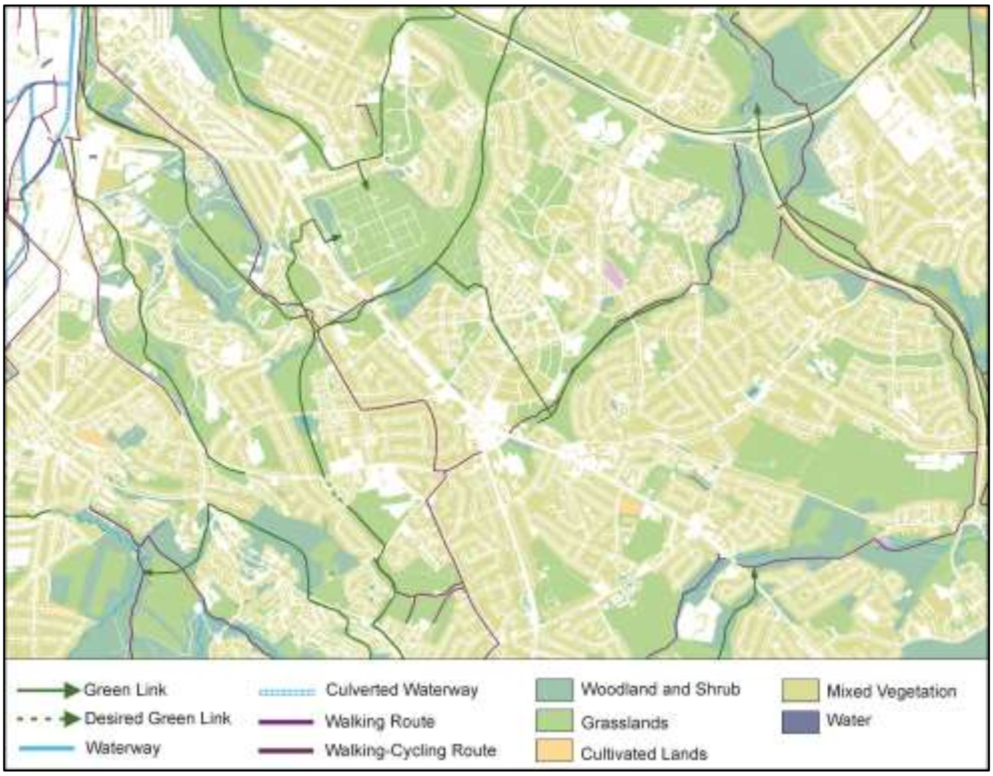


Figure 42: Details of the overlap between the Green Network and the structural connectivity networks for biodiversity

Also, in some areas the connections between the patches of *Grasslands* and *Woodlands and Shrub* networks are provided by the patches of the *Mixed Vegetation* network, where the Desired Green Links are located. As stated previously, even though the *Mixed Vegetation* network does not have strong structural connectivity, they might provide habitats for different species as well as providing visual and amenity values to people. Hence, the spatial overlaps between the Desired Green Links and the *Mixed Vegetation* network confirm the importance and value of *Mixed*

Vegetation patches in an urban context, particularly where different land use practices restrict the creation of new habitats for species or green and open spaces for people.

Whilst the connections between the Waterways and the Culverted Waterways are also provided by Green Links, as stated previously, the network of *Water* features completely overlaps with these in the Green Network. Also, to some extent, the Green Network coincides spatially with the network of *Cultivated Lands* on the outskirts of the city and with the network of *Mixed Vegetation* throughout the study area, particularly with *Roadside Vegetation* and *Railway Vegetation*. Figure 43 represents the details of the overlap between the network of *Cultivated Lands* and the Green Network. As can be seen, whilst *Cultivated Lands* are considered as part of the Green Network, these areas are connected to the networks of *Grasslands* and *Woodlands and Shrub* by defining the Green Links in these areas.

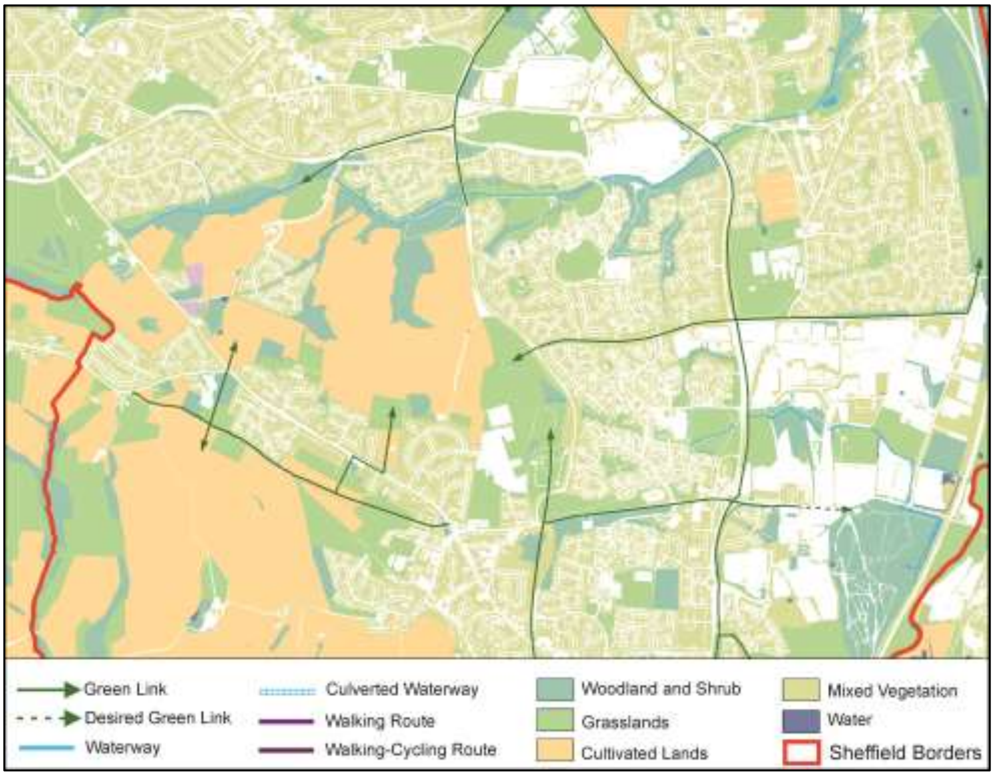


Figure 43: Details of the overlap between the network of *Cultivated Lands* and the Green Network

Even though the importance of *Private Gardens* has been emphasised in the Green Environment Policy Background Report (SCC, 2013a), there are only a few spatial coincidences between the Green Network and *Private Gardens*. Figure 44 shows "Conservation Areas", which include large *Private Gardens*. In spite of the fact that

Private Gardens cannot be managed by SCC and may not even have vegetation cover on them, we cannot ignore their potential to support physical connections between other habitat types. Therefore, if these areas were included in the Green Network, this would enhance the structural connectivity and integrity of the Green Network at a wider landscape scale.

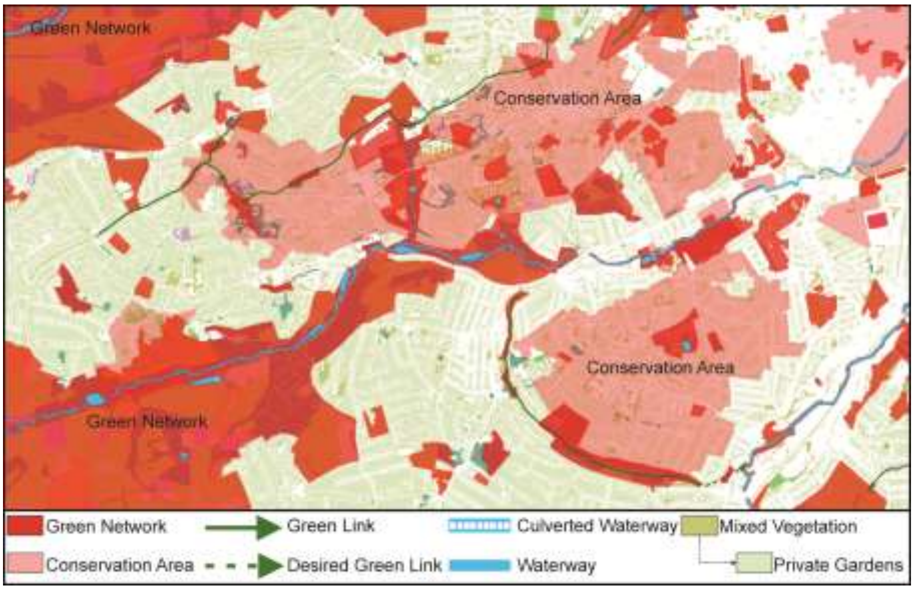


Figure 44: Details of the Intersection of the Green Network and structural connectivity routes for biodiversity

Sheffield City Council recognises the value of *Railway Vegetation*, *Private Gardens*, and *Roadside Vegetation* as well as key habitats for biodiversity, such as *Woodland and Shrub,* as part of the Green Network. As indicated by the Council in the Green Environment Policy Background Report (SCC, 2013a), these areas can form continuous habitats or large semi-natural areas in an urban context. The Green Network as I defined it spatially includes some spatial overlaps with these land cover sub-types, but it is unclear how much of each of these are included in the Green Network.

Despite this, taking into account the relationships between the delineated structural connectivity routes for biodiversity and the Green Network, I suggest that the Green Network has potential to accommodate a variety of species with a diversity of different land cover types. Nevertheless, the physical connections between the different types of land covers as habitats for species can be improved by the use of structural connectivity networks for biodiversity.

7.3.1.2 Structural Connectivity Routes for People and the Sheffield Green Network

Structural connectivity routes for people are composed of the networks *Recreation and Leisure* and *Mixed Vegetation*, and for both of these networks, *Paths and Pavements* constitute the main routes of walking for people.

Figure 45 illustrates spatial overlaps between the Green Network and the structural connectivity networks of *Mixed Vegetation* and *Recreation and Leisure*. The most connected land use type, *Countryside / Urban Fringe* is located within the boundaries of the Peak District Park and so is excluded from the comparisons.

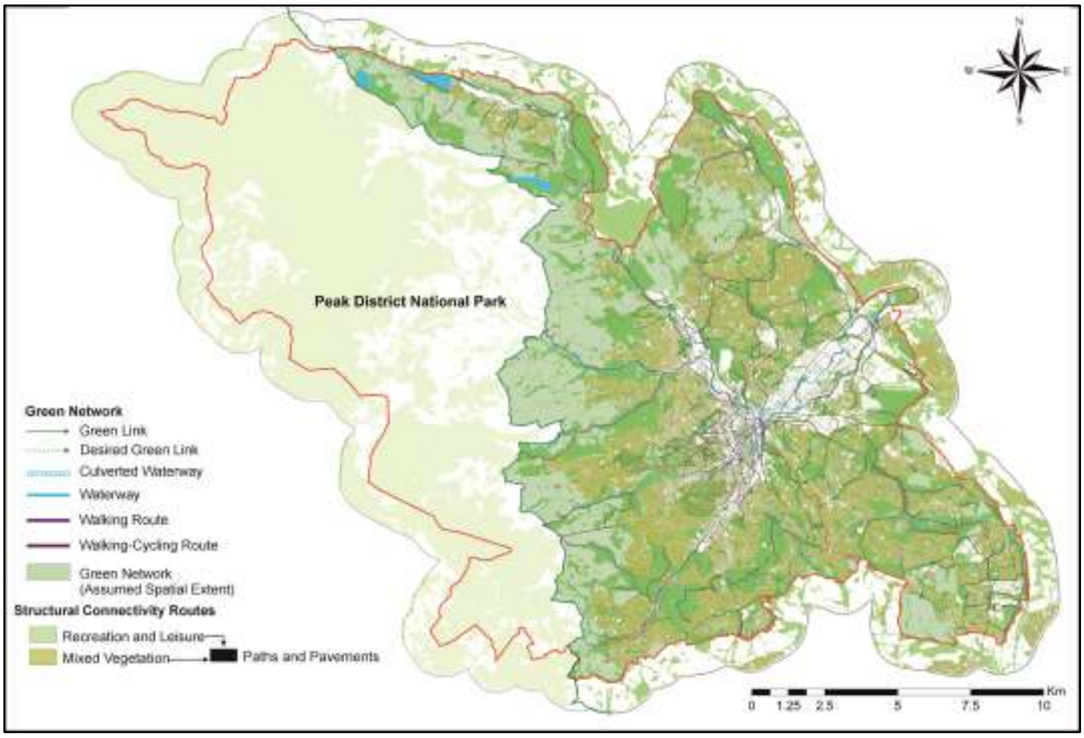


Figure 45: Intersection of the Green Network and structural connectivity routes for people

The Green Network, with the spatial extent that I defined, largely coincides with the network of *Recreation and Leisure*. Amongst the components of the *Recreation and Leisure* structural connectivity network, all the *Publicly Accessible Green and Open Spaces* completely intersect with the Green Network, apart from some patches of *Amenity Greenspaces, Natural and Semi-natural Greenspaces* and *Paths and Pavements*. Additionally, the connections in and between the *Publicly Accessible*

Green and Open Spaces in the Green Network are provided by the Green Links and Desired Green Links (Figure 46).

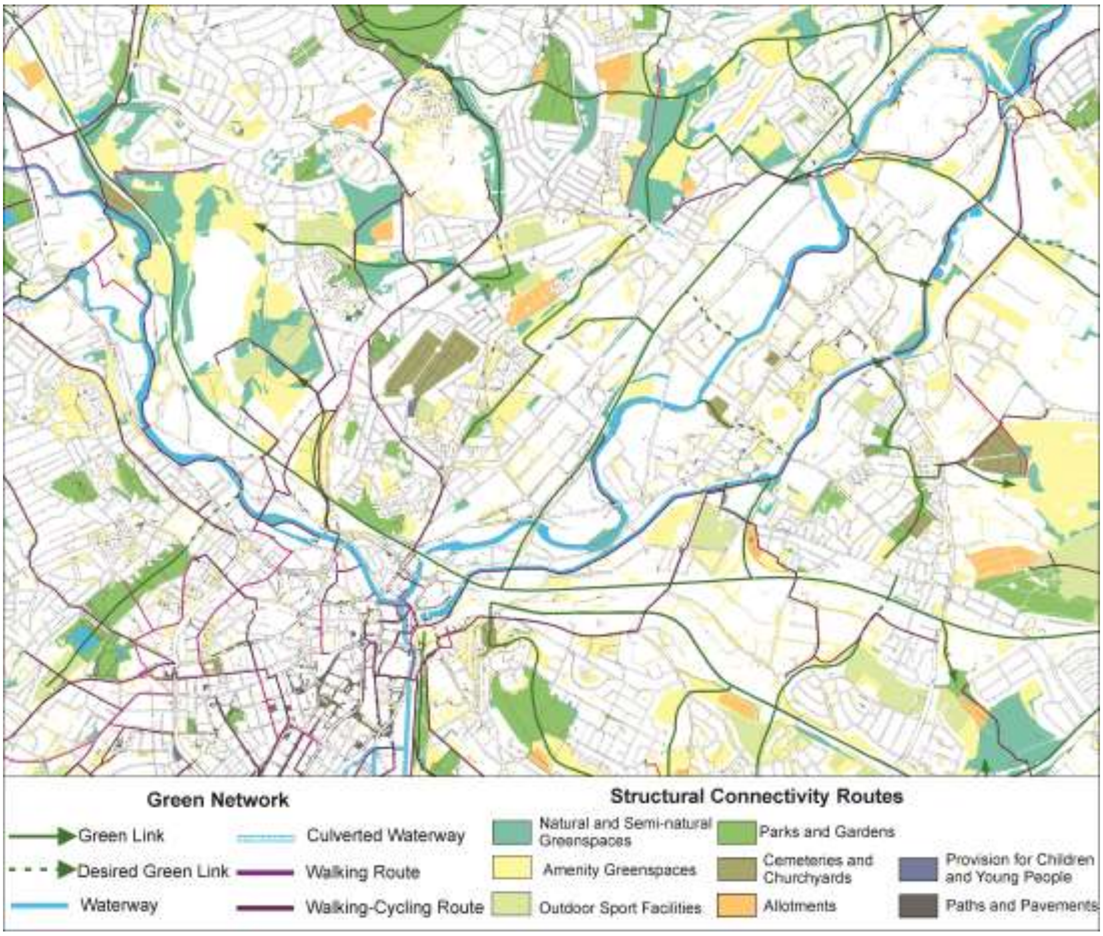


Figure 46: Details of the overlap between the Green Network and the structural connectivity network of Recreation and Leisure -1

As seen in Figure 46, there are also some coincidences between the actual and proposed Walking and Cycling Routes of the Green Network, and the *Paths and Pavements* component of the *Recreation and Leisure* network. Whilst the actual and proposed Walking and Cycling Routes of the Green Network are mainly concentrated in and around the built-up areas of Sheffield where the river corridors confluence in the city centre, they link the Publicly Accessible Green and Open Spaces and enhance the connectivity for the movement of people. Also, some of these routes follow the river corridors where the Waterways and Culverted Waterways of the Green Network are located.

Conversely, the spatial differences between the Green Network and the *Recreation and Leisure* network are caused by the areas of *Amenity Greenspaces* and *Natural and Semi-natural Greenspaces* in private ownership (see Chapter 3, Part 2), as well as the inclusion of all the patches of *Paths and Pavements* in the *Recreation and Leisure* structural network (Figure 47).

