# Habitat Connectivity – Developing an indicator for UK and country level reporting.
# Phase 1 Pilot Study

**Forest Research & Centre for Ecology and Hydrology**

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# 1 Executive summary

## Introduction

1.1 Biodiversity decline is thought to be occurring as the result of habitat loss and fragmentation from human activity over a long period. The process of fragmentation involves the sub-division of large habitat patches into smaller patches. This occurs as a result of land-use change, urbanisation, road building and other infrastructure, and inappropriate habitat management.

1.2 Habitat fragmentation hinders the movement of individuals among small, isolated populations, threatening their long-term viability. Fragmentation may also inhibit species movement in response to predicted climate change impacts on their climate space.

1.3 In an attempt to address biodiversity decline from fragmentation and provide climate change adaptation strategies, conservation policy and action is expanding from site-based to landscape-scale.

1.4 In order to assess the effectiveness of conservation actions, there is a need to monitor change through time and identify whether habitat fragmentation continues to challenge biodiversity conservation.

1.5 The impacts of habitat fragmentation can be examined by assessing the structural connectivity or connectedness of the landscape, by examining the spatial structure or pattern of the landscape. Functional connectivity, on the other hand, is a measure of the ability of a species to move through a landscape. Functional connectivity is essentially species-based; a landscape can exhibit low structural connectedness at the same time exhibiting different degrees of species-specific functional connectivity. There is growing interest in the use of functional connectivity indicators, particularly in fragmented landscapes such as the UK.

## Aims and Objectives

1.6 The UK Biodiversity Partnership Standing Committee has agreed to develop and use a suite of 18 biodiversity indicators to report progress towards 2010 targets and provide an effective communication tool for biodiversity assessment. One of these, an indicator of *habitat connectivity/fragmentation,* requires identification and testing. This indicator, which is aligned with the Convention on Biological Diversity (CBD) and European Union (EU) requirements, is intended to assess the change in habitat fragmentation and impacts on habitat connectivity and biodiversity.

1.7 The overall aims of the pilot study were to identify and test the most suitable and accepted methodology and data sources for the production of UK and country level indicators of functional habitat connectivity and provide recommendations for further development.

## Method

1.8 Spatial land-cover data sets, Land Cover Map (LCM) and Countryside Survey (CS) produced by the Centre for Ecology and Hydrology were tested in the pilot study to examine functional connectivity indicators. A beta version of the most recent LCM product (in development during 2007/8) showed a number of inconsistencies and was currently unsuitable for further analysis; the final product may be well suited for future analyses. Therefore, CS data for 10 sample squares were used in the pilot study to investigate approaches for the development of a connectivity indicator.

1.9 In order to assess functional connectivity a number of species-landscape interactions were defined. These interactions related to negative edge impacts from, and the permeability of, the surrounding landscape. This resulted in a number of alternative area (no edge, fixed edge, weighted edge) and distance (Euclidean and least-cost) options for further analysis.

1.10 These alternative area and distance options were then analysed by simple landscape metrics, to describe the general change in landscape structure and aid interpretation of connectivity measures, and three different groups of connectivity measures – Graph theory, Buffer radius and Incidence Function Models (IFM) – to assess functional connectivity. This analysis was first conducted on 1 CS sample square to refine the options for further application on all 10 CS sample squares.

## Results

1.11 From the analysis of the single CS sample square the preferred area option was based on a weighted edge as this takes account of changes within the surrounding landscapes. Similarly, the least-cost distance option was accepted as this incorporates changes in landscape permeability. All three connectivity measures demonstrated potential to assess functional connectivity within the single CS sample square and were accepted for further analysis.

1.12 The study of the CS sample square also identified the need to consider whether connectivity measures were patch or grid-based, as patch-based measures may suggest an increase in connectivity with increased fragmentation. As a result, patch and grid/hybrid-based versions of the connectivity measures were included in the analysis of the 10 CS sample squares.

1.13 All connectivity indicators were able to detect change within the 10 CS sample squares. However, the change reported by some patch-based measures (buffer radius mean habitat area and patch-based IFM) were inconsistent with the observed landscape change. These measures predicted an improvement in connectivity with an increase in fragmentation. The grid/hybrid-based measures (grapy theory and IFM) were able to detect change consistently with observed landscape change.

## Conclusion and recommendations

1.14 The report demonstrates that there is a trade-off between indicator complexities, inputs required and outputs they provide. On the one hand, very simple indicators which require minimal inputs do not realistically report on ecological processes such as connectivity. On the other hand, relatively complex mechanistic-type models are far more difficult to parameterise. Between these extremes are relatively simple heuristic approaches, based on sound theory and expert opinion, which can offer connectivity indicators based on a limited knowledge of how species interact with landscapes.

1.15 The urgency to implement conservation policy means that the there is often little time to wait until more complete data have been assembled. The pace of both land-use and climate change requires that policy and action must be based on acceptable principles, albeit subject to change in the light of emerging research. An adaptive modelling approach is a very practical response to the need for adaptive management, where one informs the other and vice-versa.

1.16 As a result of this study, it is concluded that the proposed indicator should be developed using a combination of metrics. It should comprise an area metric with a weighted edge, a least-cost distance metric and a hybrid (patch/grid-based) Incidence Function Model (IFM) applied to the Countryside Survey (CS) data. This proposed approach allows the indicator to take account of changes to area, isolation, edge and matrix as a result of fragmentation.

1.17 A comparison of the proposed spatial data and connectivity indicator with indicator suitability criteria, developed by CBD and EU, confirmed that both were highly suitable for indicator development, with the only concern being the limited extent of the CS data which may not reflect wider landscape change.

1.18 In the short term, to apply the indicator to a wider selection of CS sample squares to enable UK and Country level reporting there is a need to:

- *Further develop the GIS based hybrid IFM indicator tool.*
- *Ensure CS data is in the required format with linear features added.*
- *Review and revise the edge and permeability values.*
- *Further review the performance of the proposed indicator by examining change in landscape scenarios.*

1.19 In the longer term, there would be a need to tackle scale issues, linked to the limited extent of CS data, by utilising larger extent data, possibly LCM. There is also an ongoing need to validate connectivity with empirical evidence for selected focal species.

## Contents

## Figures and Tables

# 2 Introduction

## *2.1 The need for biodiversity indicators*

Indicators are increasingly relied upon to monitor performance against policy objectives and targets and to aid the development of policy. Indicators are intended to summarise and distil complex information into simple, robust measures that can be used to assess relative change or trends over time. This is particularly difficult in the field of environmental science where there are many potential measures but a paucity of consistent time series data at a national scale. However, despite these challenges, environmental indicators have become a key component of evidence-based policy-making.

In 2002 the UK and other countries made a commitment, as part of the UN Convention on Biological Diversity (CBD), "*to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth*". This commitment was subsequently endorsed at the World Summit on Sustainable Development.

In order to assess progress towards the 2010 target, the CBD proposed the development of a limited number of indicators for global assessment and for communication of biodiversity trends. The intention of the CBD parties was to apply indicators at global, regional, national and local levels to aid the implementation of the commitment, and to support national biodiversity strategies and action plans. The parties were also invited to use or establish national indicators to assess progress towards national and/or regional targets.

The European Union took the decision to develop a set of headline biodiversity indicators, based on the CBD framework, to assess progress towards the 2010 target. The European Environment Agency (EEA) subsequently established the Streamlining European Biodiversity Indicators 2010 (SEBI2010) project to implement this decision and promote consistent biodiversity indicators and monitoring across Europe.

Following these international developments and building on work at the country level, the UK Biodiversity Partnership Standing Committee agreed to develop and use a suite of 18 biodiversity indicators to report progress towards 2010 targets and provide an effective communication tool for biodiversity assessment beyond 2010 (UK Biodiversity Partnership, 2007). Four of these indicators required further development and testing including an indicator of *habitat connectivity/fragmentation*. This indicator, which is aligned to CBD and EU indicators as outlined in Table 1, is intended to assess the change in habitat fragmentation impacts on habitat connectivity and biodiversity.

**Table 1** – UK habitat connectivity indicator aligned with the CBD and EU biodiversity indicator frameworks.

| CBD focal area & indicator | EU headline indicator title | SEBI2010 indicator | UK Biodiversity indicator |
|---|---|---|---|
| Ecosystem integrity and ecosystem goods and services **Indicator:** Connectivity / fragmentation of ecosystems | 13. Fragmentation of natural and semi-natural areas | New indicator based on use of Corine Land Cover (CLC) data **Previously:** Status and trends of forest spatial patterns per biogeographical region and country | 14. Habitat connectivity / fragmentation |

## *2.2 Habitat fragmentation and connectivity*

The habitats and landscapes of the UK, in common with much of Europe and the world, have undergone considerable loss and fragmentation through a long history of human activity (Kirby and Thomas, 1994; Riitters *et al.*, 2000; Wade *et al.*, 2003). Further habitat loss and fragmentation is still regarded as a serious threat to biodiversity conservation, even though many habitat fragments have been protected by site-scale conservation measures (Saunders *et al.*, 1991; Andren, 1994, 1997; Fahrig, 2003; Eycott *et al.*, 2008).

Biodiversity decline resulting from habitat fragmentation is likely to be compounded by climate change, as many species may be forced to adjust their range quite rapidly pole-wards and to higher elevations (Berry *et al.*, 2002; Thomas *et al.*, 2004). The fragmented nature of habitat in many landscapes, contained within an increasingly hostile matrix, may seriously inhibit this range adjustment and prevent species from tracking future movements of their climate space (Opdam and Wascher, 2004; Hopkins *et al.*, 2007).

The combined threat of fragmentation and climate change has prompted a marked shift in policy and action from site-based conservation to the consideration of sites within a larger 'landscape' context. This shift acknowledges that individual site conservation remains an important but insufficient action to secure biodiversity in the long-term (Margules and Pressey, 2000; Hopkins *et al.*, 2007). Indeed, landscape scale measures aimed at improving habitat connectivity have been proposed as climate change adaptation management, to help species disperse more effectively to track their changing climate space (Woodland Trust, 2002; Pearson and Dawson, 2003; Opdam and Wascher, 2004; Hopkins *et al.*, 2007).

Many countries have specific obligations to develop such 'landscape' strategies to combat fragmentation and improve habitat connectivity between important biodiversity sites. For instance, the EU Habitats Directive (European Community, 1992) promotes the creation of ecological networks to improve the ecological coherence of SACs (Special Areas of Conservation) and SPAs (Special Protection Areas) as part of the Natura 2000 network across the European Union. Indicators of fragmentation or connectivity have a role in helping to assess the performance of such measures and the degree to which conservation aspirations and targets are being met.

# 3 Assessing fragmentation and connectivity

In order to develop an effective connectivity indicator it was necessary to review the literature on the process of fragmentation and the consequences for biodiversity, and to identify particular landscape features that directly impact on habitat connectivity (Eycott *et al.*, 2008). There was also a clear need to review approaches to the assessment of habitat connectivity for the UK landscape, whether based on an analysis of landscape structure or of function. There are two main ways of looking at habitat connectivity:

1) **Structural** connectivity or connectedness of the landscape is the degree to which habitat patches are physically linked;
2) **Functional** connectivity is dependant on species dispersal abilities, the size and spatial arrangement of habitat patches and the nature of land cover and land use in the intervening matrix. The same landscape can be functionally connected for one species but not for another.

## 3.1 *Process and consequences of fragmentation*

The process of fragmentation involves the sub-division of large habitat patches into smaller patches (Figure 1). This process may have occurred over long periods of time as a result of forest clearance for agriculture, urbanisation and other land uses. Dissection of large habitat patches by linear features such as tracks or roads can also result in the formation of smaller discrete patches. The fragmented patches may be eroded further by land use activities or even completely destroyed. These factors, combined with inappropriate habitat management, may lead to a general decline in habitat quality and extent.