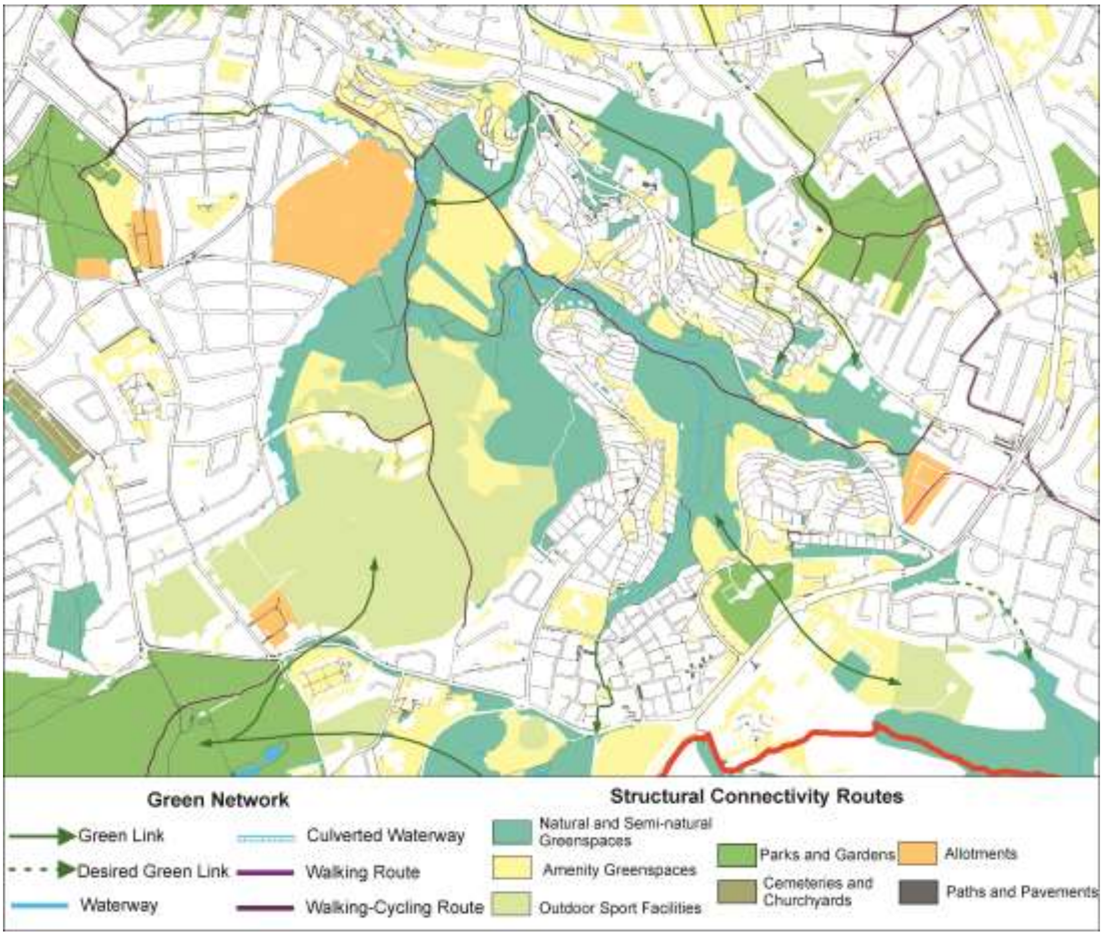


Figure 47: Details of the overlap between the Green Network and the structural connectivity network of Recreation and Leisure -2

Within the components of the *Mixed Vegetation* structural network, excluding the *Railway Vegetation* and *Private Gardens* land uses, the remaining parts of this network are publicly accessible. Conversely, apart from the Green Links and Desired Green Links, the Green Network also includes Walking and Cycling Routes as part of the connectivity routes for the movement of people. These routes are composed of actual and proposed cycle paths and footpaths, which link the components of the Green Network, primarily with the intention of increasing accessibility. As with the *Recreation and Leisure* structural network, the *Mixed Vegetation* network includes *Paths and Pavements*, and so coincides to some extent with public footpaths and cycle paths. Apart from this, there is little or no coincidence between the other components of the *Mixed Vegetation* structural network and the Green Network, particularly where the land is covered by *Private Gardens*.

Overall, the Green Network and the potential structural connectivity routes for people coincide with each other, excluding the areas within the Peak District National Park. Furthermore, almost all green and open spaces have been included in both of these approaches. However, as emphasised earlier, even though the Sheffield City Council is aware of the value of *Private Gardens, Roadside Vegetation* and *Railway Vegetation* in an urban context, there is little coincidences between the Green Network and these land uses. Hence, I would expect the SCC to include these areas as part of the Green Network, since they may provide visual and amenity values to the public even though they cannot support the actual movement of people. Moreover, the SCC does not include all *Paths and Pavements* in the Green Network and therefore it would be a good practice for the SCC to include these as part of the Green Network in order to enhance and support the movement of people.

To conclude, the SCC can benefit from these structural network models to gain a deeper understanding of the present state of different land cover and land use types as well as evaluating the quality of different areas with regard to structural connectivity. The structural networks for both people and biodiversity provide an informed assessment of the existing land cover types in terms of their physical relationships and connectivity. The delineated structural networks can therefore be used to support and enhance the Green Network planning decisions.

7.3.2 Functional Connectivity Routes and the Sheffield Green Network

One of the most important functions of the Green Network is defined as allowing and increasing the movement of biodiversity and people by providing connectivity in Sheffield. Similarly, the generated least-cost corridors for the selected species and people also aim to determine the functional connectivity routes for biodiversity and the public. Therefore, in this section I compared and contrasted the functional connectivity routes with the Green Network for the selected ten species and for people to find out whether they coincide spatially in terms of their extents and components. The comparisons were made in ArcGIS by increasing the transparency of each layer and analysing the relationships between the least-cost corridors (both for people and biodiversity) and the Green Network.

7.3.2.1 Functional Connectivity Routes for Biodiversity and the Sheffield Green Network

The spatial extent of the Green Network is not defined because Sheffield City Council has not determined a specific footprint for its components. However, in order to be able make comparisons between alternative functional connectivity routes, I have assumed that the Green Network includes all components linked by the Green and Desired Links as well as all *Water* features within the urban part of Sheffield. Based on this assumption, the Green Network occupies around 30% of the whole of Sheffield. This figure suggests that all of the connectivity routes I defined for species have a larger extent than the Green Network. However, here it is important to bear in mind that the Green Network is only located in the urban part of Sheffield, excluding the areas within the Peak District Park, whereas the functional connectivity routes for the selected species have been modelled for the whole of the research area. Figure 48 represents the overlaps between the Green Network and the connectivity routes for the selected bird species.

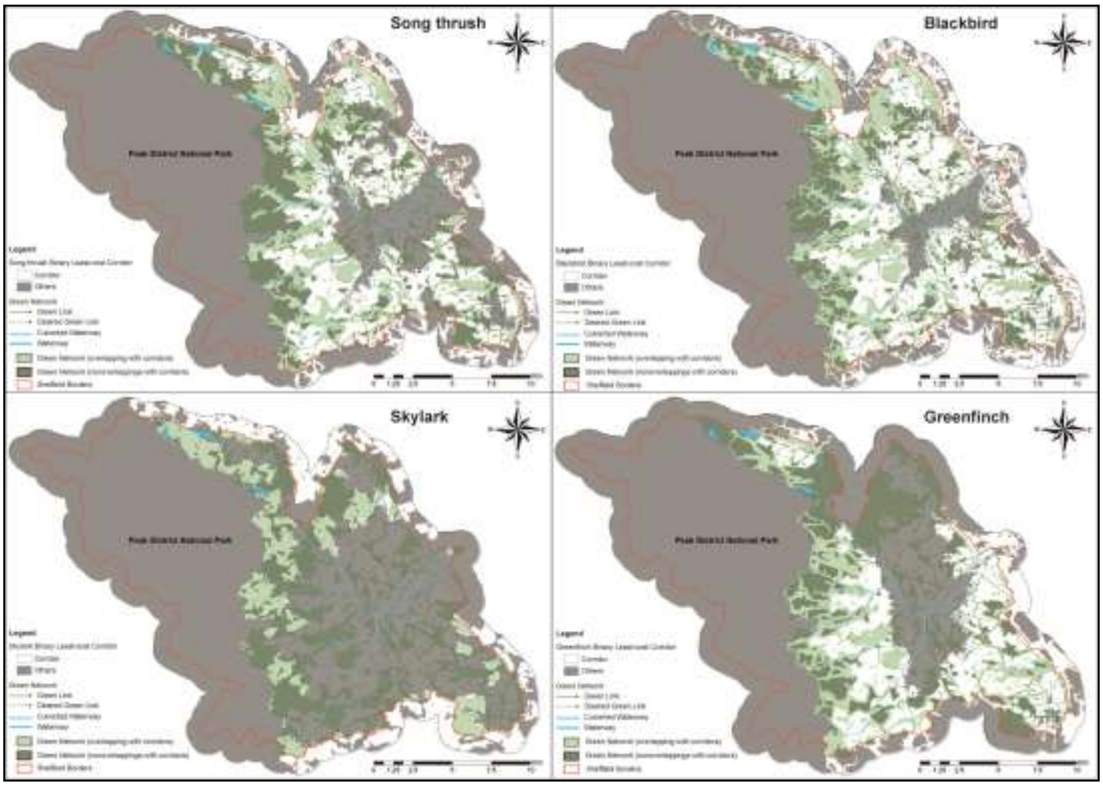


Figure 48: Intersection of the Green Network and functional connectivity routes for birds

In general, we can see that the Green Network provides functional connections for the movement of Song thrushes, Blackbirds and Greenfinches, on the basis of least-cost ecological connectivity models. On the other hand, Skylarks can only benefit from the Green Network where the Green Belt is located. Apart from these areas, the Green Links and Desired Green Links do not support ecological connectivity for Skylarks, since they are concentrated around the central parts of Sheffield. Therefore, the spatial differences between the Green Network and potential connectivity routes for the Skylark can be attributed to their habitat preferences and likely movement characteristics. However, a note of caution is due here since the functional ecological connectivity routes represent the areas of the highest suitability for their movements and in reality the selected bird species can also pass over most of the unsuitable land cover types.

Among all the selected species, the Brown long-eared bat and the Pipistrelle bat seem to gain maximum benefit from the Green Network, since the spatial coincidence between their potential connectivity routes and the Green Network is the greatest, with a complete overlap (Figure 49).

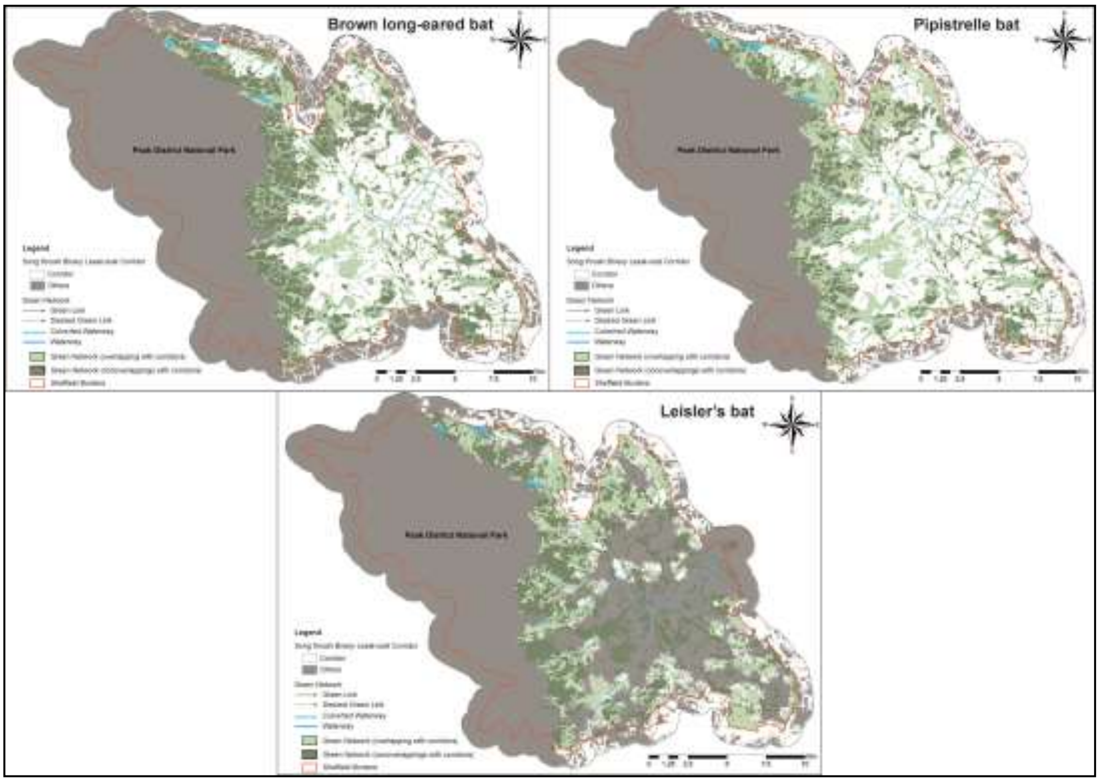


Figure 49: Intersection of the Green Network and functional connectivity for bats

On the other hand, as anticipated from the habitat requirements of Leisler's bats, the spatial intersection between the connectivity routes for these bats and the Green Network is very low. The overlaps are mostly concentrated in the Green Belt, where the Green Network extends towards the wider Countryside area with suitable land cover types for their movements.

Overlaps between the Green Network and the functional connectivity routes for the selected reptile species are shown in Figure 50. In terms of reptile species, the Green Network largely coincides with the potential connectivity routes for Common lizards and Slow-worms, which indicates that the Green Network provides functional connections for the movement of these species. However, as anticipated from the earlier analysis, there are few coincidences between the Green Network and the potential connectivity routes for Grass snakes, based on their habitat requirements and likely dispersal characteristics. As with Leisler's bats, the overlaps for Grass snakes are mainly located within areas of the Green Belt.

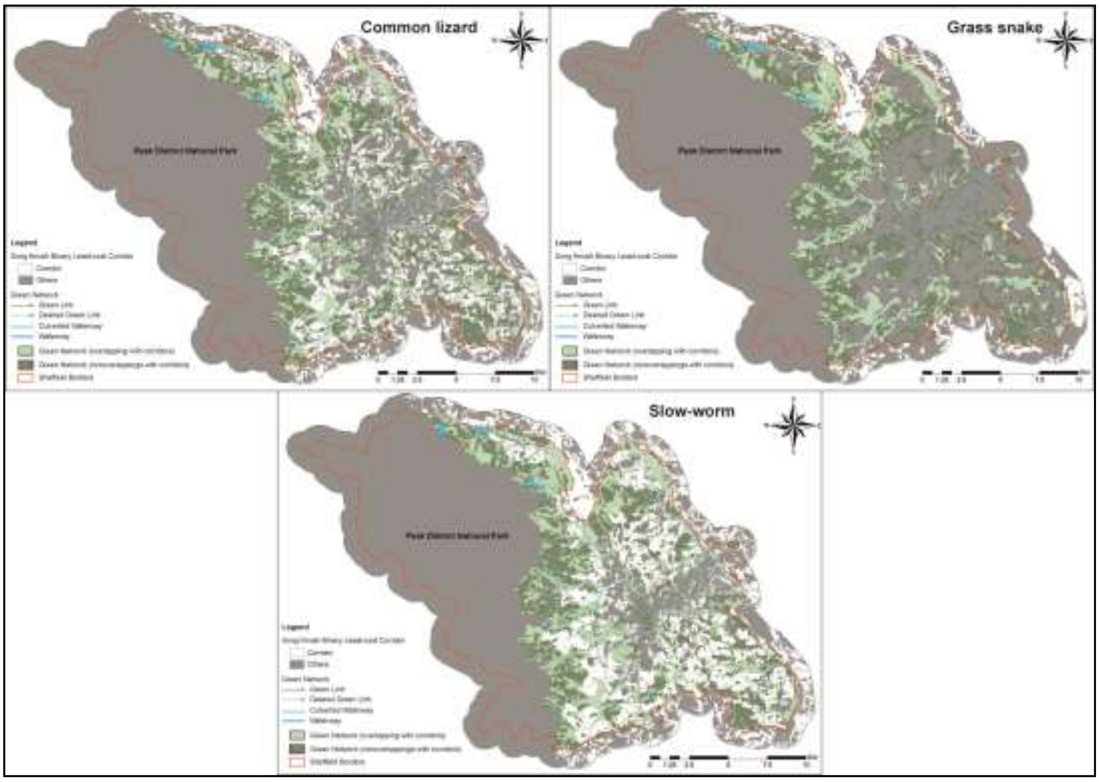


Figure 50: Intersection of the Green Network and functional connectivity routes for reptiles

The spatial comparison of the Green Network with the alternative functional connectivity routes confirms that the Green Network is notionally capable of supporting biodiversity by accommodating a variety of species. However, one of the most important problems relates to its representation, since it is hard to determine which land covers are included in the Green Network. The Sheffield City Council explains the reason behind not having a specific footprint for the Green Links as:

> *"There has been no set width established for a Green Link within Sheffield, to allow each link to be considered on its own merits, and to avoid the concept of a minimum width. The danger with a minimum width is that where a very large valley exists, such as the Loxley Valley, then to set a minimum width of 20 metres, for example, would suggest that open land beyond that 20 metres plays no role in the effectiveness of the network. This would be inaccurate, would potentially devalue the wider valley's worth and would be likely to encourage inappropriate development as a result. To have an indicative line and an open interpretation taking account of circumstances on the ground will ultimately be of more benefit to the value and integrity of the network. (SCC, 2013a)"*

There is logic to not setting a defined footprint for the Green Links (or the whole of Green Network) since a uniform width may not meet the requirements of different species. However, this leaves the question of how each of these Green Links and Desired Green Links would be evaluated spatially in terms of the ecological requirements of different species, since the effectiveness of the Green Network for biodiversity is clearly related to each species' minimum requirements. Further, it is difficult to understand how different land cover types can contribute to, and enhance, the effectiveness of the Green Network without knowing to what extent different land cover types are included as part of the Green Network.

Additionally, Sheffield City Council recognises the importance of *Railway Vegetation*, *Roadside Vegetation* and *Private Gardens* as key parts of the Green Network, because of their capacity to provide important habitat areas for a variety of species. Moreover, comparisons between the alternative connectivity routes for the selected species and the Green Network revealed that there are some Green and Desired Green Links that pass through or connect these land cover types as part of the Green Network. In spite of this, it is difficult to understand their contribution to the Green Network without a spatially explicit representation.

7.3.2.2 Functional Connectivity Routes for People and the Sheffield Green Network

One of the main aims of the Green Network is to encourage and improve the movement of the people in Sheffield through different activities such as walking and cycling. Therefore, in this section I compared the Green Network with the generated alternative routes of connectivity for people. With regard to the movement of people, the Green Network includes actual and proposed routes for walking and cycling as well as other components, such as open spaces (e.g. *Parks and Gardens, Amenity Green Spaces*), cemeteries and playing fields.

The initial step was to intersect all potential connectivity routes for people between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*, *Industrial and Commercial Unit*s, and *Public Buildings,* taking into account the effects of public accessibility and its combination with slope on pedestrian movement (Figure 51). In the resulting two layers, the white areas represent the most suitable areas for walking. These layers were then overlapped with the Green Network dataset for comparison purposes.

Although, both of the layers seem to overlap with the Green Network, there are significant differences in the number of components forming the Green Network and the potential connectivity routes. As seen above in Figure 41, the generated connectivity routes for people are distributed throughout the study area. Within these routes, *Publicly Accessible Green and Open Spaces* are linked to each other with the existing *Paths and Pavements* and *Roadside Vegetation*. On the other hand, with regard to the Green Network, not all the *Paths and Pavements* are included as part of the actual and proposed Walking and Cycling Routes. However, even though *Paths and Pavements* may or may not have green spaces (e.g. street trees, verges) around them, they provide access to *Publicly Accessible Green and Open Spaces*. Therefore, the actual potential for enhancing the accessibility routes is much higher compared to the potential disclosed by the Green Network.

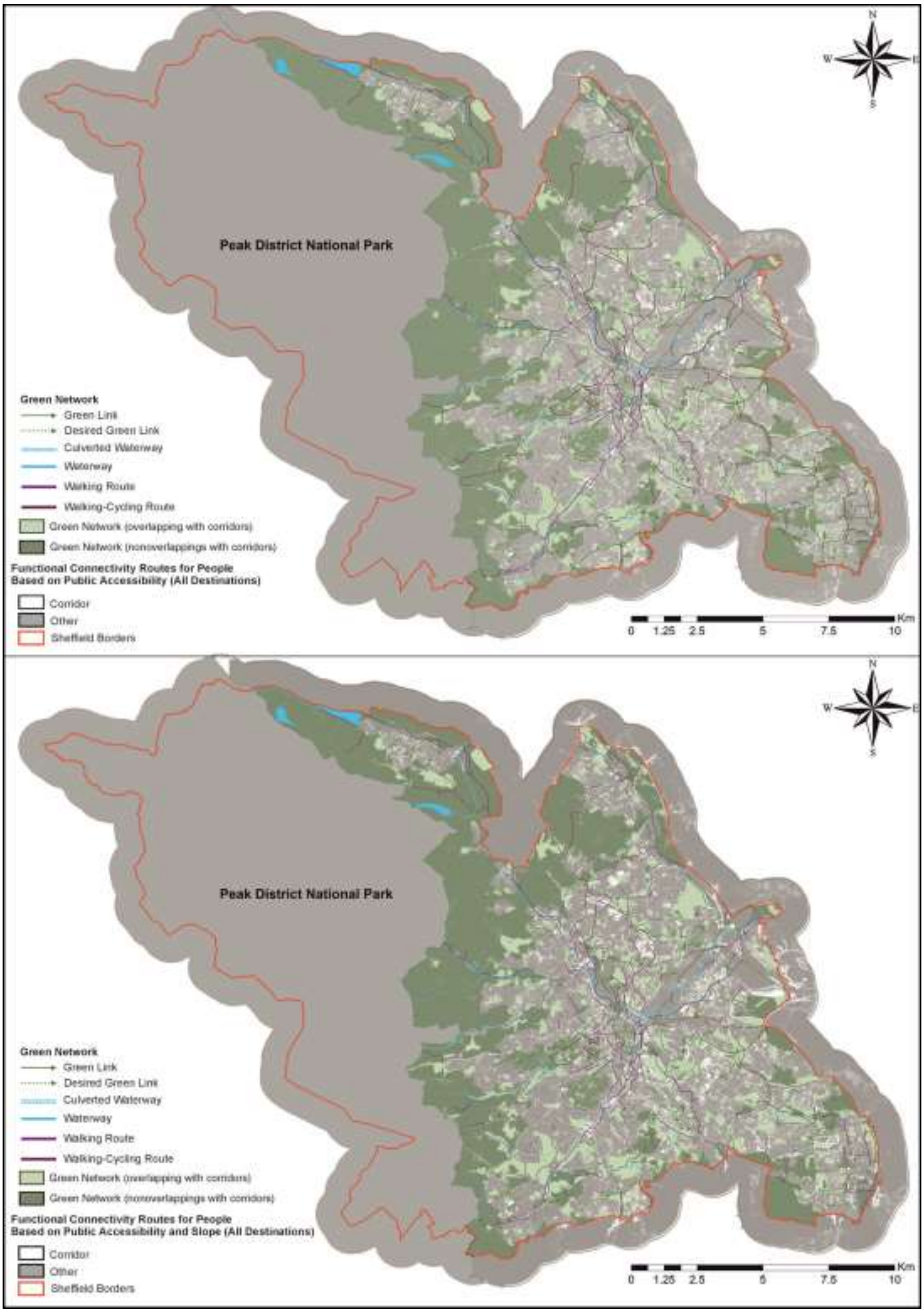


Figure 51: Intersection of the Green Network and functional connectivity routes for people (for all destinations)

Additionally, Figure 52 shows the details of the overlap between the Green Network and the functional connectivity routes for people for all destinations. Whilst the Green Links pass through or connect the *Publicly Accessible Green and Open*

Spaces, there are also Desired Green Links which follow the existing *Paths and Pavements* and connect the Green Links in the lowermost sections of the River Don. Moreover, the actual and proposed Walking and Cycling Routes overlap with some of the *Paths and Pavements* as well as being located alongside the main rivers with the aim of enhancing and supporting public accessibility

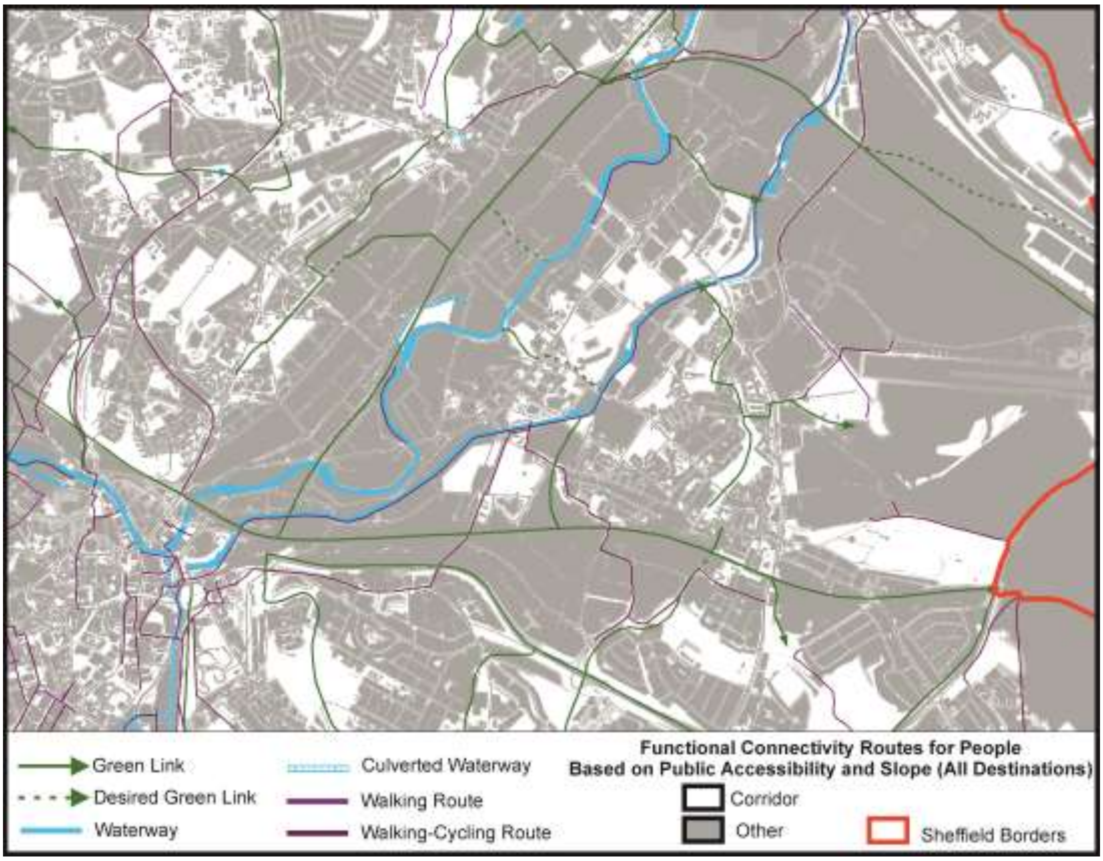


Figure 52: Details of the overlap between the Green Network and the functional connectivity routes for people

7.4 Comparison of the Derived Connectivity Routes with the Living Don

The Living Don is the Sheffield and Rotherham Wildlife Trusts' Living Landscape plan which aims "*to enhance and expand a series of interconnected ecological networks, from the headwaters of the River Don on the Sheffield Moors via the urban centres of Sheffield and Rotherham, as far as Sprotbrough, Doncaster*" (Rivers, 2013b). The Living Don is split up into six Priority Landscape Areas (PLAs), with five of these areas falling inside the boundaries of Sheffield. The PLAs within the boundaries of Sheffield are: Sheffield and Peak District Moors, Western Valleys, River Don, South Sheffield Greenway and Blackburn Valley (see Chapter 4).

7.4.1 Structural Connectivity Routes and the Living Don

7.4.1.1 Structural Connectivity Routes for Biodiversity and the Living Don

In order to compare and contrast structural connectivity routes for biodiversity with the Living Don ecological network, I overlaid them in ArcGIS. In general, the Living Don coincides with all of structural connectivity routes for biodiversity (Figure 53).

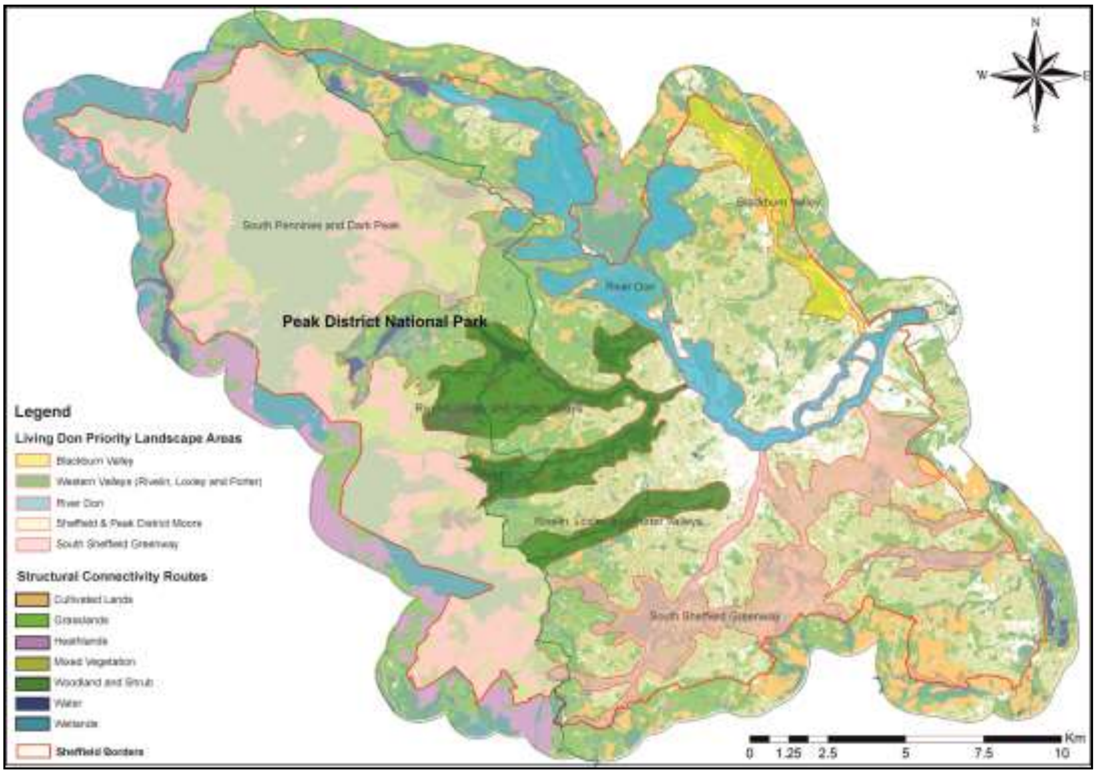


Figure 53: Intersection of the Living Don and structural connectivity routes for biodiversity

In addition, in order to be able to complement my visual assessment of overlays on the PLAs of the Living Don, I measured the degree of physical connectivity for each structural connectivity network. The results of the FRAGSTATS landscape metrics are given below in Table 30. This table summarises the Percentage of Landscape (PLAND %), Area-weighted Mean Radius of Gyration (GYRATE_AM), Area-weighted Mean Euclidean Nearest Neighbour Distance (ENN_AM) and Area-weighted Mean Proximity Index (PROX_AM). These metrics give an indication of the degree of structural connectivity for each land cover type (structural habitat network).

Table 30: The results of the FRAGSTATS landscape metrics for the structural connectivity routes within the PLAs

Sheffield and Peak District Moors PLA	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Wetlands	36.48	2281.94	8.33	6952.32
Water	2.16	307.29	10.01	441.44
Heathlands	32.83	613.51	9.31	31408.85
Woodland and Shrub	11.63	275.30	10.58	12530.32
Grasslands	15.26	297.85	12.00	9883.52
Cultivated Land	0.25	58.07	265.95	21.41
Mixed Vegetation	0.46	112.66	12.68	244.72
Other Land Covers	0.93			

South Sheffield Greenway PLA	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Wetlands	0.02	23.96	7725.58	0.12
Water	0.71	61.22	28.56	34.71
Heathlands	0.37	36.72	150.01	7.07
Woodland and Shrub	28.25	247.46	6.59	3818.68
Grasslands	28.49	165.03	7.51	3056.55
Cultivated Land	2.49	157.69	108.53	249.01
Mixed Vegetation	19.02	79.01	5.08	712.77
Other Land Covers	20.65			

River Don PLA	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Wetlands	0.05	34.43	1151.93	0.57
Water	3.10	246.79	9.87	413.51
Heathlands	1.10	72.48	172.86	20.72
Woodland and Shrub	38.80	361.62	6.76	12451.75
Grasslands	22.35	147.42	11.23	2373.61
Cultivated Land	4.05	101.18	113.05	110.08
Mixed Vegetation	7.33	66.93	8.07	256.95
Other Land Covers	23.22			

Western Valleys PLA	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Wetlands	0.07	37.88	1976.00	0.45
Water	3.45	289.46	7.17	436.28
Heathlands	5.45	232.96	30.86	18084.01
Woodland and Shrub	27.43	260.59	6.31	6312.82
Grasslands	39.32	238.83	6.54	8616.61
Cultivated Land	4.34	87.03	46.25	116.47
Mixed Vegetation	8.87	61.82	7.73	351.43
Other Land Covers	11.07			

Blackburn Valley PLA	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Water	1.04	75.62	95.12	26.30
Heathlands	0.39	45.83	12.87	323.67
Woodland and Shrub	42.65	296.22	5.17	11738.65
Grasslands	19.36	167.92	13.30	420.66
Cultivated Land	2.64	94.77	19.67	138.89
Mixed Vegetation	12.35	82.12	6.09	370.42
Other Land Covers	21.57			

As the largest PLA, the Sheffield and Peak District Moors occupy 11672.47 ha within the boundaries of Sheffield. It is located on the western parts of Sheffield and mainly within the boundaries of the Peak District National Park. The Sheffield and Peak District Moors PLA largely coincides with the structural connectivity networks of *Wetlands* (36.48%) and *Heathlands* (32.83%). In particular, the *Wetlands* network represents very strong physical / structural connectivity within the boundaries of this PLA with the highest GYRATE_AM (2281.94) value and the lowest ENN_AM value (8.33 m). On the other hand, the *Wetlands* network showed a small PROX_AM value (6952.32), which is an indication of weak structural connectivity.

However, this result should be evaluated with caution since it may provide misleading interpretations. As explained by Botequilha-Leitão et al (2006), multiple factors affect the value of the proximity index, such as the area and number of the neighbouring patches. In this regard, I further analysed the mean area and area-weighted mean area as well as the variability in patch size for the *Wetlands* network. Considering that the AREA_AM (2575.88 ha) is more than 50% of its total area (4258.31 ha) with the largest AREA_MN of 25.97 ha, it was obvious that *Wetlands* is composed of one extremely large patch as well as many small sized ones. This interpretation was also confirmed by the highest value of AREA_SD (257.31) and a high value of AREA_CV (990.98). Therefore, the value of PROX_AM is biased by the presence of very small neighbouring patches. Hence, we can safely claim that *Wetlands* has the strongest structural connectivity within the boundaries of the Sheffield and Peak District Moors PLA.

In addition, the Sheffield and Peak District Moors PLA spatially overlaps with other structural networks with strong physical connectivity, such as *Heathlands, Woodland and Shrub*, and *Grasslands*. Therefore, we can suggest that the Sheffield and Peak District Moors PLA is composed of a mosaic of structurally connected land cover types. Consequently, the Sheffield and Peak District Moors PLA has the potential to support biodiversity by including different land cover types as habitats with varying spatial coverage.

The second largest PLA, the South Sheffield Greenway starts from the edges of the Peak District National Park in the west and lies in the southern parts of Sheffield. This PLA covers approximately 3020 ha and mainly coincides with the structural connectivity networks of *Grasslands* (28.49%), *Woodland and Shrub* (28.25%) and *Mixed Vegetation* (19.02%). Among these habitats networks, *Woodland and Shrub* represent the highest structural connectivity with the highest values for PROX_AM (3818.68) and GYRATE_AM (247.46), and a low value for ENN_AM (6.59 m). As expected, *Grasslands* and *Mixed Vegetation* have the second and third highest structural connectivity. There are also overlaps between the network of *Water* features and the South Sheffield Greenway, where most of the *Woodland and Shrub*, and *Grasslands* are clustered around. For example, Meers Brook, Shire Brook and in particular, the River Sheaf play an important role in providing connections from the city centre to the South Sheffield Greenway.

As its name suggests, the River Don PLA is located around the River Don and the Sheffield & Tinsley Canal, covering an area of 2820.6 ha. From the northern parts to the city centre, the River Don PLA mainly intersects with the structural networks of *Woodland and Shrub* (38.80%) and *Grasslands* (22.35%), where the *Running Water* features constitute the backbone of this PLA. Covering an extensive area within the River Don PLA, *Woodland and Shrub* represent the highest structural connectivity with the highest values of GYRATE_AM (361.62) and PROX_AM (12451.75), and the lowest ENN_AM (6.76 m).The *Grasslands* network, on the other hand, has a relatively weaker structural connectivity compared to the *Woodland and Shrub* network (GYRATE_AM=147.42, PROX_AM=2373.61 and ENN_AM=11.23 m). The remaining parts of the River Don PLA largely coincides with the network of *Water* (3.10%) and there are few overlaps with the other structural networks due to the presence of high density *Buildings and Structures* and *Paved Surfaces,* in areas of industrial land use. It is obvious that structurally the River Don PLA provides strong linear connections for biodiversity, especially to the north of the city centre, where the land is rich in different types of *Woodland and Shrub* and *Grassland* patches. However, the structural connectivity of the surrounding areas of the lower River Don and the Sheffield & Tinsley Canal could be further enhanced by improving the existing *Woodland and Shrub*, *Grassland* and *Mixed Vegetation* patches.

The Western Valleys PLA is composed of three parallel networks that provide connections between the Sheffield and Peak District Moors PLA and the South Sheffield Greenway and the River Don PLAs. It covers an area of 2711.21 ha. The

River Loxley, the River Rivelin, the Porter Brook and their valleys form the main routes within the Western Valleys PLA. Therefore, it overlaps with the network of *Water* features (both running and standing water) by occupying 3.45% of the total area of the Western Valleys PLA. Also, this PLA includes *Grasslands* (39.32%), *Woodland and Shrub* (27.43%), *Mixed Vegetation* (8.87%), *Heathlands* (5.45%) and *Cultivated Land* (4.34%). On the other hand, remaining land cover types within this PLA cover only 11.07%. The *Heathlands* network reported the highest value for PROX_AM (18084.01). However, when its spatial coverage was considered together with a high value of ENN_AM and relatively low value for GYRATE_AM, we can safely claim that its structural connectivity is weaker than the networks of *Woodland and Shrub* and *Grasslands.*

Finally, as the smallest PLA, Blackburn Valley (689.47 ha) is located in the northeast of Sheffield around Blackburn Brook. It largely coincides with the networks of *Woodlands and Shrub* (42.65%), *Grasslands* (19.36%) and *Mixed Vegetation* (12.35%). Even though this PLA occupies a very small area compared to the others, it includes a variety of land cover types. As expected, *Woodlands and Shrub* represent the highest structural connectivity compared to the other habitat networks.

I then measured the degree of connectivity for the structural connectivity routes (habitat networks) in the areas that lie outside of the Living Don ecological network. As can be seen in Table 31, almost half of the areas that lie outside the Living Don ecological network are composed of other land cover types, where there is no vegetation, wetland or water features.