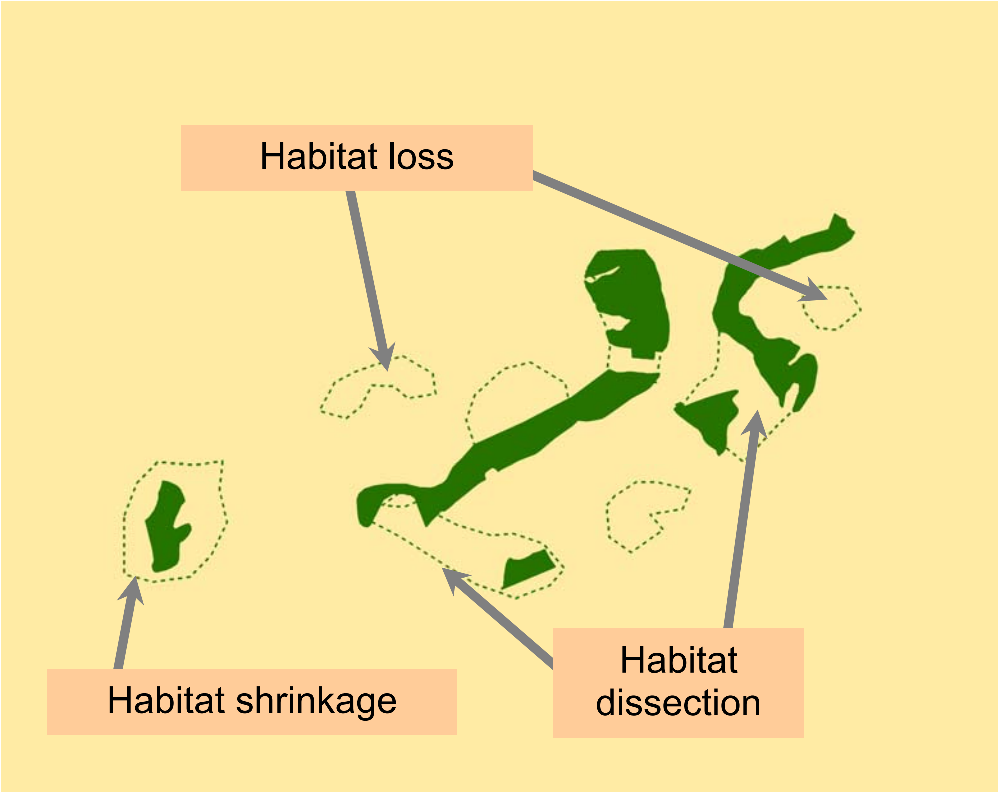



**Figure 1** – Illustration of key elements within the process of habitat fragmentation. The dotted line depicts previous habitat extent.

Habitat fragmentation has a direct impact on the *area*, *isolation* and *edge* of habitat patches, as outlined in Figure 2. In general terms, fragmentation causes a decrease in the area of available habitat and the size of dependent populations, an increase in ecological isolation between patches and an increase in the amount of edge habitat. The creation of additional edge habitat may further reduce the availability of core habitat, decrease population size and increase extinction risk. Edge impacts are often associated with changes in micro-climate, invasive species, predation and human pressures.

Two scientific theories - island biogeography (MacArthur and Wilson, 1967) and metapopulation dynamics (Hanski, 1998) - predict that: the reduction in area (and population size) may lead to an increased risk of local extinction; while the increase in ecological isolation may cause a reduction in the exchange of individuals between isolated patches. The movement of individuals among small, isolated fragmented populations is an important ecological process in fragmented landscapes (Tischendorf and Fahrig, 2000b2000a). These movements, which may improve the long-term viability of small, isolated populations, may maintain genetic diversity, rescue declining populations, re-establish populations, and maintain networks of populations through metapopulation dynamics (Hanski, 1998).

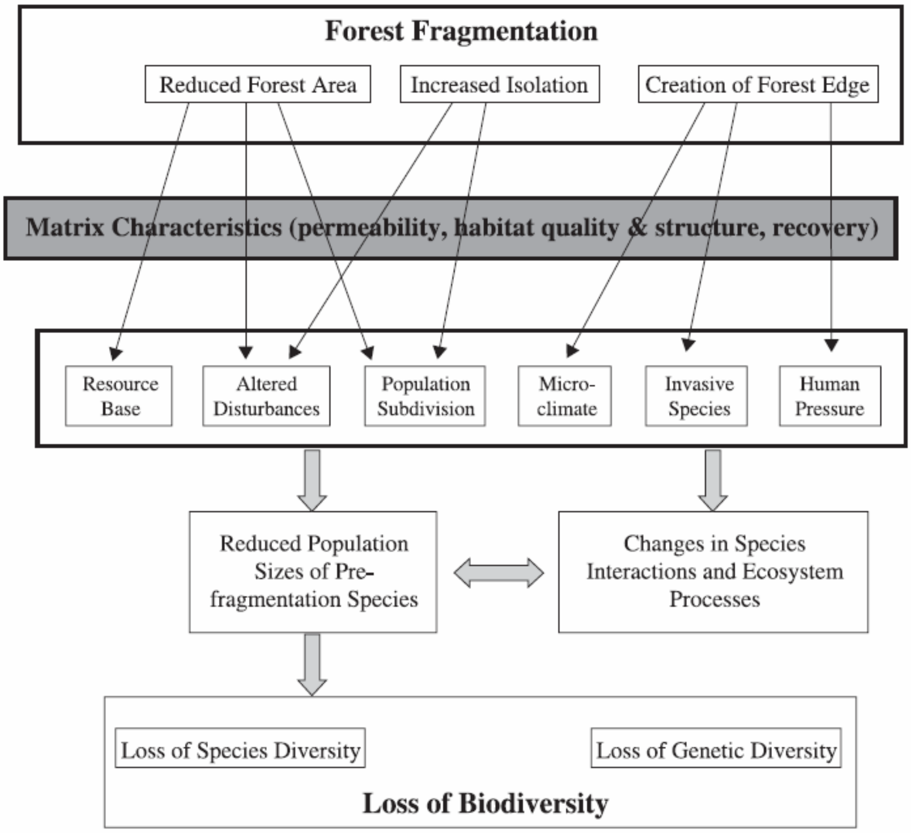



**Figure 2** - Conceptual model of fragmentation effects from Kupfer *et al.* (2006), modified from Zuidema *et al.* (1996) and Lindenmayer and Franklin (2002) to incorporate matrix effects.

The characteristics of the surrounding *matrix* (Figure 2) are increasingly recognised as having a strong influence on fragmentation impact (Zuidema *et al.*, 1996; Lindenmayer and Franklin, 2002; Kupfer *et al.*, 2006) in addition to the direct effects of area, isolation and edge. The surrounding landscape matrix may exacerbate fragmentation by further reducing the area of habitat, and increasing ecological isolation and detrimental edge impacts; the influence is based on the degree of hostility or permeability of the matrix. For instance, an intensive agricultural/urban landscape matrix may cause increased detrimental edge impacts, thereby reducing the area of suitable core habitat. The reduction of area is a key impact as habitat connectivity is often area-weighted (Hanski, 1999), with larger patches contributing more to movement between patches than smaller patches with the same ecological isolation. The hostile landscape matrix, with low permeability, may also reduce the probability of species dispersal and movement between patches, thereby increasing functional isolation. The impact of the matrix on habitat fragmentation may be relatively large in the UK due to the extensive degree of habitat loss and fragmentation, coupled with a relatively intensive agricultural and urbanised landscape.

In summary, habitat connectivity is broadly based on the interplay between the area and isolation of fragmented habitats, and how the surrounding landscape matrix may alter these attributes. The area of effective habitat can be considered a function of the area of habitat minus the area affected by edge impacts; these in turn are related to the characteristics of the surrounding matrix. Similarly, the effective isolation between patches can be considered a function of the actual distance between them and the attributes of the intervening landscape matrix, particularly the extent to which it hinders or favours dispersal.