Table 31: The results of the FRAGSTATS landscape metrics for the structural connectivity routes that lie outside of the Living Don ecological network

Outside of the Living Don Ecological Network				
	PLAND	**GYRATE_AM**	**ENN_AM**	**PROX_AM**
Wetlands	3.51	902.78	902.78	19514.42
Water	0.76	270.85	35.19	364.05
Heathlands	4.38	416.57	42.55	20617.24
Woodland and Shrub	7.08	247.04	17.24	3124.01
Grasslands	19.33	256.38	8.50	11865.73
Cultivated Land	5.29	184.55	24.15	4701.42
Mixed Vegetation	11.24	85.40	5.20	1230.69
Other Land Covers	48.41			

When comparing the habitat networks of *Wetlands* and *Heathlands* (the most connected networks) within the PLAs of the Living Don ecological network and areas that lie outside the Living Don, it is clear that their spatial coverage in the Sheffield and Peak District Moors PLA is the highest. Additionally, the degree of connectivity for these habitat networks is the strongest in the Sheffield and Peak District Moors PLA compared to the networks outside the Living Don. However, the connectivity of these networks is relatively low in the other PLAs, since they are the rarest habitat types in those PLAs. On the other hand, the coverage of the *Woodlands and Shrub* network is the highest in all PLAs with a higher structural connectivity than the areas outside the Living Don ecological network.

Except for the Sheffield and Peak District Moors PLA, the coverage of the *Grasslands* network is higher in all PLAs than the areas that lie outside the Living Don. However, it is clear that the coverage of the *Grasslands* network in the areas that lie outside the Living Don is the highest amongst all habitat networks with the highest structural connectivity. Also, further visual examination of the *Grasslands* network together with the land use map revealed that most of these areas are composed of *Improved Grassland* and used for agricultural purposes. Hence, this might be a reason for SRWT to exclude these areas from the Living Don ecological network. Likewise, the percentage of the *Cultivated Land* network and its structural connectivity is the highest in the areas that lie outside the Living Don ecological network. Conversely, the percentage of the *Mixed Vegetation* network is the highest in the areas that lie outside the Living Don except for the South Sheffield Greenway PLA. However, upon examination, its structural connectivity is the highest outside the Living Don ecological network compared to all the PLAs. Finally, the *Water* features network has the largest coverage in all the PLAs except for the South Sheffield Greenway PLA. Also, apart from the South Sheffield Greenway and Blackburn Valley PLAs, the *Water* features network has the strongest structural connectivity compared to the outside of the Living Don ecological network.

It is also important to note that some habitat networks did not report strong structural connectivity in all PLAs. However, that does not necessarily mean that the degree of connectivity is weak but may mean that these habitats are rare (or even not present) in a particular PLA. For example, as emphasised previously in Chapter 4, the *Water* features, valleys and their surrounding areas have a vital role in forming the whole Living Don ecological network. Even though the network of *Water* features has poor structural connectivity, we cannot ignore its importance in providing habitat areas for a variety of species as well as supporting movement by linking important habitat areas for biodiversity. Moreover, the valleys and areas surrounding *Water* features are generally rich in different land cover types. Consequently, taking into account the physical connectivity of each structural network within the boundaries of the Living Don ecological network, it is likely that the Living Don has a high potential to contribute to the ecological connectivity for biodiversity.

7.4.1.2 Structural Connectivity Routes for People and the Living Don

The Living Don ecological network plan that I was able to access does not have a clear representation of the areas that can be used by people for different purposes, such as recreation and movement. Therefore, I compared the Living Don plan with the derived structural networks for people on the assumption that people can benefit from the whole Living Don area. It is also useful to remember that the structural connectivity networks for people were developed on the basis of the physical connections of different types of *Natural and Semi-natural Land* uses, without considering their actual accessibility. Additionally, I took into account *Paths and Pavements* as part of the potential routes of connectivity for people because of their important role in providing main movement routes for pedestrians.

Figure 54 shows the intersections of the Living Don and the *Recreation and Leisure* and the *Mixed Vegetation* structural networks. Similar to the structural connectivity analysis for biodiversity in the previous section, I analysed the degree of connectivity for the *Recreation and Leisure*, and the *Mixed Vegetation* networks within all PLAs and also for areas that lie outside the Living Don ecological network. The results of landscape metrics for the *Recreation and Leisure* network are given in Table 32.

Among the spatial components of the *Recreation and Leisure* structural network, *Countryside / Urban Fringe* is totally included within the boundaries of the Peak District National Park. Thus, the whole of the *Countryside / Urban Fringe* overlaps with the Sheffield and Peak District Moors PLA. Additionally, 81.18% of the Sheffield and Peak District Moors PLA is composed of the *Recreation and Leisure* network. When examining the results of the landscape metrics as a measure of the structural connectivity, it is obvious that the Sheffield and Peak District Moors PLA reported the strongest connectivity for the *Recreation and Leisure* network over all the other PLAs. This suggests that the Sheffield and Peak District Moors PLA has a high potential to support a network for people.

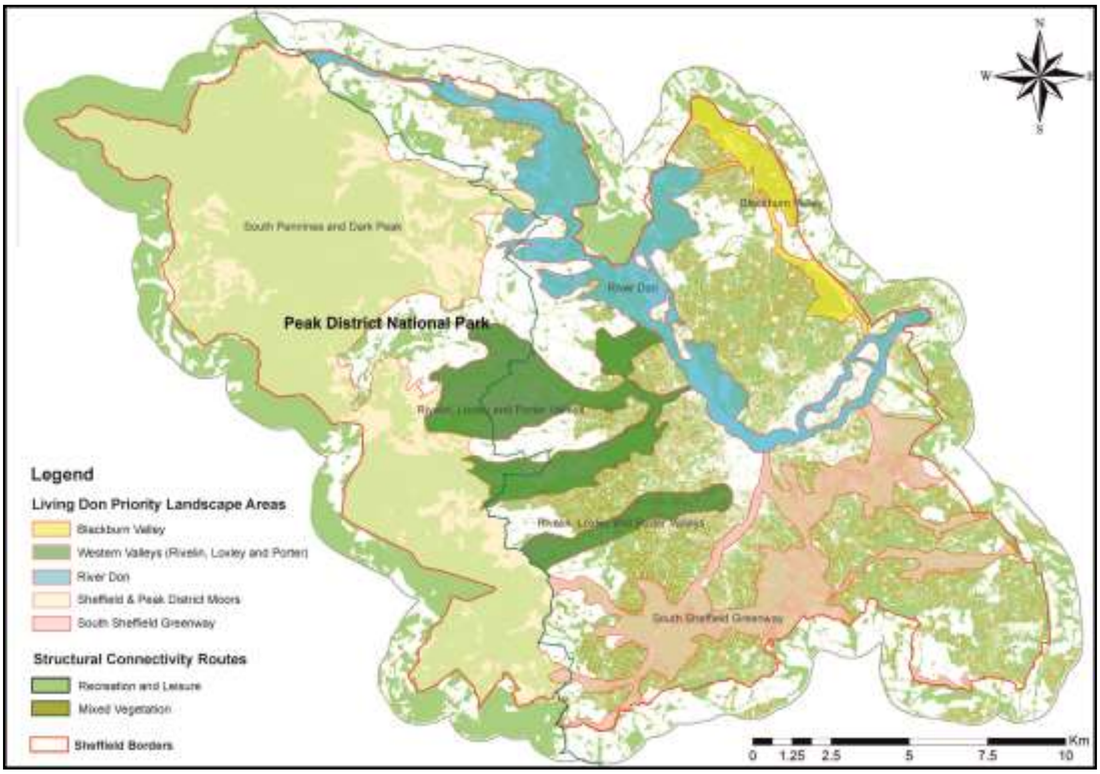


Figure 54: Intersection of the Living Don and structural connectivity routes for people

Table 32: The results of the FRAGSTATS landscape metrics for the *Recreation and Leisure* structural networks within the PLAs

	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Sheffield and Peak District Moors PLA				
Recreation and Leisure	81.18	2385.13	4.35	162018.77
South Sheffield Greenway PLA				
Recreation and Leisure	59.30	328.36	4.22	11906.62
River Don PLA				
Recreation and Leisure	48.38	340.95	5.58	12485.36
Western Valley PLA				
Recreation and Leisure	42.20	308.69	5.00	13543.83
Blackburn Valley PLA				
Recreation and Leisure	63.10	370.17	4.17	9370.78
Outside of the Living Don				
Recreation and Leisure	27.69	566.43	5.51	39368.06

The other four PLAs within the urban part of Sheffield coincide with the *Recreation and Leisure* network, but some areas in this network may not be publicly accessible, such as *Allotments* and *Natural and Semi-natural Greenspaces*. In terms of structural connectivity of the *Recreation and Leisure* network, the Sheffield and Peak District Moors PLA is the strongest, followed by the Western Valleys PLA, River Don PLA and the South Sheffield Greenway PLA. On the other hand, even though the coverage of the *Recreation and Leisure* network in the Blackburn Valley is the second highest, it does not provide as stronger physical connections as the other PLAs.

Finally, when compared to the areas which lie outside the Living Don and within its PLAs, it is obvious that the Living Don covers a large proportion of the whole *Recreation and Leisure* network i.e. 59.39 %. Therefore, we can safely claim that all PLAs in the Living Don ecological network can provide a structurally connected *Recreational and Leisure* network for people. Despite the fact that some of these areas may not be publicly accessible, their visual and amenity value for people cannot be ignored.

The results of landscape metrics for the *Mixed Vegetation* network are given in Table 33.

Table 33: The results of the FRAGSTATS landscape metrics for the *Mixed Vegetation* structural network within the PLAs

	PLAND	GYRATE_AM	ENN_AM	PROX_AM
Sheffield and Peak District Moors PLA				
Mixed Vegetation	0.48	118.02	411.43	11.79
South Sheffield Greenway PLA				
Mixed Vegetation	20.82	131.57	4.94	1936.77
River Don PLA				
Mixed Vegetation	7.64	76.30	6.72	556.83
Western Valley PLA				
Mixed Vegetation	9.59	71.38	5.50	650.00
Blackburn Valley PLA				
Mixed Vegetation	12.71	104.68	5.60	604.10
Outside of the Living Don				
Mixed Vegetation	14.63	104.80	5.10	2598.97

The Living Don covers only 19.55% of the *Mixed Vegetation* network. The structural connectivity of the *Mixed Vegetation* seems to be the strongest with the highest value for PROX_AM (2598.97) and a low value for ENN_AM (5.10 m) in the areas which lie outside the Living Don. The proportion of this network is 14.63% in the areas that lie outside the Living Don, which corresponds to 80.45% of the whole *Mixed Vegetation* network. On the other hand, amongst all the PLAs the South Sheffield Greenway PLA reported the highest structural connectivity for the *Mixed Vegetation* network. Apart from this, all other PLAs reported quite low structural connectivity for the *Mixed Vegetation* network. This network also includes some publicly inaccessible areas, such as *Private Gardens* and *Railway Vegetation*. However, based on their visual and amenity value for people, these areas should be included as part of the networks for people to support their well-being.

7.4.2 Functional Connectivity Routes and the Living Don

7.4.2.1 Functional Connectivity Routes for Biodiversity and the Living Don

The Sheffield and Rotherham Wildlife Trust aims "to restore the Living Don network to a functioning ecological network of wildlife-rich habitats and green infrastructure, using the river and canal corridors as the backbone, to maximise its potential for biodiversity and people" (Rivers, 2013a). Delivering biodiversity therefore benefits is considered as one of the major objectives of the Living Don. However the definition of ecological connectivity routes requires the consideration of the habitat quality and ecological requirements of species to deliver biodiversity functions (Baguette et al., 2013). To understand how well the Living Don ecological network actually functions as habitats for a diversity of organisms, I compared and contrasted the spatial extent and components of the Living Don ecological network and the least-cost binary corridor maps for selected species.

The spatial extent of the Living Don ecological network (56.83% of Sheffield) is larger than all the individual corridors for all the selected species. The Living Don is well distributed all over Sheffield and, as mentioned in the previous section, includes a variety of land cover types. Figure 55 shows the overlaps between the Living Don network and the least-cost binary corridors for bird species.

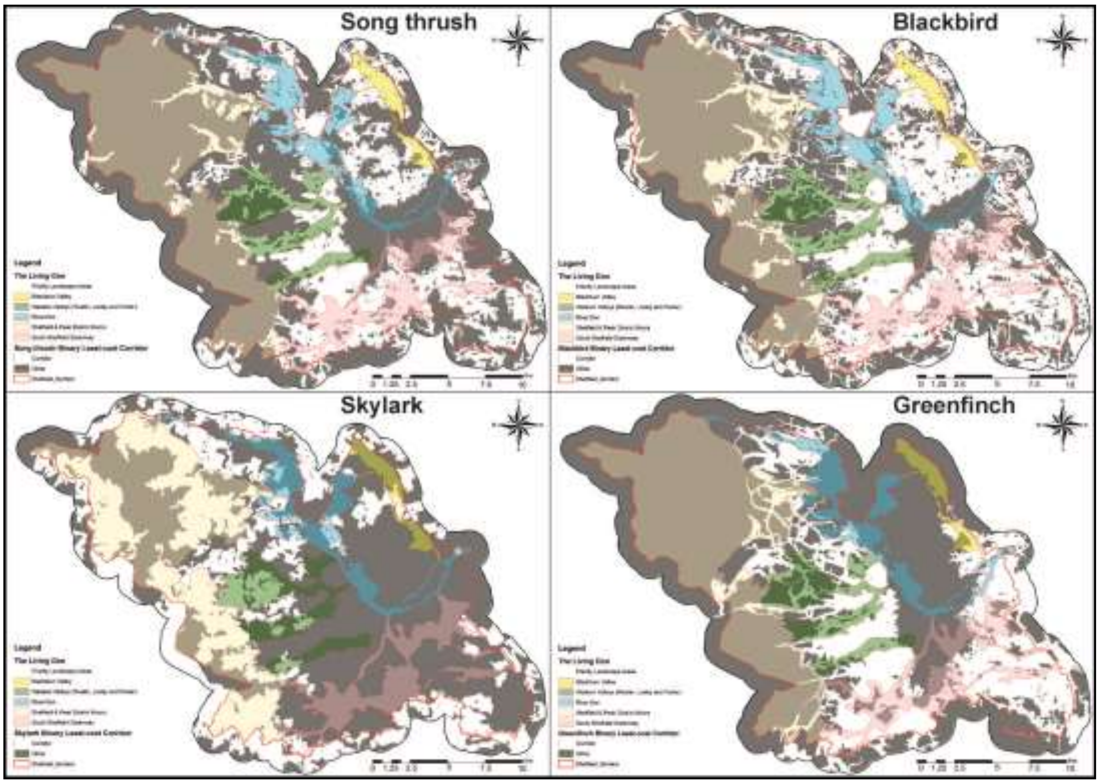


Figure 55: Intersection of the Living Don and functional connectivity routes for birds

Table 34 shows the proportion of each functional connectivity route for the selected species within all the individual PLAs as well as inside and outside of the Living Don ecological network.

The spatial coverage of functional networks for birds ranges from 31.23% to 45.18% within the whole Living Don ecological network and therefore seems to support the ecological connectivity for all bird species according to their habitat preferences and movement behaviours. For example, whilst the Sheffield and Peak District Moors PLA supports the movement of Skylarks by meeting their ecological requirements with the highest 35.53% spatial coverage, the remaining PLAs provide only weak ecological connections for these.

On the contrary, all of the PLAs, excluding most areas in the Sheffield and Peak District Moors, provide stronger functional connections for Song thrushes, Blackbirds and Greenfinches.

Table 34: The proportion of the least-cost corridors for the selected species within and outside of the PLAs

	Sheffield and Dark Peak Moors (%)	South Sheffield Greenway (%)	River Don (%)	Western Valleys (%)	Blackburn Valley (%)	Inside of Living Don (%)	Outside of Living Don (%)
BIRDS							
Song thrush	6.77	11.73	10.02	9.05	3.15	40.71	59.29
Blackbird	9.35	9.80	8.65	7.66	2.53	38.00	62.00
Skylark	35.53	1.08	3.21	4.95	0.41	45.18	54.82
Greenfinch	6.87	10.59	3.72	9.22	0.83	31.23	68.77
BATS							
Brown Long-eared Bat	7.03	10.30	8.57	6.41	2.35	34.66	65.34
Pipistrelle Bat	9.18	9.01	8.58	7.04	2.21	36.02	63.98
Leisler's Bat	29.45	6.61	7.16	6.02	2.36	51.59	48.41
REPTILES							
Common lizard	25.87	7.55	6.76	7.03	2.11	49.32	50.68
Grass snake	44.35	4.70	5.92	5.95	1.61	62.52	37.48
Slow-worm	23.39	7.43	6.39	6.50	1.97	45.68	54.32

The Blackburn PLA provides lower degrees of ecological connectivity for all the selected bird species. However, Song thrushes, Blackbirds and Greenfinches may benefit from the South Sheffield Greenway and Western Valleys PLAs. In addition, as can be seen in Figure 44, the lower parts of the River Don PLA do not seem to provide functional connections for the selected bird species.

Overall, we may claim that the Living Don ecological network has the potential of supporting ecological connectivity for all the selected bird species. However, as the proportion of functional connectivity routes outside the Living Don ecological network for the selected bird species are high, ranging from 54.82% to 68.77%, this may impact the Living Don ecological network to achieve its potential.

When visually examined with due consideration to the habitat preferences of the selected bird species, it was found that these areas are mainly located in the urban periphery and dominated by *Mixed Vegetation* (*Private Gardens, Roadside Vegetation* and *Railway Vegetation*). Based on this, special emphasis should be put on enhancing connectivity in these areas, particularly for Song thrushes, Blackbirds and Greenfinches.

With regard to bats, we can say that all the selected bat species can benefit from the Living Don ecological network as a whole. As with the bird species, the functioning of individual PLAs differs for different bat species (Figure 56).

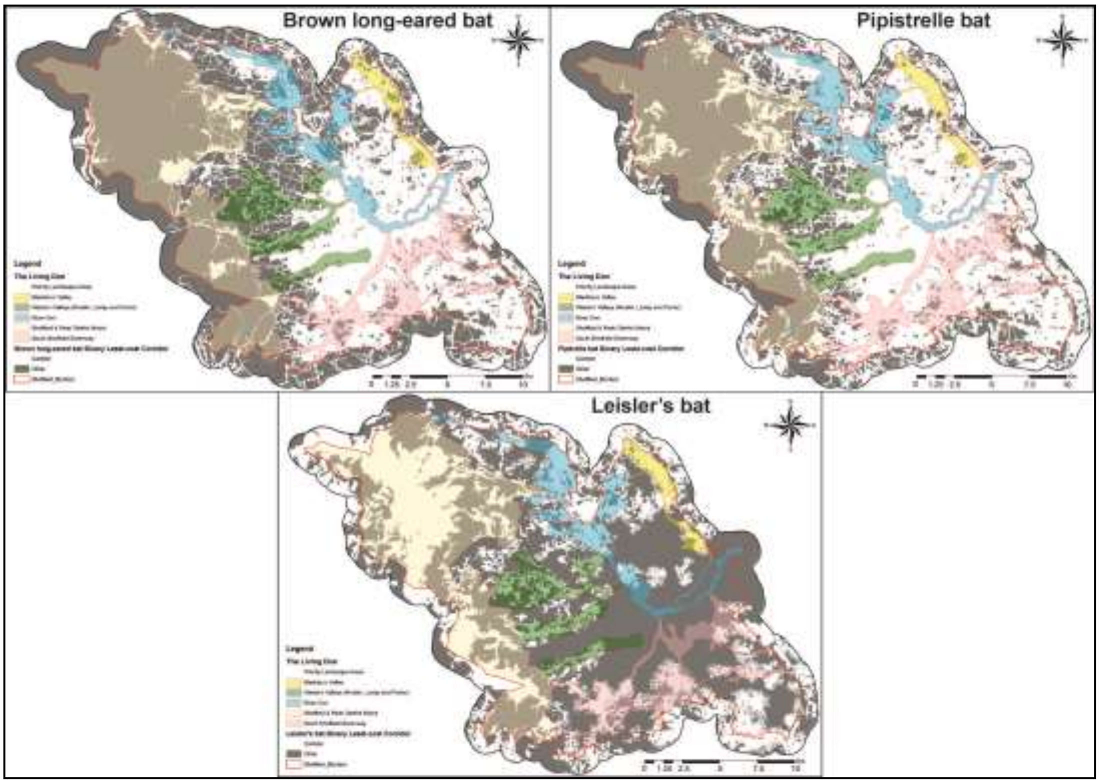


Figure 56: Intersection of the Living Don and functional connectivity routes for bats

Whilst the potential ecological connectivity routes for Brown long-eared bats and Pipistrelle bats almost completely coincide with the River Don, the Western Valleys, the South Sheffield Greenway and the Blackburn Valley PLAs, there are only some overlaps with the Sheffield and Peak District Moors PLA. Whilst the Blackburn Valley and the River Don PLAs cover an area of 689.47 ha and 2820.60 ha, respectively, the coverage of the functional connectivity routes for Pipistrelle bats in these PLAs are 616.93 ha and 2395.69 ha (89.48% and 84.94% overlap). Similarly, the overlap between the Western Valleys and the potential ecological connectivity routes for Pipistrelle bats is 72.50%. In addition to these, the coverage of the potential ecological connectivity routes for Brown long-eared bats is very similar to Pipistrelle bats. Therefore, as anticipated from the visuals, the potential of the Blackburn Valley, River Don and Western Valleys PLAs to support ecological connectivity for Pipistrelle bats and Brown long-eared bats is the highest amongst all the PLAs. However, when the percentage of each species' functional connectivity routes in these PLAs examined in Table 32, it is obvious that they include more or less the same amount of land for the connectivity routes of Pipistrelle and Brown long-eared bats.

As seen in Figure 56, Leisler's bats may benefit from the Sheffield and Peak District Moors PLA. While the percentage of the ecological connectivity routes for Leisler’s bats is the highest in the Sheffield and Dark Peak Moors PLA (29.45%) of all the PLAs within the Living Don, the overlap between the ecological connectivity routes for Leisler’s bats and the Sheffield and Peak District Moors PLA is quite high (52.12%). On the other hand, most of the potential connectivity routes for Leisler's bats coincide with all the other PLAs, apart from the lower River Don and the upper South Sheffield Greenway PLAs.

Finally, when I examining the spatial coverage of functional connectivity routes outside the Living Don ecological network for the selected bat species (Table 32), we can see that most of the functional connectivity routes for Brown long-eared and Pipistrelle bats lie outside of the Living Don (65.34% and 63.98% respectively). These results largely depend on the use of *Buildings and Structures* as habitats for these bats. However, it is also important to emphasise the contribution of *Mixed Vegetation* around the *Buildings and Structures* to support ecological connectivity for these bats. Hence, similar to bird species SWRT should consider the patches of *Mixed Vegetation* as part of the Living Don ecological network.

As expected, the coverage of the functional connectivity routes for all reptile species is the highest in the Sheffield and Peak District Moors amongst all the PLAs of the Living Don ecological network (see Table 32). Particularly, 44.35% of the whole ecological connectivity routes for Grass snakes lie inside the Sheffield and Dark Peak Moors PLA, where the dominant land cover is composed of *Wetlands* and *Heathlands*. Also, Grass snakes may effectively use the Western Valleys and the Blackburn PLAs, where the functional connectivity routes for these species cover more than half of these PLAs (see Figure 57).

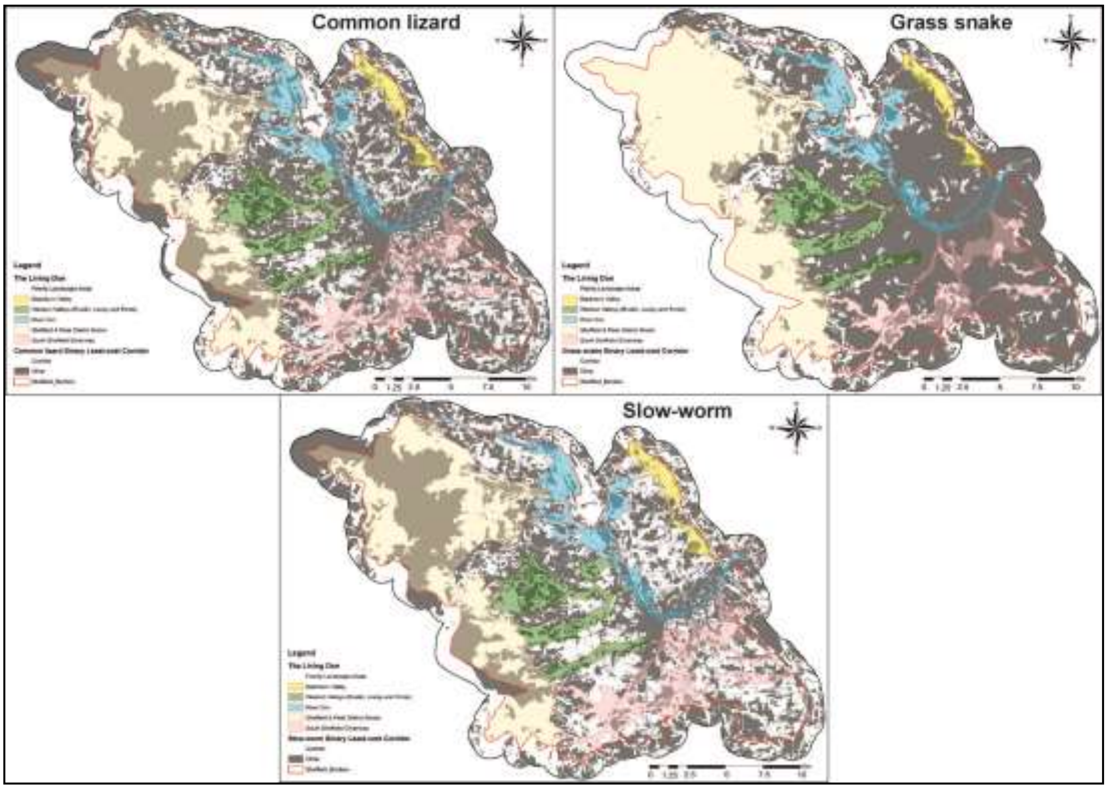


Figure 57: Intersection of the Living Don and functional connectivity routes for reptiles

It is also obvious that Common lizards and Slow-worms utilise the whole of the Living Don ecological network, since their ecological connectivity routes largely coincide with the Living Don. On the other hand, the lower River Don PLA does not provide functional connections for Common lizards and Slow-worms. However, whilst the Sheffield and Peak District Moors PLA supports these two species, the areas covered with *Wetlands* form breaks in the ecological connectivity routes.

The proportion of functional connectivity routes for the selected reptile species outside the Living Don ecological network is the lowest off all the selected species, in particular for Grass snakes (37.48%). Hence, we can claim that the whole Living Don has a high potential to support the ecological connectivity for the selected reptile species.

In general, there is an important amount of congruency between the Sheffield and Rotherham Wildlife Trust's approach, the Living Don, and the least-cost corridors for the selected species. On the assumption that the least-cost corridors reflect the actual ecological connectivity routes for the selected species, then we can suggest that the Living Don has a capacity to accommodate a variety of species with different ecological requirements. Currently, the Living Don is composed of five PLAs within the boundaries of Sheffield and each of these PLAs have the potential for supporting biodiversity by including a variety of land cover types as habitats for species. However, based on the least-cost corridors, there are some additional areas where we have functional connectivity routes for species and these areas can be integrated into the Living Don ecological network. Obviously, this will be highly dependent on which species we wish to accommodate within the Living Don network.

Most importantly, the areas where the ecological connectivity routes intersect with each other for most of the species can be used to enhance connections for the Living Don ecological network. In this context, it may be useful to consider *Roadside Vegetation*, *Railway Vegetation* and *Private Gardens* as part of the Living Don ecological network. As can be seen in Figure 58a, there is a large amount of land covered by *Private Gardens* and *Roadside Vegetation* between the River Don and the Blackburn Valley PLAs, which constitutes ecological connectivity routes for Song thrushes, Blackbirds, Brown long-eared bats, Pipistrelle bats, Common lizards and Slow-worms. Figure 58 explicitly shows the potential areas for the improvement of ecological connectivity for the aforementioned species as it represents the intersection of their least-cost corridors.

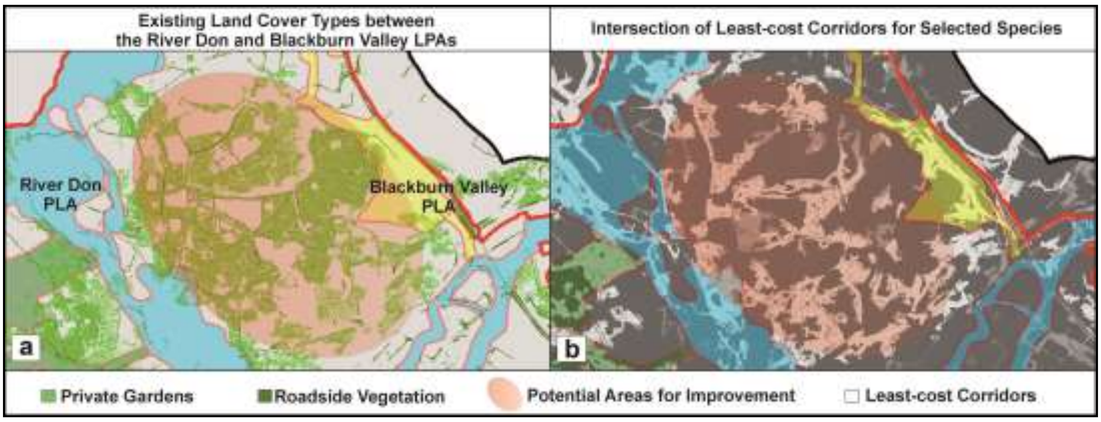


Figure 58: Details of the intersection of least-cost corridors for all selected species and Living Don-1

Another potential area to increase ecological connectivity for these species is located between the Western Valleys and Sheffield and Peak District Moors PLAs. As in the previous example, Figure 59 shows that this area is dominated by *Private Gardens* and *Roadside Vegetation*. Hence, by incorporating these land cover types into the network approach, the Living Don could increase the potential to enhance and improve the ecological connections for the identified species. Regarding *Roadside*

Vegetation, the Sheffield and Rotherham Wildlife Trust have recognised its value as part of a wider network approach - since the interviewee has indicated that they were "planning to cooperate with AMEY" (a commercial company responsible for the management of the roadside verges, trees and shrubs in Sheffield for the next 25 years).

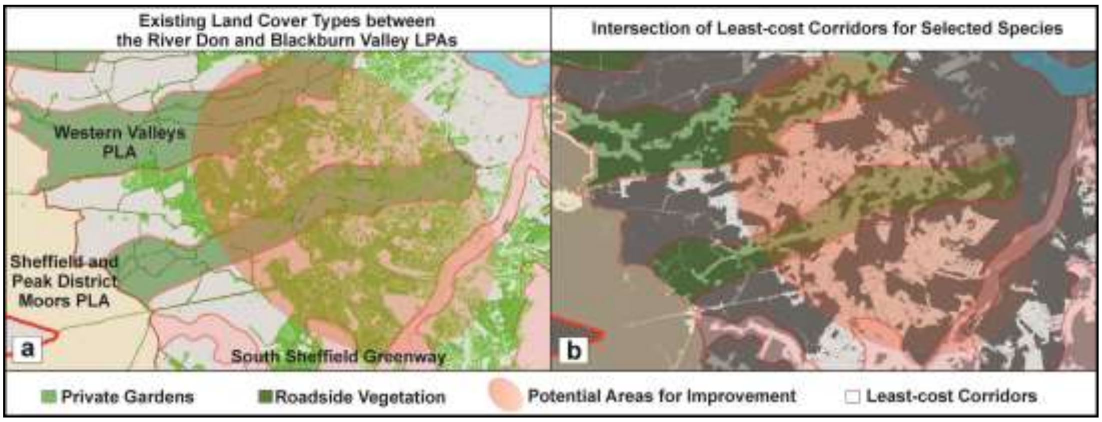


Figure 59: Details of the intersection of least-cost corridors for all selected species and the Living Don-2

Figure 60 shows the details of the intersection of least-cost corridors for all the selected species and the Living Don in the lowermost sections of the River Don PLA. The white areas represent the overlap of connectivity routes for the selected species, whilst the grey areas indicate no functional connectivity routes. The presence of water courses and their surrounding habitats are vital for the Living Don ecological network in terms of connectivity, as they naturally provide linear connections. In this regard, the River Don PLA plays a crucial role for the whole of the Living Don ecological network. However, the lower part of the River Don PLA is perhaps the exact opposite, since most species cannot benefit from these areas.

This may be due in part to the ecological requirements and movement behaviours of the selected species. However, it does also seem likely that the landscape matrix restricts movement in this region. Correspondingly, it is important to analyse the opportunities to enhance ecological connectivity for a variety of species by focusing on the potential for habitat creation in this area.

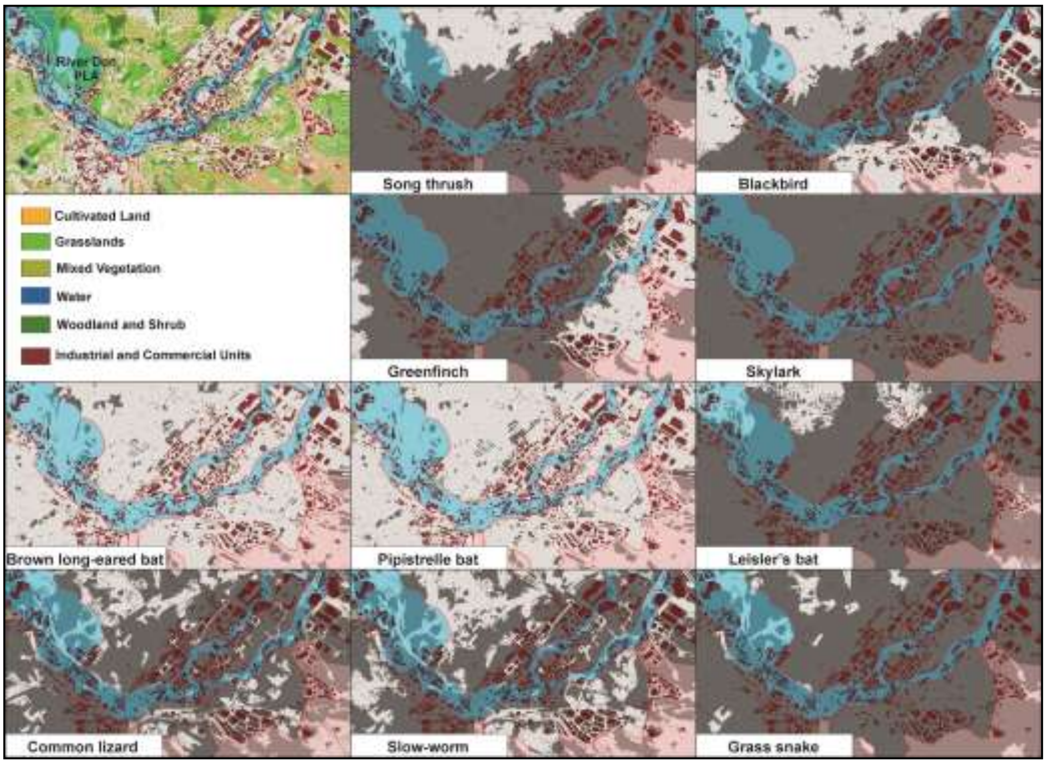


Figure 60: Details of the intersection of least-cost corridors for all selected species and the Living Don-3

7.4.2.2 Functional Connectivity Routes for People and the Living Don

The Living Don ecological network aims to engage people across green and open spaces throughout the network. However, the digital map of the Living Don that I received did not illustrate the areas that are used by people and therefore it was difficult to evaluate which parts of the Living Don have been allocated for pedestrian movement. The comparisons are, therefore, based on the assumption that the overlaps between the least-cost corridors and the Living Don network represent walking routes for people.

The main aim in identifying alternative least-cost corridors for people was modelling functionally connected networks of green and open spaces for the public in an urban environment, which would contribute to their movement across these spaces and the surrounding landscape. In this regard, three main routes were identified between *Residential Buildings* and *Publicly Accessible Green and Open Spaces*, *Residential Buildings* and *Industrial and Commercial Units*, and *Residential Buildings* and *Public Buildings*. For the delineation of each of these alternative routes, the effects of public accessibility and its combination with slope on pedestrian movement have been modelled. As a result, I obtained six alternative connectivity routes for people.

In order to compare and contrast the alternative connectivity routes for people with the Living Don ecological network, I firstly intersected the least-cost corridors for each route, based on public accessibility. Then I intersected the remaining three least-cost corridors, taking into consideration the effects of public accessibility and slope. In this way, two wider alternative connectivity routes for people were generated (see Figure 61). As mentioned previously, because the functional connectivity routes for people do not include the areas within the boundaries of the Peak District National Park, these areas are excluded from the comparisons.

Figure 61, represents the intersections between the Living Don and functional connectivity routes for people, where white areas represent all connectivity routes for people and the light grey areas represent the areas that are not covered by corridors. As a whole, these areas illustrate the potential movement routes for people from their homes to the different destinations mentioned above. To some extent, the Living Don network coincides with these connectivity routes for people where we have quite large green and open spaces. However, similar to the connectivity routes for species, there are potential areas to support and enhance the connectivity for people in between the PLAs. In addition to visual assessment of overlays, I also calculated the proportion of the alternative connectivity routes for people in ArcGIS, which are given in Table 35.

The South Sheffield Greenway PLA includes the highest percentage of intersection with all of the functional connectivity routes for people based on both the effects of public accessibility and its combination with slope on pedestrian movement. Also, when compared to its total area, the proportion of the all functional networks for people is the highest within the South Sheffield Greenway PLA. On the other hand, the intersection between the Blackburn Valley PLA and all the functional connectivity routes for people is the lowest in all the PLAs of the Living Don. However, when considering the total area of the Blackburn Valley PLA, it was found that the proportion of each functional network within this PLA was the second highest amongst the remaining PLAs (with more than 30%).