## *3.2 Assessing habitat connectivity*

The assessment of conservation action to maintain and expand habitat area is relatively straightforward. However, the assessment of action to improve habitat connectivity is more complex due to the different responses of species to the landscape, and the interplay between patch area, patch quality, isolation, edge and the nature of the intervening or surrounding matrix.

Many fragmentation/connectivity indicators address the structural changes in so-called ‘binary’ landscapes where land is regarded as habitat or non-habitat. The SEBI2010 fragmentation/connectivity indicator is still under review, but the previously proposed indicator (Table 1) was based upon structural assessments of such binary landscapes (Vogt *et al.*, 2007). Such structural assessment approaches, aimed at assessing fragmentation rather than connectivity, focus upon the area and edge of fragmented habitats and give only limited consideration of isolation and the impact of the surrounding matrix (see Figure 2). In many areas throughout the world, such structural approaches may be adequate in detecting change in habitat fragmentation based on a loss of habitat and an increase in geographical isolation. This is especially true for those landscapes experiencing ongoing and significant habitat loss – where a structural indicator, incorporating changes in habitat area, number of patches, patch size and nearest neighbour distance, may be informative.

However, within highly fragmented, strongly human-influenced landscapes such as the UK, the impacts of habitat fragmentation are more complex and subtle. The pattern of habitat loss occurred many tens or hundreds of years ago, and habitat area is now relatively stable; but these remaining habitats are located within dynamic, highly heterogeneous landscapes. As a result, the impacts of fragmentation upon connectivity come from changes in this wider landscape matrix, for instance from agriculture, commercial forestry and urban development. Basic structural connectivity indicators would struggle to identify change in such landscapes and to recognise the importance and complexity of the matrix. These indicators would also fail to identify the impact of recent policy measures that target the landscape matrix and promote ecological restoration through, for example - agri-environment schemes, woodland planting and similar initiatives, as addressed in Section 2.2. These initiatives have the potential to improve connectivity and assist in the adaptation to the impacts of fragmentation and climate change.

There is now a general consensus in the literature that connectivity is best defined by the interaction between particular species and the landscape in which they occur (Crooks and Sanjayan, 2006). A functional approach recognises that connectivity is essentially a species-based attribute, with a single landscape having many possible connectivity measures based on the habitat requirements and dispersal ability of particular species. Functional approaches also address the influence of the landscape matrix in promoting or hindering species movement, through the assessment of the degree to which a landscape structure facilitates or impedes the movement of individuals among habitat patches (Taylor *et al.*, 1993; With *et al.*, 1997).

## *3.3 Aim of pilot study*

A new indicator is therefore required to meet UK commitments, and to capture the type of conservation action being promoted in existing, fragmented landscapes. The specific aim for the pilot study is to:

**Identify and test the most suitable and accepted methodology and data sources for the production of UK and country level indicators of functional habitat connectivity and provide recommendations for further development.**

As a consequence of the review in Section 3, and using the DPSIR indicator framework (Driving forces, Pressure, State, Impact, and Response) (Figure 3) (European Environment Agency, 2003), the proposed habitat connectivity indicator is essentially an indicator of the 'state' of the landscape and its 'impact' on habitat connectivity for biodiversity.

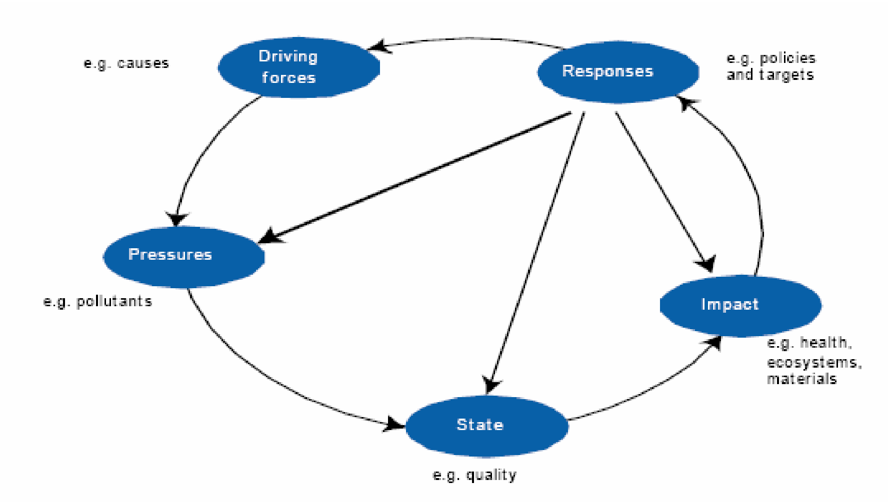



**Figure 3** - The DPSIR framework for reporting on environmental issues (European Environment Agency, 2003).

Within this indicator framework (Figure 3) the drivers of landscape change may include land use / agricultural change, urbanisation, climate change, and specific actions to improve landscape structure, connectivity and interactions between them.

The proposed indicator is focussed upon the *state* of the landscape, as a product of landscape drivers, and the relative *impact* of these on habitat connectivity and temporal *change*. Therefore, the following three steps are necessary to develop an effective indicator:

1. **State** – the need for spatial land-cover data which captures those landscape features which impact on habitat connectivity as identified in Section 3.1:
    - Area
    - Isolation
    - Edge
    - Matrix

2. **Impact** – the need for functional connectivity measures, as opposed to structural measures, to assess the interplay between species responses, landscape attributes, and their potential impact on habitat connectivity as identified in Section 3.2.

3. **Change** – the need for temporal data to assess the change in the state of the landscape and the relative impact on habitat connectivity.

To assist the development of an effective indicator a set of 13 criteria have been proposed for this study (Table 2); building on existing criteria used for the EEA core set of indicators and the CBD national level indicators (SEBI2010 Expert Group, 2005).

**Table 2** – Indicator criteria adapted from EEA and CBD indicator criteria (SEBI2010 Expert Group, 2005).

| No. | Criteria |
|---|---|
| **1** | Policy relevant and meaningful |
| **2** | Biodiversity relevant |
| **3** | Scientifically sound and methodologically well founded |
| **4** | Progress towards 2010 targets |
| **5** | Broad acceptance and easy to understand |
| **6** | Affordable monitoring, available and routinely collected data |
| **7** | Affordable modelling |
| **8** | Spatial and temporal coverage of data |
| **9** | National scale and representativeness of data |
| **10** | Sensitive to detect change |
| **11** | Representative of DPSIR framework |
| **12** | Small number – low complexity |
| **13** | Aggregation and flexibility – range of scales |

The steering group also identified a need for the indicator to assess the impact of changes in the area, isolation, edge, matrix, and persistence of habitats (item 2 & 3 in Table 2). The primary success criterion for the indicator was agreed to be sensitivity to detect change (item 10) in functional connectivity (item 2 & 3) using existing data (item 6). Secondary success criteria included the capacity for the indicator to: fit the required monitoring interval (item 1 & 4), and be easily measured (item 7 & 12), understandable (item 3 & 5) and repeatable (item 6).