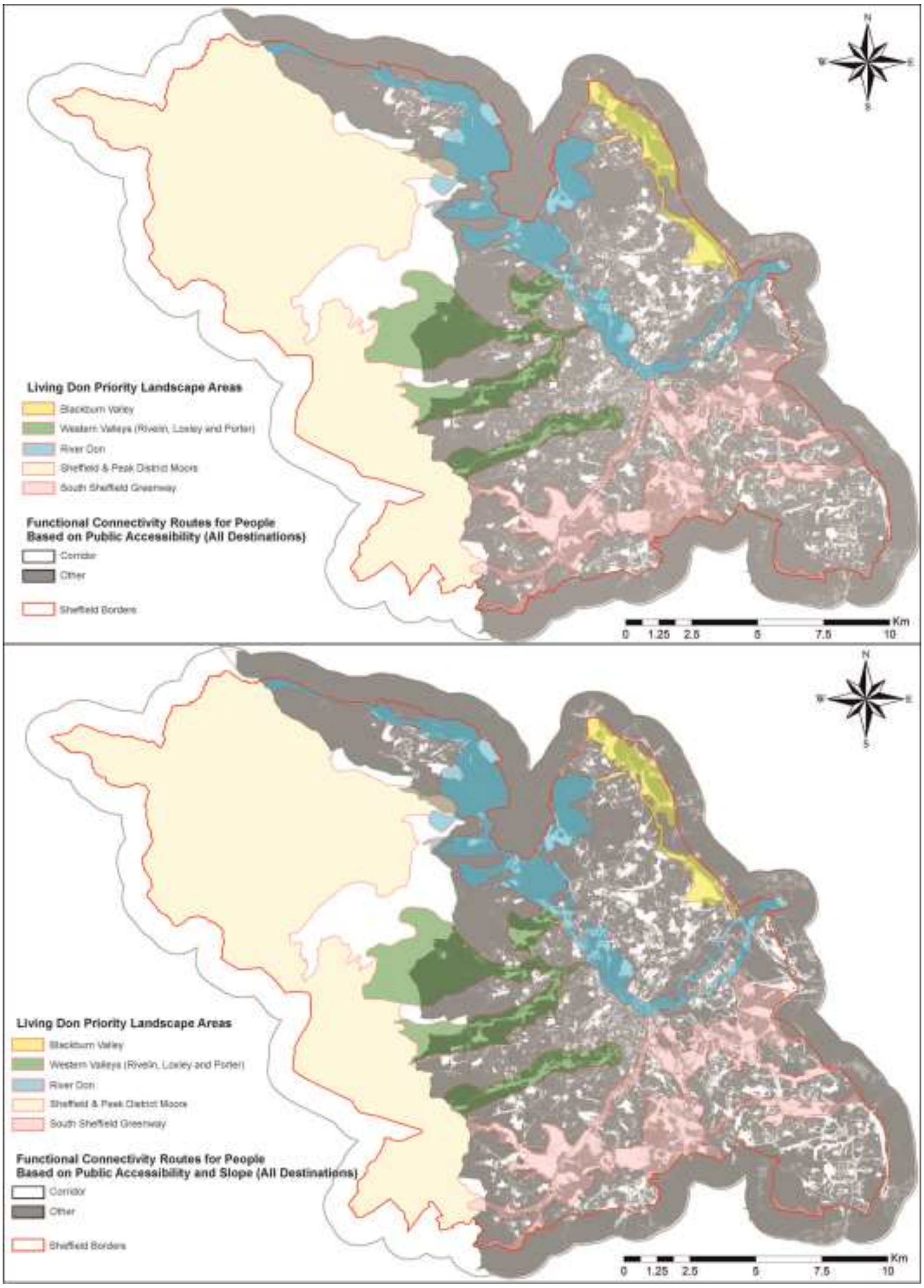


Figure 61: Intersection of functional connectivity routes for people and the Living Don

Table 35: The proportion of the least-cost corridors for people within and outside of the PLAs

	South Sheffield Greenway (%)	River Don (%)	Western Valleys (%)	Blackburn Valley (%)	Inside of Living Don (%)	Outside of Living Don (%)
Public Accessibility						
Between Residential Buildings and Publicly Accessible Green and Open Spaces	22.46	8.24	8.36	4.32	43.39	56.61
Between Residential Buildings and Public Buildings	22.12	7.50	7.89	3.98	41.49	58.51
Between Residential Buildings and Industrial and Commercial Units	23.19	7.81	7.37	4.21	42.58	57.42
Public Accessibility and Slope						
Between Residential Buildings and Publicly Accessible Green and Open Spaces	23.18	8.21	7.63	4.44	43.46	56.54
Between Residential Buildings and Public Buildings	21.14	7.75	6.83	4.17	39.88	60.12
Between Residential Buildings and Industrial and Commercial Units	21.48	7.64	6.46	4.32	39.90	60.10

The proportion of the functional networks for people within the River Don and the Western Valleys PLAs are similar to each other, with relatively high values. Based on these figures, we may suggest that these PLAs are better in providing connectivity to the public compared to the Blackburn Valley PLA.

Finally, the proportion of the functional connectivity routes which lie outside the whole Living Don, indicate that more than half of these routes are not included in the Living Don ecological network. In spite of this, there are some areas where SRWT have opportunity to support and enhance the connectivity for people. Figure 62 represents the details of overlap between all potential connectivity routes for people and the Living Don.

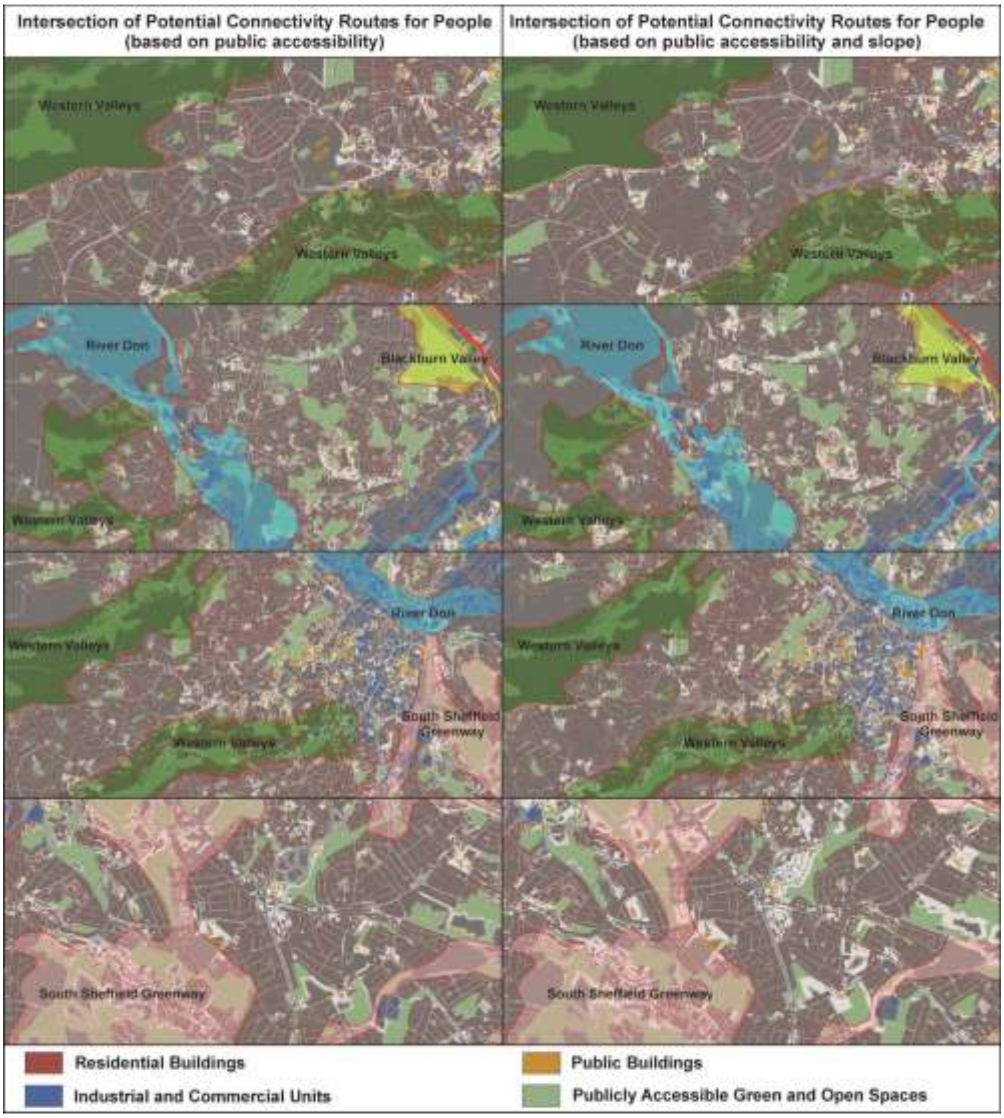


Figure 62: Details of the Intersection of Functional Connectivity Routes for People and the Living Don

The potential connectivity routes for people shown in in the first column are based on public accessibility, whereas the second column represents the same routes based on public accessibility and slope combined. In this figure, while all potential connectivity routes for people are shown in white, grey areas represent those that are not covered by connectivity routes. Additionally, *Publicly Accessible Green and Open Spaces* are shown in light green to make them distinguishable. There are some *Publicly Accessible Green and Open Spaces* which are not included in the Living Don ecological network. Hence, it would be good practice to include *Publicly Accessible Green and Open Spaces* in between the individual PLAs in order to help the Living Don ecological network to engage people with the network and deliver public benefits. Such an approach would be particularly useful to connect upper parts of the River Don and Blackburn PLAs, and Western Valleys and lower parts of the

River Don PLAs, where there are large *Publicly Accessible Green and Open Spaces*. As with the species' connectivity routes, we can clearly see the significant contribution of *Roadside Vegetation* in the potential connectivity for people. In this context, if we intend to maximise the use of the Living Don by people, the connections in between the PLAs can be improved by integrating all *Publicly Accessible Green and Open Spaces*, *Paths and Pavements* and *Roadside Vegetation* into the Living Don network.

7.5 General Discussions and Conclusions

This chapter has concentrated on comparing and contrasting the derived alternative routes of connectivity both for biodiversity and people with each other, and also with actual green and ecological network approaches in Sheffield, by analysing the relationships between their structural properties. I attempted to determine:

- if there are spatial coincidences between the derived connectivity routes for biodiversity and people, and the Green Network and the Living Don ecological network,
- the potential of the landscape matrix to support the potential connectivity routes for biodiversity and people with consideration being given to improving connectivity in urban landscapes, and
- the compatibility of different land cover / use types with the potential routes of connectivity for biodiversity and people, taking into account space limitations in urban landscapes.

Broadly speaking, the derived routes of connectivity and the actual green and ecological network approaches appear to have both differences and similarities in their spatial extents and components. Here I discuss the general conclusions that can be drawn from these comparisons.

7.5.1 Structural Connectivity versus Functional Connectivity

The generated connectivity routes for biodiversity differ from each other based to a large extent on how the connectivity is identified and used to derive the alternative routes. Initially, for the identification and selection of the components of the alternative connectivity routes, high structural connectivity was taken as the main criterion. The resulting structural connectivity routes were composed of the sub-categories of the broad land cover types without reference to the ecological requirements of particular species.

Alternatively, the functional connectivity routes were developed on the basis of the ecological requirements of 10 selected local species. Here, it is quite important to remember that each species was selected for the purpose of reflecting differences and similarities in their habitat requirements. Accordingly, and as expected (Ricketts, 2001; Verbeylen et al., 2003), the resulting ecological connectivity routes were quite different from each other in terms of their spatial components, patterns and extents, depending on the chosen species' ecological requirements and their likely dispersal characteristics across the landscape.

The comparisons of the structural and functional connectivity routes confirmed that the aggregation of a set of physically connected land cover types may provide functional connections for some species. For example, the structural *Wetlands* network represented the highest structural connectivity and provides functional connections for Grass snakes and Leisler's bats in the western part of the study area, however, the majority of the selected species did not benefit from this network. These results seem to be consistent with other research which found that some species may benefit from the physical connectedness of habitat patches (Tewksbury et al., 2002; Varkonyi et al., 2003 in Taylor et al., 2006). From this point of view, these results suggest that structural connectivity may enhance functional connectivity for some species or species groups (Fagan and Calabrese, 2006; Taylor et al., 2006)

On the other hand, some small and physically disconnected land cover patches within some land cover types may serve as functionally connected routes for the movement of some species, such as the key role of *Roadside Vegetation* in providing functional connections for the movement of Blackbirds, Greenfinches, Brown Long-eared bats, Pipistrelle bats, Common lizards and Slow-worms. These results are in agreement with Taylor et al. (2006) who claim that “habitat does not necessarily need to be structurally connected to be functionally connected”. In this regard, in order to maximise the effectiveness of networks for the benefit of biodiversity and wildlife, we should keep in mind that ecological connectivity is a species dependent concept

(Merriam, 1984; Taylor et al., 1993; Lindenmayer and Fisher, 2006; Watts et al., 2008).

Similarly, alternative connectivity routes for people were developed on the basis of structural and functional connectivity. For the delineation of structural connectivity routes, I only took into account the different types of green and open space falling within *Natural and Semi-natural Land* uses as the components of the networks. The primary concern of these networks was determining the areas of highest physical connectivity which would support accessibility to the public as well as providing visual and amenity values to people. *Paths and Pavements* were not considered as the components of the potential connectivity routes since they do not include any vegetation cover. Moreover, even though *Private Gardens, Railway Vegetation,* and some parts of *Amenity Greenspaces, Natural and Semi-natural Greenspaces* and *Allotments* are publicly inaccessible, they were still considered as part of the connectivity routes.

In the case of functional connectivity routes for people, the main objective was to develop the networks of potential accessibility, where people can actually walk between the different destinations. Hence, the components of these networks were composed of land uses that are completely accessible to the public.

The most obvious difference to emerge from the comparisons of structural and functional connectivity routes for people was the spatial extent of the networks. Furthermore, the components of these networks were quite different from each other, since they were defined on the basis of different expectations. For example, the structural connectivity network of *Mixed Vegetation* was composed of *Railway Vegetation*, *Roadside Vegetation* and *Private Gardens*, in which the only publicly accessible component was *Roadside Vegetation*. On the other hand, all components of the functional connectivity routes are physically / legally accessible to the public. Moreover, even though the spatial patterns of functional connectivity routes were different from each other, the functional connections in between different destinations are largely provided by *Paths and Pavements* and *Roadside Vegetation*. This result may be explained by the criterion to derive strucutral and functional connectivity routes for people.

Overall, the results of comparisons between structural and functional connectivity routes for both biodiversity and people demonstrate that the landscape structural analysis can be really useful to understand (1) the availability of existing land cover / use types, (2) their spatial characteristics and, (3) the relationships between different landscape types (Botequilha-Leitão et al., 2006; Wiens, 2006). However, if we intend to provide functional connections for the movement of biodiversity and people, we should initially decide on which ecological and social functions we expect from networks. Then, based on these functions (such as providing habitats for particular species, supporting and enhance the movement of species, improving walking routes for people), we should integrate the specific requirements of the selected species and / or people into the network development process of, in order to optimise their effectiveness. Otherwise, the use of structural connectivity as the main criteria for the delineation of potential connectivity routes can lead to inappropriate planning decisions and land management strategies in an urban landscape, where the land is quite valuable as there is a high demand for different land uses (Taylor et al., 2006).

7.5.2 Deriving Multifunctional Connectivity Routes

The most obvious finding to emerge from structural and functional connectivity analyses is that the potential connectivity routes should be defined taking into consideration the ecological requirements of the associated species or species groups to deliver biodiversity benefits (Fagan and Calabrese, 2006; Opdam et al., 2006).

In addition to this, the comparisons of different functional connectivity routes for the selected species confirmed that the spatial extent, components and pattern of connectivity routes depend on the ecological requirements and movement behaviours of species that we take into consideration. Overall, as with the species' connectivity routes, we can safely say that the spatial extent, pattern and components of the potential connectivity routes for people may be refined by the functions we are looking for (such as providing walking routes for those people with high and low mobility, connectivity routes between residential buildings and workplaces or commercial areas).

With regard to species networks, the overall results of the comparisons of functional connectivity routes corroborate the ideas of Beier and Noss (1998), who suggested that "what constitutes a suitable corridor varies among species". Hence, when planning and designing functional connectivity routes for biodiversity, we should decide which species and / or species groups that we intend to support and define the areas of multiple benefits for the biodiversity.

As mentioned earlier, researchers generally select and use one or a small number of species as surrogates in connectivity conservation and planning studies (Lambeck 1997; Caro and O'Doherty, 1999). The use of surrogate species can help researchers to reduce the efforts of addressing the ecological requirements of many individual species in a landscape (Wiens et al, 2008). In this regard, various surrogate species approaches have been proposed, such as focal, indicator and umbrella species. However, it is necessary to be aware that the selection of surrogate species is challenging and there is no consensus on which species requirements should be the network building process for the benefit of biodiversity (Margules and Pressey, 2000; Watts et al., 2010).

Boitani et al. (2007) mention the increasing use of focal and indicator species in the ecological network planning approach as surrogate species with the hope that species will benefit from the same network. Indicator species have been selected both for their rapid and sensitive responses to environmental changes and as being representatives for diversity of other species (Landres et al., 1988). Focal species, on the other hand, (Lambeck, 1997) are selected from a group of species which are intended to represent and meet the requirements of other species. However, much of the current literature on the selection of target species criticises the usefulness of focal and indicator species to meet the requirements of biodiversity (Lindenmayer et al., 1998; Margules and Pressey, 2000; Lindenmayer and Fischer, 2002; Boitani et al., 2007). The most important criticism of much of the literature on the use of indicator / focal species is that (1) to what extent the presence of individual species or species groups can indicate the presence of other taxa and (2) to what extent the ecological requirements of different species can be considered as the surrogacy of the overall biodiversity (Lindenmayer et al., 2002; Boitani et al., 2007).

Whilst the selection of species remains as an unsolved problem, it is widely accepted that the definition of ecological connectivity routes should be based on a multi-species approach (Sanderson et al., 2002; Opdam et al., 2006; Cushman et al., 2013).

In this regard, Baguette et al. (2013) suggest an alternative approach to design of ecological networks that seeks to maximise the benefits to as many species as possible. For the planning of ecological networks, they recommend the selection and use of umbrella species “which are considered to be representative of the ecosystem in which they live”. In broad terms, their approach includes the identification of different ecosystems within landscapes and the associated species for each ecosystem, mapping habitats for each species, delineating individual linkages for each of the species in the group and finally overlapping all of these individual networks to derive an ecological network for all selected species. On the other hand, Baguette et al. (2013) also draw attention to the possible spatial conflicts among individual network areas for some species as the result of the overlapping process (such as a decrease in the individual network area for some species). In such cases, they recommend to analyse the conservation status and ecological requirements of species on a case specific approach. Overall, this approach seems to be promising for maximising the benefits of ecological connectivity routes to as many species as possible.

As with the aforementioned approach, Beier et al. (2006 and 2008a) suggest a simple union process of all individual least-cost networks, in which all pixels included in one or more single-species corridor are covered by the resulting corridor for all species under consideration. However, Beier et al. (2006) also mention that the resulting corridor may be larger than what is actually required to support all selected species. Beier et al. (2008a) recommend a further step to prevent such a problem for the implementation of the network. For this purpose, they removed corridor areas for individual species in the resulting corridor (where there is no overlap for individuals networks) and enlarged multi-species networks to include each of the species-specific habitat patches Beier et al. (2008a).

Moreover, Singleton et al. (2002) used a similar approach to overlap single species networks. According to their approach, all single species networks were overlapped using the median value for each landscape parameter from the species specific least-cost models (e.g. cost values, dispersal distances) and species specific habitat data. However, this approach has been criticised by Beier et al. (2008b) as it may generate a network in which some (or all) of the single species networks may disappear, as a result of changing the species specific parameters.