# 4 Broad habitatMethods

## 4.1 Overall approach

The primary purpose of the indicator is to detect change in habitat connectivity through time. To accomplish this, spatial data must capture the defined landscape features over a large spatial extent to allow UK and country level reporting, have high spatial resolution to accurately capture small features, and have the ability to capture change through time. This section describes the choice of appropriate spatial data, the pre-treatment applied to the spatial data to permit the testing, and finally the selection of connectivity measures for testing (Figure 4).

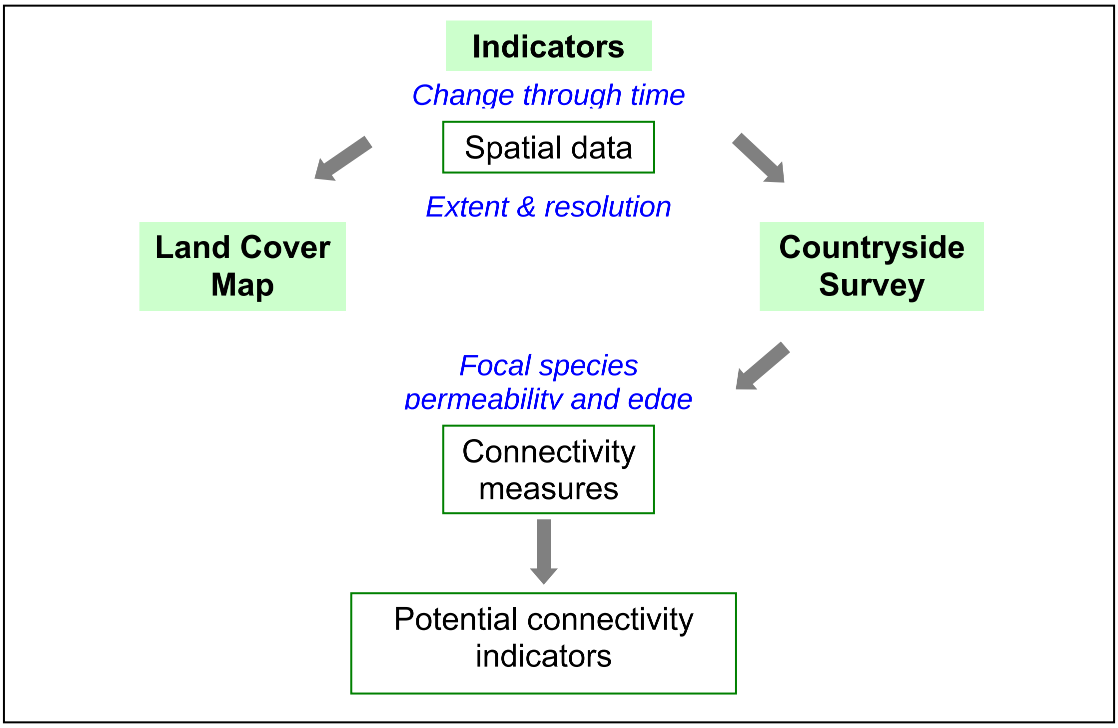



**Figure 4** – Overview of indicator development process.

The existing spatial data, Land Cover Map (LCM) and Countryside Survey (CS) developed by the Centre for Ecology and Hydrology (CEH) appeared to offer the greatest potential. LCM data is extensive covering the whole of the UK, but at a relatively low spatial and ecological resolution. In comparison, CS sample squares are limited in extent but offer very high resolution and ecological detail. Both data sets map the landscape features of habitat and matrix, and have the potential to detect change between snapshots at different times. These two contrasting data sets also appeared to provide the opportunity to examine scale issues, in terms of data extent and resolution. However, initial testing revealed the LCM is currently unsuitable for the specific purpose of testing and applying a connectivity indicator in the near future. An account of the steps leading to this decision is provided in Appendix 1. The remainder of this report uses the CS data.

A number of connectivity measures were applied to CS data. The analysis focussed upon 'potential' connectivity measures which have the ability to combine physical landscape attributes with limited species-based information (landscape permeability and edge impacts) and provide a measure of potential connectivity. Measures range from fairly simple metrics to more complex analyses, providing a balance between the data required for parameterisation and the information they yield. The following section explains the methods in more detail.

## *4.2 Spatial data*

The digital dataset used within this pilot study is Countryside Survey: Field Survey produced by the Centre for Ecology and Hydrology (CEH).

### *4.2.1 Countryside Survey: Field Survey*

The Field Survey component of Countryside Survey, developed by CEH, is a study or 'audit' of the natural resources of the UK countryside (Haines-Young *et al.*, 2000). This has been achieved from an in-depth field study of a sample of 1km sample squares throughout the UK. The sample of 629 sample squares represents all the major habitat types in the UK, with quantitative and qualitative information recorded on Broad and Priority habitats, as well as linear and point features. The Countryside Survey has included landscape features in surveys undertaken in 1984, 1990, 1998 and 2007.

For this pilot indicator study, CEH provided CS data for sixteen 1km sample squares at two date points: 1990 and 1998. The data were supplied in two distinct forms: land cover as polygons and linear features as polylines.

**Addition of linear features**
Following consultation with the project steering group and CEH, selected linear features were included in the pilot study (Table 3). Linear features such as hedgerows and roads may have a significant effect on habitat connectivity, either as a conduit or barrier to movement (Eycott *et al.*, 2008).

**Table 3** - Linear features to be included in the indicator pilot study.

| Land Use | Habitat | General definition* |
|---|---|---|
| Woodland | Forestry | Band of trees or scrub <5m wide |
| | Woodland Linear Feature (WLF) Natural Shape | Unmanaged line of trees or scrub |
| | WLF Unnatural Shape | Managed line of trees or scrub |
| Transport | Constructed tracks | Track manufactured with stone or hard material |

*Additional information concerning the creation and meaning of linear features can be found in the Countryside Survey Field Handbook.

In order to utilise linear features in the assessment of habitat connectivity it was necessary to represent the polylines as polygons and convert these features into a raster environment for spatial modelling. All woodland linear features were included as conduits with high permeability for movement, rather than as habitat. Constructed tracks were included as potential barriers with low permeability. Rivers were included in CS as polygons with a minimum width of 2.5m. The addition of smaller streams and rivers of less than 2.5m width was considered unnecessary, adding too much complexity.

To convert linear features into polygons, selected features were buffered and added to the main dataset as polygons (as outlined in Table 4 below). Different buffer widths were used for the two linear features to ensure that, for example, a woodland linear feature would not be obscured by a road should both occur on the same polyline.

**Table 4** - Buffer applied to the linear feature and the new Broad Habitat classification created.

| Land Use | Buffer Applied | New Broad Habitat |
|---|---|---|
| Woodland | 5 m | Woodland Linear Features |
| Transport | 2.5 m | Road Linear Features |

**Selection of sample squares**
Of the 16 CS sample squares provided by CEH, 10 were selected as suitable for further analysis (details in Appendix 2 - Section 9). The two criteria were that the CS sample square should contain woodland habitat in both time frames; and that the sample square should demonstrate a degree of landscape change.

## *4.3 Data resolution*

The representation of narrow linear features, such as roads and rivers, within raster data can be problematic. If a coarse raster resolution is used, linear features may cease to be continuous and shortcuts, or ‘cracks’, are artificially created (Rothley, 2005). This can cause errors in calculating functional distance (for example in the least-cost approach) by effectively creating shortcuts through barriers that would otherwise have low permeability. Even relatively few cracks can effectively compromise the least-cost approach, as illustrated in Figure 5.

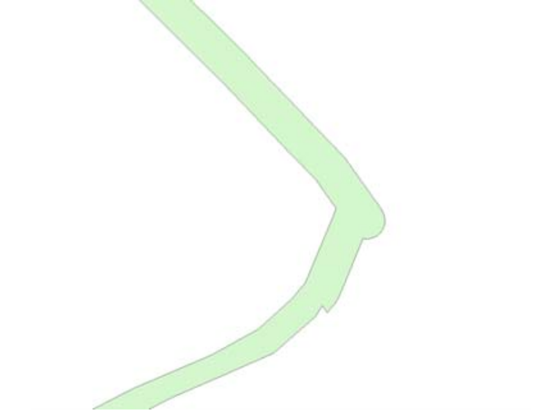
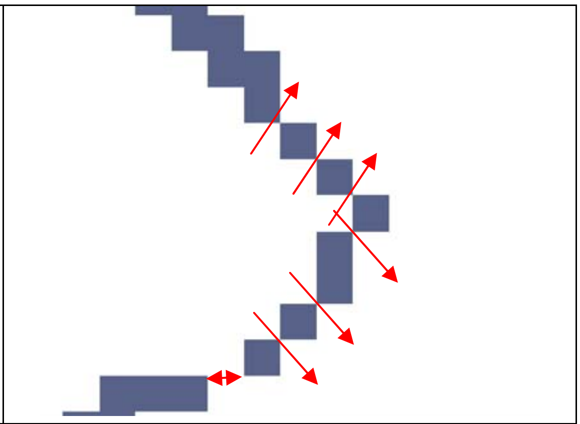
|  |  |
|---|---|
| A single linear feature represented as a polygon | After rasterisation the single feature has split into two without a diagonal neighbour (identified by short red arrow). There are also six cracks (long red arrows) with diagonal neighbours through which connectivity is calculated |

**Figure 5** – Problem of rasterising linear features.

Choice of resolution for a raster is a balance between accurate spatial representation of data and the computational time for the connectivity analysis. To determine a suitable raster resolution we used a bespoke GIS tool to compare different resolutions with the original vector datasets. The tool creates simple measures of the number of features and area assigned to each land-cover type, as well as more advanced measures which determine how individual features are affected by the conversion to raster. The analysis was applied to: 0.1, 0.5, 1, 5 and 10m resolution grids for a number of CS sample squares. An example output from one CS is shown in Table 5, but can be considered representative of other sample squares.

**Table 5** - The output from resolution analysis for one CS sample square.

**Count of features by type**

| **Test variable** | **Vector data: No. polygons** | **Raster data: resolution (m) 0.1** | **0.5** | **1** | **5** | **10** |
|---|---|---|---|---|---|---|
| Arable and Horticulture | 1 | 1 | 1 | 1 | 1 | 1 |
| Boundary and Linear Features | 7 | 7 | 7 | 7 | 7 | 10 |
| Broadleaved Mixed and Yew Woodland | 19 | 19 | 19 | 19 | 19 | 16 |
| Calcareous Grassland | 7 | 7 | 7 | 8 | 7 | 8 |
| Improved Grassland | 6 | 6 | 6 | 6 | 6 | 6 |
| Neutral Grassland | 2 | 2 | 2 | 2 | 2 | 2 |
| Urban | 1 | 1 | 1 | 1 | 1 | 1 |

**Area of features by type**

| **Test variable** | **Vector data: polygon area ($m^2$)** | **Raster data: resolution (m) 0.1** | **0.5** | **1** | **5** | **10** |
|---|---|---|---|---|---|---|
| Arable and Horticulture | 162 | 162 | 162 | 163 | 175 | 100 |
| Boundary and Linear Features | 27,065 | 27,065 | 27,059 | 27,072 | 27,125 | 27,200 |
| Broadleaved Mixed and Yew Woodland | 419,392 | 419,395 | 419,410 | 419,440 | 419,600 | 420,200 |
| Calcareous Grassland | 272,594 | 272,592 | 272,600 | 272,584 | 272,675 | 271,700 |
| Improved Grassland | 274,713 | 274,711 | 274,727 | 274,698 | 274,450 | 274,800 |
| Neutral Grassland | 5,226 | 5,226 | 5,224 | 5,228 | 5,250 | 5,200 |
| Urban | 753 | 753 | 753 | 751 | 725 | 800 |

**Count of features by type**

| **No. of splits in features** | **Raster data: resolution (m) 0.1** | **0.5** | **1** | **5** | **10** |
|---|---|---|---|---|---|
| No Split | 42 | 42 | 41 | 42 | 38 |
| 2 Splits | | | 1 | | 3 |
| 3 Splits | 1 | 1 | 1 | 1 | 2 |
| 4 Splits | | | | | |
| 5 Splits | | | | | |
| 5+ Splits | | | | | |
| No. Disappeared | | | | | |

**Percentage area change in feature**

| **Feature area change** | **Raster data: resolution (m) 0.1** | **0.5** | **1** | **5** | **10** |
|---|---|---|---|---|---|
| 1-5% Change | 42 | 42 | 42 | 37 | 25 |
| 5-10% | | | | 4 | 5 |
| 10-20% | 1 | 1 | 1 | 2 | 8 |
| 20-30% | | | | | 3 |
| 30-50% | | | | | 2 |
| 50-100% | | | | | |
| +100% | | | | | |
| No. Disappeared | | | | | |

The results clearly showed that there was no improvement in accuracy to be gained from running the analysis at a resolution of less than 1m. The increase in processing time required to analyse higher resolution grids is not linear; this would be important in country-wide implementation of an indicator but was not a limiting factor in the pilot due to the small size of the study areas. There was reduced accuracy at a resolution coarser than 1m, so that running the analysis at 1m resolution appeared the ideal choice.