Collectively, the methodological approaches used in abovementioned studies outline a critical role for overlapping individual species networks to derive a multi-species network which is capable of maximising the benefits to as many species as possible. Here it is important to note that, these approaches can be adapted to functional connectivity routes for people in order to delineate a comprehensive network, in which different destinations are connected to each other. However, these researchers have not provide a detailed information on how much coincidence may provide multiple functions within the resulting network or the criteria for judging whether the match between networks is good or not for the selected species. Hence, it is obvious that the delineation of a multi-functional network will require a further consideration of how much coincidence may provide multiple functions both for species and people.

Finally, it is crucial to emphasise that the validation of derived multifunctional networks for species and people may be the most important step in planning and designing networks. At this stage, solving such an issue is well beyond the scope of this research. However, it is useful to emphasise that the establishment of multifunctional connectivity routes on to the ground is a long-term planning strategy, and requires a large amount of investment (Beier et al., 2008b; Lawton et al., 2010; Cushman et al., 2013). Watts et al. (2010) suggest that the validation of species networks can be based on empirical / biological data, but also remind the potential issues related to the availability of sufficient data and possible land use / cover changes in the landscape during validation. On the other hand, with regard to networks for people, the validation can be achieved through interviews, surveys, and observations (Weldon et al., 2007).

7.5.3 Alternative Connectivity Routes and Actual Green and Ecological Networks

Both the Green Network and the Living Don approaches mainly aim to enhance connectivity in Sheffield for the benefit of biodiversity and people. There are similarities in the spatial components of actual network approaches, particularly in the areas of large natural and semi-natural lands, main rivers and their valleys. This was an expected outcome, since these areas were regarded as the backbone of the Green Network and the Living Don ecological network (see Chapter 4).

Regarding the comparisons of the spatial extents of these approaches, it was difficult to draw clear inference from the Green Network map, as it is shown as a conceptual plan, and there is no indication of the width or actual footprint of the Green and Desired Green Links. The Sheffield City Council has taken such a decision deliberatively to provide flexibility for site by site judgements. In one sense this decision seems to be broadly consistent with earlier scientific evidence, which recommends determining different corridor widths for different species' movement, instead of using fixed corridor widths (Beier and Loe 1992; Beier et al., 2008b; Brodie et al., 2014).

Moreover, regarding the representation of the Green Network in the SLP, the interviewee from SCC mentioned that "*…the original maps they were far better defined. They showed up. I think there was a dilution really of the strength of the policies...*". Accordingly the interviewee added that "*…if you have not got something clearly defined it makes it far more difficult to argue in planning that you are actually taking part of a green link...*". As seen, the interviewee highlighted the possibility that the representation of the Green Network on the Proposals Map would be detrimental to its functioning. Hence, the Green Network should be clearly identified to prevent the risk of subjective judgements and misleading planning decisions. On the other hand, the spatial extent and components of the Living Don ecological network are clearly defined and provides functional connections for both biodiversity and people (see Chapter 4).

The comparisons revealed that there are significant differences in the structural components and spatial extents of the derived and actual green and ecological network approaches based on how they are defined. Broadly, the comparisons between actual green and ecological networks and derived structural connectivity routes confirmed that the Green Network and the Living Don are composed of a variety of land cover and use types. This was simply interpreted as being capable of accommodating all species and supporting their ecological requirements as well as being able to provide visual / amenity values and accessibility to people.

In terms of the ecological connectivity and use by the public, I focused on the results of the comparisons with the functional connectivity routes, as I believe they are more reliable compared with structural connectivity routes. Both the Green Network and Living Don have spatial coincidences with the routes of connectivity for most of the selected species (7 out of 10 species). Although selection criteria for the components of the actual networks were mainly based on habitat availability and quality, without an explicit reference to particular species, these results confirmed that both the Green Network and Living Don approaches seem to support at least one species from the selected groups of birds, bats and reptiles.

The Sheffield and Peak District Moors Priority Landscape Area, as part of the Living Don, also supports the ecological connectivity for three species (Skylarks, Leisler's bats and Grass snakes). Furthermore, the Green Network has some spatial coincidences with the potential connectivity routes for these species. In spite of this, the connectivity routes for these species are largely located within the boundaries of the Peak District National Park and the extent of the Green Network is limited by the boundaries of Sheffield Local Planning Authority. Therefore, we can only claim that the Green Network seems to support ecological connectivity for these species by supporting the connections into the Peak District National Park.

On the other hand, both the Green Network and Living Don include the areas around the lower River Don as part of their network approaches. These areas are heavily dominated by industrial activities, and so largely covered by buildings, other structures and hard surfaces. When compared with the potential connectivity routes for all species, it seems that only Brown long-eared bats and Pipistrelle bats can fully benefit from these areas. Therefore, the potential of the lower River Don area should be examined carefully in the light of the requirements of different species. Based on the derived functional connectivity routes and the actual structure of this area, we suggest that street and wall plantings and green roofs could be considered as a means of enhancing ecological connectivity.

Planning is a long term process, so I may also suggest that habitat creation should be part of the future planning strategy for the lower parts of River Don (e.g. by specifying wider building setbacks along the river, or minimum tree planting requirements). It is obvious that these areas are largely covered by *Industrial Buildings* and surrounding *Sealed Surfaces*, and so it would be unrealistic to remove some or all of these areas for habitat creation. However, as emphasised by Lawton et al. (2010) one approach to habitat creation can be to soften boundaries between existing habitats and other land uses and allow a more gradual transition. Hence, in the case of the lower River Don, this approach can be realised in practice by creating green roofs, green walls as well as enhancing existing *Roadside Vegetation* along *Paths and Pavements*.

Finally, it is important to note that the functional connectivity analyses for the selected species revealed that the land cover types of *Private Gardens* and *Roadside Vegetation* have quite a high potential to support ecological connectivity for a variety of species. Accordingly, both the Sheffield City Council and Sheffield and Rotherham Wildlife Trust have recognised and appreciate the value and importance of such areas to support and enhance ecological connectivity in a wider landscape context. Broadly speaking, these land covers have not been incorporated in their network approaches. However, as indicated by Ahern (1995), the integration of networks of connectivity into planning practice can be achieved through considering the land ownership, political / managerial trends and limitations. One of the most important ways of changing the land management of privately owned areas is stakeholder engagement (Lawton et al., 2010; Durham et al., 2014).

Similarly, both the Green Network and the Living Don aim to involve people with nature and encourage the movement of people by providing accessibility. This aim was reflected in the Proposals Map for the Green Network by representing the actual and proposed walking and cycling routes. However, the map I obtained from SRWT for Living Don ecological network, does not illustrate the particular areas for the movement of people within the network.

The Green Network almost completely overlaps with the derived connectivity routes for people, where we have public footpaths and *Publicly Accessible Green and Open Spaces.* Apart from these examples, the extent of the derived connectivity routes for people is greater than the Green Network, as they include all *Paths and Pavements*, and *Roadside Vegetation* as the key elements of the walking routes for people. Hence, the number of structural components of the alternative connectivity routes for people is somewhat greater than the Green Network and distributed across the urban part of Sheffield.

On the other hand, as stated previously, the digital map of Living Don ecological network that I have obtained from SRWT does not illustrate particular areas from which people can benefit. On the assumption that the map I obtained from SRWT for the Living Don ecological network includes the overlaps with the areas of *Publicly Accessible Green and Open Spaces, Paths and Pavements* and *Roadside Vegetation* for the use of people, then we can claim that it provides public accessibility to people to some extent. However, the Living Don ecological network may enhance the public accessibility by incorporating highlighted opportunity areas, based on the delineated potential connectivity routes, into their actual network plans. These opportunity areas include large *Publicly Accessible Green and Open Spaces*, and generally located between upper parts of the River Don and Blackburn PLAs, and between the lower parts of River Don and Western Valleys PLAs (see section 7.4.2).

In urban areas, one of the most important challenges in the green and ecological network planning processes is to take into account the connectivity related issues holistically due to the requirement of a large amount of data. In this regard, the delineated models have a great potential to address such a challenge for SCC and SWRT. Also, SCC and SWRT can add different economic, social and environmental parameters into the development of their network approaches to make more effective and informed planning decisions based on the methodological approaches that I used.

Also, the results of this research suggest that the landscape matrix can also be a habitat in its own right. For example, the habitat patches and ecological connectivity routes of Grass snakes and Skylarks are located in and around the Peak District National Park, where the dominant land covers are *Heathlands*, *Wetlands* and *Unimproved Grasslands*. By contrast, Greenfinches and Song thrushes mainly benefit from the ecological connections provided by the patches of *Mixed Vegetation*, *Woodlands* and *Shrubs*. Similarly, if we intend to develop the potential connectivity routes for people, from which they may benefit visually and physically (e.g. whilst walking, or cycling), then the spatial extent and arrangement of the network would change by including additional land uses, such as publicly inaccessible green and open spaces, water features and cycling routes.

Based on the outcomes of structural and functional connectivity routes, we can safely claim that the wider landscape matrix in Sheffield has a high structural diversity with a variety of different land cover and use types. Hence, we can claim that Sheffield has a high potential to support a variety of species as well as providing various benefits to the public.

Overall, from the perspective of defining connectivity routes in an urban landscape, these comparisons also suggest that the spatial extent and components of green and ecological networks depend on:

- the functions that we want to provide (ecological connectivity or public accessibility),
- which species we want to provide / increase ecological connectivity for,
- which group of people we aim to increase public accessibility for (highly mobile people and / or people with restricted mobility),
- destinations that we want to connect for the use of people, and
- the different methodological approaches that we use to define connectivity routes.

Chapter 8 Conclusions

8.1 Introduction

As one of the most important landscapes functions, the maintenance and enhancement of landscape connectivity has been an important issue for biodiversity conservation and landscape planning. In this regard, several attempts have been made to define green and ecological networks spatially in order to support landscape connectivity, and to protect biodiversity as well as maintaining human well-being. The main purpose of this research, therefore, was to examine different ways of defining green and ecological networks and their functionality for biodiversity and people.

This is the first study to investigate different scientific and planning approaches to the definition of potential connectivity routes for biodiversity and people in Sheffield, which is crucial in both a social and ecological sense, as we intend to maximise the effectiveness of those networks being preserved in, or planned into urban areas. Also, this research provides new insights into the ways of planning and designing potential connectivity routes in an urban landscape, which vary according their methodological approaches, scales, main aims and the intended functions that we expect them to provide. Additionally, this research may serve as a prototype for planning and conservation practices in Sheffield by providing a framework for the exploration of alternative approaches to define potential connectivity routes. Finally, the alternative functional connectivity models (least-cost corridors) can be imposed into the existing green and ecological network approaches to determine the potential areas of high connectivity both for biodiversity and people as well as the areas where connectivity needs to be enhanced.

This final chapter is a summary of conclusions from the general discussions, complete with implications, constraints, and recommendations for future research, and is divided into three parts. The first part briefly mentions the research aims, objectives and research questions with an emphasis on the main methodologies used for achieving these. Then, it moves on to an overview of the main findings and their important aspects, and identifies the main limitations of this research. The chapter concludes with important implications and recommendations for future research.

8.2 Reflections on research Aims, Objectives and Research Questions

This research seeks to create a better understanding of the relationships between the ways of defining green and ecological networks by critically analysing the current approaches in Sheffield according to their main aims, functions, spatial extents, as well as exploring the potential for alternative approaches. Therefore, this research presented an integrated framework for the exploration of different ways of planning potential connectivity routes for both biodiversity and people, which may vary according to their underlying aims and planning strategies, and intends to bridge the gap between science and practice within the context of putting the science of landscape ecology into planning practice.

The research topic and the specific research objectives are multidisciplinary in nature. Hence, on the basis of a case study approach, a mixed and exploratory research methodology was required, in which theory and application play equally important roles. In this context, a variety of methods, both qualitative and quantitative, were applied to achieve the main aim and objectives of this research.

Objective 1. to analyse the current approaches used by planners and conservation organisations to define green and ecological networks in Sheffield, and identify the criteria according to which spaces and their associated habitats are included in connectivity routes,

1.1. How are ecological and green networks defined in Sheffield at present?

1.2. How are the spatial components of the actual green and ecological networks identified?

1.3. What are the differences (if any) between the ways of defining the objectives and spatial coverage of these networks?

Initially I analysed the Sheffield Nature Conservation Strategy (SNCS- 1991), the Sheffield Unitary Development Plan (UDP- 1998) and the Sheffield Local Plan (SLP- 2013), by comparing their contents and proposal maps. In this way, the evolution of the green network approach in Sheffield has been assessed. In Sheffield, green and ecological network approaches have been developed and supported both by governmental bodies and non-governmental organisations. Therefore, after analysing the prevailing green network planning policy documents in Sheffield, this research moved on to the examination of the Green Network (the Sheffield City Council) and the Living Don (Sheffield and Rotherham Wildlife Trust) approaches to obtain a deeper understanding of the underlying rationale for these networks. The examination of existing network approaches was carried out through a mixed methods approach combining semi-structured interviews and ArcGIS analyses. While, semi-structured interviews were used to carry out an in-depth exploration of the existing green and ecological network approaches in Sheffield, ArcGIS analysis was used to examine the spatial coverage and structural components of the Green Network and Living Don plans. The results of the whole analysis have explained the process of network definition and design from the perspective of planners and conservationists in the case of Sheffield.

Objective 2. to identify the criteria for site selection and developing new ways of conceptualising potential routes of connectivity based on underlying land cover and land use data,

2.1. Can criteria be derived to identify the potential routes of connectivity?

2.2. What forms do the potential routes of connectivity constructed using these criteria take?

The key concept on which the green and ecological networks are grounded is connectivity. Landscape connectivity can be defined both structurally and functionally. Accordingly, on the basis of structural and functional connectivity measures, the potential for different approaches to the definition of potential connectivity routes for biodiversity and people were explored using a GIS-based approach. The structural connectivity routes were delineated by the use of ArcGIS together with FRAGSTATS, on the basis of the degree to which different land cover and use types are structurally / physically linked to each other. For the delineation of functional connectivity routes, a least-cost corridor modelling approach (ArcGIS) was used. With regards to the functional connectivity routes for biodiversity, the information on the ecological requirements of ten selected species and their likely dispersal characteristics was elicited using an expert opinion process. On the other hand, the functional connectivity routes for people were derived from the physical / legal accessibility of different land use types.

Objective 3. to compare and contrast the existing and derived connectivity routes, and analyse their constituent components, spatial coverage, structural and functional connectivity with a view to informing landscape planning practice,

3.1. Do the derived routes of potential connectivity and accessibility coincide with each other and the actual green and ecological networks?

3.2. How does the landscape matrix complement or detract from the potential routes of connectivity and what are the best possibilities for improving the functionality of connectivity in urban areas considering potential habitat use by organisms and/or accessibility to the public?

3.3. Considering the space limitations in urban landscapes, are some types of land uses and morphologies more compatible with the potential routes of connectivity. If so how can we measure their compatibility?

The final comparative analysis chapter seeks to understand the relationship between existing and alternative network approaches, and explores how differing landscape morphologies within a wider landscape matrix support or detract from their ecological connectivity and public accessibility functions according to what we define spatially. Therefore, the alternative connectivity routes have been compared and contrasted with each other and current ecological and green networks to determine the differences and similarities in the ways of planning potential connectivity routes in an urban context, which may vary according to their purposes, targets and planning strategies. In this way, considering potential habitat use by organisms and / or accessibility to the public, possibilities for improving the connectivity both for biodiversity and people have been identified. Moreover, the compatibility of the landscape matrix and different land cover / use types with the potential connectivity routes has been evaluated.

8.3 The Overview of Research Findings

8.3.1 Emerging Key Findings

8.3.1.1 The existing Green and Ecological Networks in Sheffield

The work described in this thesis has investigated different ways of planning and designing connectivity routes in an urban landscape by critically analysing the actual approaches in Sheffield (the Green Network - Sheffield City Council and the Living Don - Sheffield and Rotherham Wildlife Trusts). The existing network approaches in Sheffield were examined on the basis of a mixed methodological approach, where semi-structured interviews with professionals involved in the development of the networks and ArcGIS analyses provided an in-depth evaluation of the actual network definition and design in Sheffield.

Both the Sheffield City Council (SCC - the Green Network) and the Sheffield and Rotherham Wildlife Trust (SRWT - the Living Don) aim to support and maintain biodiversity across Sheffield by providing landscape connectivity as well as providing recreational, visual and amenity value for people. Also, both SCC and SRWT recognise the importance of multifunctionality and a more integrated planning / designing approach at a landscape level for the development of networks. Despite the similarity of these overarching aims, the Green Network and the Living Don have been defined using different site selection criteria and methodological approaches.

To begin with, in the creation of the Green Network and the Living Don ecological network, neither SCC nor SRWT used objective measures of connectivity, such as structural or functional connectivity. On the other hand, both SCC and SRWT applied criteria to identify sites for inclusion in the potential routes of connectivity. For example, SCC took site characteristics into account (namely, richness / diversity, rarity / uniqueness, size, and landscape / aesthetic value, amenity, accessibility) for the identification of the main sites to be included in the Green Network. SRWT identified the main sites on the basis of existing datasets (such as Sites of Special Scientific Interest, Special Protection Areas, Special Areas of Conservation and Sheffield Local Biodiversity Action Plan sites) and then further refined selection of these sites according to their ecological value and overall quality.

Although different criteria were used to identify the spatial components of the Green Network and the Living Don ecological network, the backbone of both networks is formed by the main rivers and their valleys. Apart from that, the spatial representation and coverage of the two networks are quite different from each other. Firstly, the Green Network has been reflected in the Proposals Map as a conceptual plan in the Sheffield Local Plan (SCC, 2013b). Within this plan the Green Links and Desired Green Links show which areas are connected, or are intended to be connected to each other in future but the spatial extent of these connections is not made explicit; whereas the Living Don represents the full spatial extents of all the components of the whole Living Don ecological network. Secondly, while the Green Network was developed and mapped within the boundaries of Sheffield Local Planning Authority, excluding the areas within the Peak District National Park, the Living Don ecological network includes these areas.

Finally, both SCC and SRWT propose to develop multifunctional networks for biodiversity and people. Both the Green Network and the Living Don include publicly accessible green and open spaces, as well as some public footpaths and cycle paths as part of their network approaches and both approaches aim to deliver biodiversity benefits. In spite of this, in terms of enhancing biodiversity and supporting wildlife, neither SCC nor SRWT specifically refer to the ecological requirements of particular species and / or species groups. However, if we intend to maximise the effectiveness of networks for the benefit of biodiversity and wildlife, we should keep in mind that ecological connectivity is a species dependent concept (Merriam, 1984; Taylor et al., 1993; Ramalho and Hobbs, 2012). Therefore, we should take into account the ecological requirements of the species and / or species groups when developing ecological connectivity routes for biodiversity. As stated by Lawton et al. (2010) habitat creation and restoration have had an important role in reducing biodiversity decline in the UK through the application of UK Biodiversity

Action Plans since 1995. Accordingly, this might be the next phase, or there might be an extension of the LBAPs that takes into account this approach.

The evaluation of the Green Network and the Living Don approaches shows that, while both approaches share a common purpose and vision to create a network in Sheffield, there is some support for the conceptual premise that the definition of a green / ecological network is highly dependent on the methodology and site selection criteria for the inclusion of different habitats within the network.

8.3.1.2 Alternative Connectivity Routes for Biodiversity and People

After examining existing approaches to green and ecological networks in Sheffield, alternative routes of connectivity for both biodiversity and people were developed, based on the analysis of landscape structural and functional connectivity, in order to highlight and analyse different ways of defining ecological networks.

Physical connectivity of different land cover and use types was taken as the first criterion with which to develop structural connectivity routes both for biodiversity and people, without reference to the ecological requirements of particular species and people's social requirements. When compared, it was obvious that the each of the structural connectivity routes for biodiversity and people differ from each other in terms of their spatial components, patterns and extents, even if they also share some spatial components, such as the overlap between the *Recreation and Leisure* structural network for people and the *Wetlands* and *Heathlands* networks, all of which are mainly located within the boundaries of the Peak District National Park.

A different approach was taken to develop functional connectivity routes for biodiversity. Here I initially selected ten local species, and then I created ten alternative ecological connectivity routes based on these species' ecological requirements and likely dispersal characteristics. In terms of the alternative functional connectivity routes for people, the main criteria were the physical / legal accessibility of different land use types, and their combination with slope. As a result, I created six alternative connectivity routes for people between different destinations, defining the routes that people may can take from their homes to publicly accessible green and open spaces, their workplaces or to go shopping. The derived connectivity routes for the selected species and people resulted in different spatial extents and components. These results were depending on:

- species the potential connectivity corridor was modelled for,
- destinations the potential connectivity routes link for the use of public, and
- the aspects of the landscape were taken into account as constraints to the movement of the selected species and people (namely, the definition of different land cover and use types, slope, legal / physical accessibility).

The following conclusions have been drawn from the comparison of structural and functional connectivity routes for biodiversity. Regarding structural connectivity routes for biodiversity, *Wetlands* and *Heathlands* hold the highest structural connectivity and it was found that some of the selected species (e.g. Skylarks, Leisler's bats and Grass snakes) would benefit functionally from these networks as their ecological movement routes. On the other hand, it was obvious that the structural networks of *Wetlands* and *Heathlands* do not necessarily provide functional connections for the majority of the selected species (such as Blackbirds, Greenfinches and Brown long-eared bats), simply because those species do not use these areas as habitats and / or crossing these areas compared to the other land cover types is much more difficult for them.

Furthermore, the comparisons between structural and functional connectivity routes for people revealed that the spatial patterns, components and extent of these networks differ according to which aspects of the landscape we took into account, as underlying aims of the networks (e.g. physical continuity of different land use types, allowing pedestrian movement) as well as which areas were intended to be linked to each other for the use of people. For example, structural connectivity network *Urban Fringe / Countryside* (a sub-type of *Recreation and Leisure*) reported the highest structural connectivity. However, this area is located within the boundaries of the Peak District National Park and because of the lack of information on its actual accessibility to the public; this area had been excluded from the functional networks for people. This had led to a huge difference in the spatial extent of structural and functional connectivity routes. Additionally, I had considered the different types of the *Natural and Semi-natural Land* as part of structural connectivity routes for people, in which the *Roadside Vegetation* and *Paths and Pavements* reported very low structural continuity. In spite of that, *Roadside Vegetation* together with *Path and Pavements* (as part of built land uses) constituted the backbone of the structural and functional connectivity routes for people since they are completely accessible to the public and provide linear connections in between urban green and open spaces (Moseley et al., 2013).

Taken together, the importance and value of landscape structural connectivity analysis cannot be ignored, as it helps researchers to measure the spatial characteristics of different landscape components and the whole of the landscape (e.g. the availability of suitable habitat types for species, their spatial characteristics and the relationships between those habitats). However, based on structural connectivity, the potential connectivity routes consider the suitable land cover types as habitats for species (or green and open spaces for the use of people) and impermeable landscape matrix in between those, ignoring the influences of landscape matrix on the movement (With et al., 1997; Goodwin, 2003). Therefore, structural connectivity may result in misleading decisions for the selection of the spatial components and the delineation of the potential connectivity routes both for biodiversity and people. In this regard, returning to the question of determining criteria for the delineation of potential connectivity routes, it is now possible to state that the delineation of potential connectivity routes based on functional connectivity results in more reliable and realistic models compared to structural connectivity, since it takes into account the ecological requirement of species and the accessibility of different land uses.

8.3.1.3 Alternative Connectivity Routes and the Existing Networks

The comparisons between the alternative connectivity routes and the existing network approaches have shown that both the Green Network and the Living Don have some spatial coincidences with the derived alternative connectivity routes. However, in general, all of these networks have quite different spatial patterns, components and spatial extents.

The spatial overlaps between structural connectivity routes for biodiversity and the existing network approaches have been interpreted as the potential for the Green Network and the Living Don to accommodate different species with a diversity of different land cover types as well as supporting the use of people by covering a variety of *Recreation and Leisure* land uses.

On the other hand, even though both the Green Network and the Living Don ecological Network represent quite different spatial patterns and coverage compared to the derived functional connectivity routes for the selected ten species, they also have some spatial coincidences with the networks for 7 out of the10 species (from the species groups of birds, bats and reptiles). Therefore, these findings suggest that in general the Green Network and the Living Don approaches are capable of supporting the ecological connectivity for different species, although they did not refer to particular species. Additionally, since the Living Don ecological network includes the areas within the Peak District National Park, it is also capable of supporting the ecological connectivity for the remaining species, namely Skylarks, Leisler's bats and Grass snakes.

Similarly, the Green Network and the Living Don have spatial coincidences with the functional networks for people, as well. Here it is important to note that both SCC and SRWT recognised the importance of *Roadside Vegetation* as part of their network approaches. The value of *Roadside Vegetation* has been emphasised previously both for biodiversity and people, as it provides habitats and ecological connections for some of the selected species, as well as publicly accessibility routes and linear connections for people. Moreover, as indicated in previous chapters, the areas of *Roadside Vegetation* together with *Private Gardens*, as opportunity areas in an urban environment, may help to enhance ecological connectivity for species as well as providing additional amenity and visual values for people (Cook, 1991; Gaston et al., 2005; Goddard, et al., 2010; Ignatieva et al., 2011; Hambrey Consulting, 2013).

The overall results of this research clearly show that the definition of green and ecological networks is highly dependent on the methodology, ecological and / or social functions that are considered (and which it is expected that the networks will deliver), and also criteria for the inclusion of different habitats or land uses within the potential connectivity routes for biodiversity and people.

8.3.2 Limitations of the Study

Being multidisciplinary in nature, this research is situated at the interface between landscape ecology and landscape planning, and directed towards the critical analysis of existing approaches to defining urban ecological / green networks derived from different theoretical and professional perspectives (planning and ecology), as well as exploring the potential for different approaches to ecological / green networks, using a GIS-based approaches. The analysis of landscape connectivity and modelling potential connectivity routes are quite large fields in themselves and the delineation of alternative connectivity routes using different methods can suffer from several drawbacks. The overall scope of this research was constrained by the problems inherent in gathering multiple data sources for the preparation of datasets, combining land cover and land use datasets for the whole of Sheffield, gathering expert opinion, and dealing with different software (FRAGSTATS and ArcGIS) and technical issues related to working with very large datasets.

First of all, the resolution and the detail of input datasets should be able to represent real world landscape components and the ecological requirements of species, since the dependency of landscape metrics and least-cost corridor models on the resolution and detail of input datasets have been well-documented in the literature (Turner et al., 1989; Calabrese and Fagan, 2004; Botequilha-Leitão et al., 2006; McGarigal, 2013). In this regard, assembling my GIS maps for both mapping and analysis has required the identification and subsequent acquisition of numerous datasets from different agencies. The process of combining land cover and land use datasets for the whole of Sheffield to generate the maps I needed, at a very fine scale, with a high level of accuracy needed a lot of detailed data adjustment and manipulation. To find out what is needed, what is available, and then ordering datasets, securing the necessary licence agreements and generating the final datasets for analyses are time consuming processes. These issues might make such a process challenging for an organisation (i.e. Sheffield City Council, the Sheffield and Rotherham Wildlife Trusts) and might affect the feasibility of this approach depending on the available time for a project.

Moreover, in modelling the different approaches to ecological / green networks in Sheffield, I used ArcGIS 10.1 and FRAGSTATS 4.1 in combination and separately to analyse and model potential connectivity routes for people. Initially, I used FRAGSTATS in combination with ArcGIS to measure and characterise structural connectivity in my study area, based on the generated land cover and land use maps and delineated structural connectivity routes. My file sizes were so large (raster based land cover and land use maps with 2 m resolution for the whole of Sheffield), that they caused computational problems, namely insufficient memory and inordinately lengthy processing times. Hence, I struggled to find computing resources powerful enough to handle my analyses. Because of this when taking such an approach, the issues with computer power for processing analyses should be taken into account. Here, it is important to note that, these analyses would be run at a lower resolution (for example 5 m or 10 m). In this way, technical issues with computer power would be prevented. However, such an approach might affect the results of analyses (e.g. missing connections in the resulting networks due to the lower level of details in the land cover patches, see Figure 7 in Chapter 5).

With regard to the modelling process, even though the least-cost corridor approach provides a spatially explicit indication of functional connectivity routes (Galpern et al., 2012), both for biodiversity and people, across the landscape, the ecological relevance of these can be questioned. First and foremost, we should be aware that the resulting models were constrained by the amount of data available on the ecological requirements of the selected species and the actual accessibility of different land use types for the whole of Sheffield.

For example, the least-cost corridor modelling process for the selected species was limited by the lack of sufficient biological / empirical data. My initial intention was to use records of species observations to associate the selected species with existing land covers in Sheffield, as suggested by previous studies (Calabrese and Fagan, 2004; Chetkiewicz et al., 2006; Sawyer et al., 2011; Stevenson-Holt et al., 2014). I had also expected that all the Sheffield Ecology Unit’s species records (from the Recorder 6 database) would be pre-digitised; but this was not the case and consequently I needed to digitise a huge amount of raw species data, a task that took several months to complete. In the event this data turned out to be unusable as an indicator of species distribution due to inconsistencies in scale and detail between the extracted records (from Recorder 6 database) and the generated land cover maps, and I had to develop an alternative methodology to determine this.

I therefore subsequently attempted to use expert opinion to gather information on the selected species by means of the Delphi Technique. This technique has been widely accepted as an effective way of eliciting information on species by building a consensus on the ecological requirements and the likely dispersal characteristics of particular species (Eycott et al., 2011). However, the process of gathering expert opinion (particularly through the Delphi Technique) is highly dependent on the availability of experts, and especially on their willingness to participate in the research. On the other hand, the expert opinion approach has been criticised by some researchers for introducing uncertainty and bias in the resulting connectivity route models (Sawyer et al., 2011; Zetterberg, 2011). However, as stated previously, where the biological / empirical data is not available or sufficient for the parameterisation of the least-cost models, in general researchers can benefit from an expert opinion approach (Epps et al., 2007; Murray et al., 2009; Watts et al., 2010; Zeller et al., 2012).

In the case of my research, as a result of a poor response from experts, I had to rely on a single expert opinion for bird and mammal species to provide the parameters of the least-cost corridor models as opposed to my aim of having at least 3 experts for each of the selected species. Consequently, I am aware that the least-cost corridors for the selected species may be unduly subjective due the lack of multiple expert participation. However, I believe that they demonstrate that the technique is viable if sufficient numbers of experts can be found, and still have a high potential to represent ecological connectivity routes.

In terms of the potential connectivity routes for people, the most difficult part was the determination of the physical / public accessibility of each land use category in Sheffield. Even though the accessibility of the land uses was somewhat easier in the urban part of Sheffield, there were still some land uses for which I could not determine the actual public accessibility. Furthermore, the most problematic land use was *Countryside / Urban Fringe* within the boundaries of the Peak District National Park. Due to the lack of information on public accessibility, I excluded the area of this land use from the least-cost modelling process for the potential connectivity routes for people. Hence, these models can be further refined if the actual accessibility of different land uses for the whole of Sheffield can be determined.

8.4 Potentials and Recommendations for Future Research

The overall findings of this research have contributed to an understanding of the different ways of planning and designing potential connectivity routes by analysing existing green and ecological network approaches in Sheffield, developing methods for the delineation of alternative connectivity routes and finally comparing and contrasting the derived alternative routes of connectivity with each other and with the existing green and ecological networks. Based upon the limitations and the overall findings of this research, the following recommendations are proposed to support the future research and enhance potential connectivity through planning and designing multifunctional connectivity routes in urban landscapes.

8.4.1 Recommendations for the Future Research

In general terms, the overall findings of this research are that the spatial extent, components and patterns of potential connectivity routes depend on the different methodological approaches that are used to delineate potential connectivity routes, and on the different functions (ecological, social) that we expect the networks to support and provide. Additionally, notwithstanding its limitations, the least-cost corridor modelling approach has been found to be a useful tool for the exploration of the potential connectivity routes for different species (species groups) and people. However, a number of issues arising from this work also point to directions, and cautions for future work in this area:

1. It is clear that the numbers of input datasets and parameters required to model potential connectivity routes both for biodiversity and people is quite large and not easily obtained. Therefore, in accordance with the nature of such an approach, the future research should involve collaboration among researchers from different disciplines.

2. One of the most important questions raised by experts when estimating the habitat suitability and cost values (as the indication of difficulty to traverse the non-habitat patches), was the precision of the different land cover types in terms of their vegetation structure. Therefore, further research may need to assess the precision with which the vegetation structure is mapped to prevent bias in the modelling process and the resulting models. This can be achieved through conducting field work in some of the key areas depending on the selected species and /or species groups, or different types of data (e.g. Lidar datasets) showing the exact vegetation structure.
3. Bearing in mind the difficulty of obtaining expert opinion for the parameterisation of my models, further research could rely instead on biological / empirical data on the habitat preferences and movement characteristics of species. However, if the above-mentioned biological / empirical data is not available, or not sufficient, and where experts are available, further research may benefit from using the Delphi Technique to elicit information on the ecological requirements and likely movement characteristics of species to give a better estimates for the input parameters and therefore more reliable models for the potential connectivity routes.
4. In addition to considering the effects of different land cover types on the movement of species, further research could incorporate elevation into the modelling of potential connectivity routes. This might be particularly important for some species, for which elevation is a constraint.
5. Regarding the modelling of potential connectivity routes for people, the most important limitations of this research was in obtaining information on the actual accessibility of different land uses. Therefore, future research should refine the potential connectivity (accessibility) routes for people by employing information on the actual accessibility of different land use types.
6. This research assumed that all publicly accessible green and open spaces, and land uses accessible to public (such as all *Paths and Pavements, Roadside Vegetation*) are being used by people. However, in an urban landscape it is quite important to find out which areas are actually used by people, as well as the problematical areas that are not used, even though they are publicly accessible. In this regard, another future research focus could be including information on the actual use of the green and open spaces, motivations for

the use of particular spaces, as well as how people move through the landscape.

7. In modelling potential connectivity routes, this research only considered pedestrian movement. However, in reality people can benefit from potential connectivity routes in different ways (walking, cycling, or through their visual and amenity value). Hence, it would also be worth incorporating information on the different functions of green and open spaces in order to determine how these function(s) are distributed spatially.

8.4.2 Recommendations on Planning and Designing Multifunctional Connectivity Routes in Urban Landscapes

This study has developed a deeper understanding of the definition and spatial representation of potential connectivity routes in an urban landscape using different methodological approaches and comparing and contrasting all network approaches in the case of Sheffield. With regards to the development of connectivity routes in urban areas, the most striking result emerging from this research was the fact that the spatial pattern, components and extent of connectivity routes depend on how the networks are defined, based on the ecological and social functions we expect them to provide and support. Although, in Sheffield, green and ecological networks have been developed by Sheffield City Council (SCC) and the Sheffield and Rotherham Wildlife Trust (SRWT), there was a clear requirement to investigate the efficacy of these network approaches in terms of delivering biodiversity benefits and maintaining human well-being. Therefore, the findings of this study have a number of important implications for future planning and design practices aimed at multifunctional connectivity routes in urban landscapes.

1. This research has highlighted the differences and similarities between the different ways of defining connectivity routes from the perspective of SCC and SRWT and also by the use of different methodological approaches to measure and model connectivity both for biodiversity and people. While the comparisons between these networks revealed the fact that their spatial articulation is highly dependent on how we define them, and which species and people group we intended to provide connectivity for, it was also obvious

that the landscape matrix in Sheffield is capable of accommodating and supporting different species, as well as providing an extensive network for the movement of people by walking. Additionally, modelling the potential connectivity routes for both biodiversity and people through a least-cost corridor approach has yielded a fair approximation of the functional connectivity. In this regard, the least-cost corridor maps for the selected species and people developed as part of this research can be used as basis for determining the areas required to be improved in terms of connectivity. For example, according to the results of this research, *Roadside Vegetation* and *Private Gardens* represent a very high potential to support the movement of the majority of selected species.

2. The importance and contribution of *Roadside Vegetation* for the movement of people was emphasised, since they may provide a sheltered and comfortable walking experience in an urban environment. Often the vegetation itself is, practically not accessible, because it’s not continuous, is too ornamental, or the ground is too steeply sloping. The point is it may be accessible, but it may also make people feel more like walking, and may provide shade, which is becoming increasingly important. Hence, I believe that if the areas of *Roadside Vegetation* are enriched and improved by sufficient vegetation cover, together with *Paths and Pavements*, they can form the backbone of a wider network both for wildlife and people.

3. The incorporation of *Private Gardens* into the Green Network and the Living Don ecological network can be problematic, due to lack of co-operation or awareness on the part of the private landholders. A reasonable approach to tackle this issue could be to establish relationships with private landowners, to get them involved in the planning and decision mechanisms, to provide ways of engaging people in nature and nature conservation, and try to make local people to understand the value and importance of nature both for their own benefit and wildlife. Here, it is important to note that the semi-structured interviews revealed that both SCC and SRWT make a deliberate effort to improve the environmental consciousness and appreciation as well as engaging public with the nature in Sheffield. However, I believe that this process can be improved and strengthened through the cooperation between SCC, SRWT and other groups, such as the local friends-of groups.

4. The least-cost corridors developed in this research can be combined within a GIS environment (e.g. ArcGIS) to determine the areas of multifunctionality, and then can be imposed into the actual Green Network and the Living Don ecological network maps. In this way, these current approaches can explicitly represent the connectivity routes for different purposes as well as highlighting the multifunctional areas both for species and people in Sheffield. Such an approach could produce a more comprehensive and multifunctional planning approach in an urban environment where space limitations cause allocation conflicts in urban areas.
5. SCC and SRWT may produce alternative connectivity routes based on the methodological approach presented in this research. For example, I only considered ten local species to develop alternative connectivity routes within the scope of this research. In addition to these, SCC and SRWT can take into account other species and / or species groups and model alternative routes for those species. Likewise, they may investigate the possibility of different connectivity routes for people for a diversity of human activities and purposes (cycling routes provided by physical / legal access, areas of visual and amenity values provided by visual access). Thus, SCC and SRWT can determine different areas with different functional combinations using spatially explicit connectivity models.
6. Finally, as emphasised above, the competition for land in urban landscapes is fierce because of high demand for different land use options. Therefore, after the determination of the connectivity areas for different functions and / or multifunctionality, SCC and SRWT could further refine these outputs in terms of their applicability by the use of multi-criteria analysis based on a GIS environment. At this stage, it is also important to define possibilities and constraints for the planning decisions (such as the sensitivity of particular species against disturbances, precise vegetation structure in habitat and non-habitat patches, socio-cultural and socio-economic requirements and expectations, land ownership and possibilities for improvements). In this way, SCC and SRWT could achieve a more reliable and robust decision-making structure and a more feasible planning approach to support and improve multifunctionality in Sheffield.

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