## *4.4 Understanding species/landscape interactions*

As habitat connectivity is a species-based attribute (see Section 3.2) there is a need to adopt a focal species approach to assessment of habitat connectivity (Lambeck, 1997; Caro and O'Doherty, 1999; Caro, 2000). A woodland-based species was utilised for this pilot study as this aligns with the proposed EU SEBI2010 indicator (see Table 1). Woodland habitat has also experienced considerable loss and fragmentation in the UK landscape, and is the focus of much conservation activity. In light of the limited and heterogeneous nature of information on the interaction between species and the UK landscapes (see Eycott *et al.* 2008), a generic focal species was adopted. A generic focal species is a conceptual species, whose profile consists of a set of ecological requirements (habitat preference and dispersal potential) which are intended to reflect the likely needs of real species (Eycott *et al.*, 2007). The profile is based on expert opinion, and allows tests of methodology in the absence of data on 'real' species. In this case it has allowed the exploration of landscape permeability and detrimental edge impacts in relation to the selected woodland focal species. Profiles relating to real species could be substituted in time and with increased availability of appropriate empirical data.

### *4.4.1 Landscape permeability*

Landscape permeability is related to the degree to which the landscape structures facilitates or impedes movement of individuals among habitat patches. Although the use of empirical data is desirable to assess permeability, in most cases it is unavailable (Eycott *et al.*, 2008). For the pilot study it was agreed to use a Delphi approach to determine the values for landscape permeability and the extent of the detrimental edge impact to be used in parameterisation of connectivity models. The Delphi approach is commonly used to gather expert knowledge in a systematic, objective and transparent manner (MacMillan and Marshall, 2006). Although there has been criticism about potential for subjectivity, and that the values are vulnerable to expert bias or speculation, MacMillan and Marshall (2006) concluded that the approach is appropriate 'if the Delphi process is sufficiently rigorous and transparent and allows for sufficient debate and consensus building'.

The steering group suggested that an analysis be undertaken to examine similarities between the composition of broad-leaved woodland and other Broad Habitat types. This was intended to inform the selection of appropriate permeability values for various habitat types, as part of the background to the Delphi process. The analysis was conducted by Ed Mountford of JNCC, who examined the plant species attributes and Broad Habitat associations given in

PLANTATT (Hill *et al.*, 2004). The first part of the analysis looked at the Broad Habitat preferences of 211 plant species listed therein which prefer broad-leaved, mixed and yew woodland habitat. For each Broad Habitat the number of species that preferred this habitat *and* broad-leaved, mixed and yew woodland was determined. Secondly, the height of plant species that preferred broad-leaved, mixed and yew woodland was compared against the height of those preferring other Broad Habitat types. The results were shared with the group and helped underpin the permeability values shown in Table 6.

Permeability values relate to the degree to which land cover types permit species movement – in this case based upon their similarity to woodland habitats as represented by vegetation composition and vertical structure. The relative scores used for permeability affects the distance that a species can potentially move through a landscape. For example, a species can only move half as far through a landscape with a permeability value of 10 as one with a value of 5, and only a tenth of that possible in a landscape matrix with value of 1.

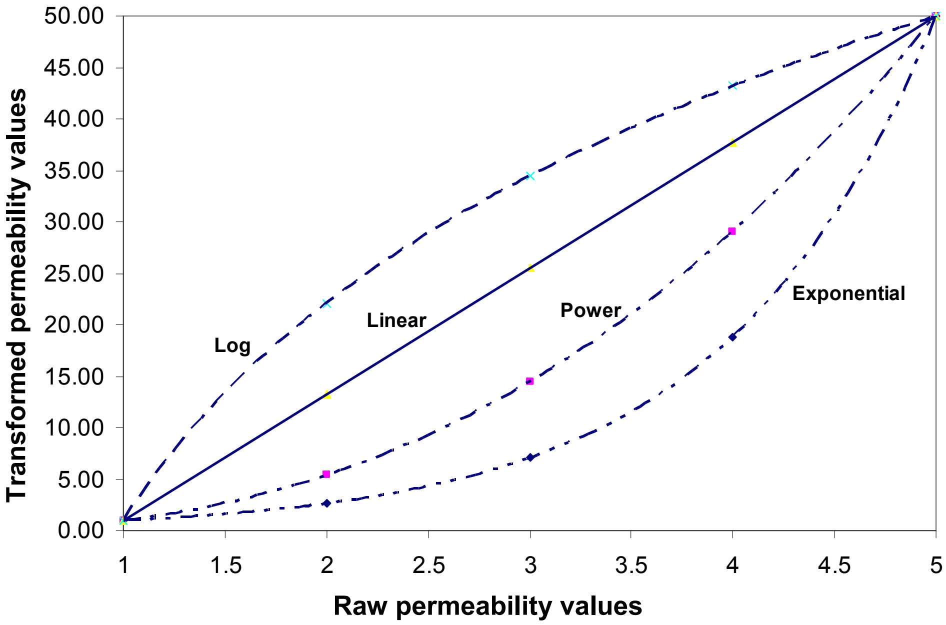
Three stakeholders suggested permeability values and these were incorporated with values from previous studies. Members of the Native Woodland Habitat Action Group (NWHAP) were also invited to participate in the process. The raw data are summarised in Table 6. Contributors used different scales, so the values could not simply be combined (averaged).

**Table 6** - Raw permeability values created by the first stage of the Delphi Analysis

| | Contributor | | | | |
|---|---|---|---|---|---|
| **Broad Habitat Classification** | **1*** | **2*** | **3+** | **4#** | **5#** |
| Acid Grassland | 4 | 4 | 2 | 30 | 35 |
| Arable and Horticulture | 5 | 5 | 3 | 50 | 40 |
| Bog | 4 | 3 | 3 | 25 | 35 |
| Boundary and Linear Features | 3 | 3 | 1 | | 30 |
| Bracken | 4 | 3 | 2 | 20 | 26 |
| Broadleaved Mixed and Yew Woodland | 1 | 1 | 1 | 1 | 1 |
| Calcareous Grassland | 4 | 4 | 3 | 30 | 35 |
| Coniferous Woodland | 3 | 4 | 1 | 20 | 16 |
| Dwarf Shrub Heath | 4 | 3 | 2 | 20 | 30 |
| Fen, Marsh, Swamp | 4 | 3 | 2 | 20 | 30 |
| Improved Grassland | 5 | 5 | 3 | 50 | 40 |
| Inland Rock | 3 | 2 | 2 | 50 | 45 |
| Littoral Rock | 5 | 5 | 3 | 50 | 50 |
| Littoral Sediment | 5 | 5 | 3 | 50 | 50 |
| Montane | 4 | 4 | 3 | 40 | 35 |
| Mosaic | 4 | 3 | 2 | | 30 |
| Neutral Grassland | 4 | 4 | 3 | 30 | 35 |
| No Allocation | 4 | 4 | | | 50 |
| Rivers and Streams | 5 | 3 | 1 | 50 | 30 |
| Road Linear Features | 5 | 3 | 3 | 40 | 30 |
| Sea | 5 | 5 | 3 | 50 | 50 |
| Standing Open Waters and Canals | 4 | 4 | 2 | 50 | 45 |
| Supra-littoral Rock | 5 | 5 | 3 | 50 | 50 |

| | | | | | |
|---|---|---|---|---|---|
| Supra-littoral Sediment | 5 | 5 | 3 | 50 | 50 |
| Urban built up areas & gardens | 5 | 3 | 3 | 30 | 30 |
| Woody Linear Features | 2 | 1 | 1 | 1 | 1 |
| * Scores ranging from 1 to 5,+ Scores ranging 1 to 3, # Scores ranging from 1 to 50 | | | | | |

For the permeability values to be comparable each range (1-3, 1-5, 1-50) was subject to a normalisation transformation. This was achieved by stretching the scores to reflect commonly used values; for this study 1-50 was used. The equation of the line with which to transform the permeability values can be created in four ways: an exponential, power, linear and log transformation as detailed in Figure 6. The exponential transformation appears to overestimate landscape permeability; whereas a log transformation causes an apparent underestimation of permeability. Normalisation using a power transformation provided a less skewed and more normal distribution of values (see bottom left Table in Figure 6). The final transformed permeability values are presented in Table 7, and the mean values were used in the remainder of the pilot study.




| | Exponential | Power | Linear | Log |
|---|---|---|---|---|
| 1 | 1.00 | 1.00 | 1.00 | 1.00 |
| 2 | 2.66 | 5.39 | 13.25 | 22.10 |
| 3 | 7.07 | 14.45 | 25.50 | 34.45 |
| 4 | 18.80 | 29.07 | 37.75 | 43.21 |
| 5 | 50.00 | 50.00 | 50.00 | 50.00 |

Values of the original score after transformation

| | Linear | Power |
|---|---|---|
| "1-10" | 2 | 2 |
| "10-20" | | 6 |
| "20-30" | 5 | 3 |
| "30-40" | 10 | 8 |
| "40-50" | 9 | 7 |

Spread of transformed values

**Figure 6** – Normalisation of permeability values with different starting ranges.

**Table 7** – Transformed permeability values based on a power transformation. Mean values were used in the pilot study.

| | Contributor | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Broad Habitat Classification** | **1** | **2** | **3** | **4** | **5** | | **Min** | **Max** | **Mean** |
| Acid Grassland | 29 | 29 | 12 | 30 | 26 | | 12 | 30 | **25** |
| Arable and Horticulture | 50 | 50 | 50 | 50 | 33 | | 33 | 50 | **47** |
| Bog | 29 | 14 | 50 | 25 | 26 | | 14 | 50 | **29** |
| Boundary and Linear Features | 14 | 14 | | | 20 | | 14 | 20 | **16** |
| Bracken | 29 | 14 | 12 | 20 | 14 | | 12 | 29 | **18** |
| Broadleaved Mixed and Yew Woodland | 1 | 1 | 1 | 1 | 1 | | 1 | 1 | **1** |
| Calcareous Grassland | 29 | 29 | 50 | 30 | 26 | | 26 | 50 | **33** |
| Coniferous Woodland | 14 | 29 | | 20 | 7 | | 7 | 29 | **18** |
| Dwarf Shrub Heath | 29 | 14 | 12 | 20 | 20 | | 12 | 29 | **19** |
| Fen, Marsh, Swamp | 29 | 14 | 12 | 20 | 20 | | 12 | 29 | **19** |
| Improved Grassland | 50 | 50 | 50 | 50 | 33 | | 33 | 50 | **47** |
| Inland Rock | 14 | 5 | 12 | 50 | 41 | | 5 | 50 | **24** |
| Littoral Rock | 50 | 50 | 50 | 50 | 50 | | 50 | 50 | **50** |
| Littoral Sediment | 50 | 50 | 50 | 50 | 50 | | 50 | 50 | **50** |
| Montane | 29 | 29 | 50 | 40 | 26 | | 26 | 50 | **35** |
| Mosaic | 29 | 14 | 12 | | 20 | | 12 | 29 | **19** |
| Neutral Grassland | 29 | 29 | 50 | 30 | 26 | | 26 | 50 | **33** |
| No Allocation | 29 | 29 | | | 50 | | 29 | 50 | **36** |
| Rivers and Streams | 50 | 14 | | 50 | 20 | | 14 | 50 | **34** |
| Road Linear Features | 50 | 14 | 50 | 40 | 20 | | 14 | 50 | **35** |
| Sea | 50 | 50 | 50 | 50 | 50 | | 50 | 50 | **50** |
| Standing Open Waters and Canals | 29 | 29 | 12 | 50 | 41 | | 12 | 50 | **32** |
| Supra-littoral Rock | 50 | 50 | 50 | 50 | 50 | | 50 | 50 | **50** |
| Supra-littoral Sediment | 50 | 50 | 50 | 50 | 50 | | 50 | 50 | **50** |
| Urban built up areas & gardens | 50 | 14 | 50 | 30 | 20 | | 14 | 50 | **33** |
| Woody Linear Features | 5 | 1 | 1 | 1 | 1 | | 1 | 5 | **2** |

### *4.4.2 Edge values*

The edge values represent the deleterious impact of adjoining land cover types on habitat, often reflecting the intensity of land-use. In contrast to the relative nature of the permeability values, steering group members involved in the Delphi process were asked to contribute their estimates for different land cover types of the actual distance over which edge impacts may penetrate into woodland. Contributors were also asked to provide a justification/rationale for their values. The values are summarised in Table 8 and were used as a general guide to inform the choice of final edge impact values. The steering group agreed that semi-natural habitats would have no detrimental impact, whereas intensive agricultural and urban landscapes would have a significant edge impact.

**Table 8** – Edge impact values (m) from Delphi analysis process. Final values were used in the pilot study.

| | Contributor | | | | |
|---|---|---|---|---|---|
| **Broad Habitat Classification** | **1** | **2** | | **Mean** | **Final** |
| Acid Grassland | 0 | 5 | | 3 | **0** |
| Arable and Horticulture | 50 | 10 | | 30 | **30** |
| Bog | 0 | 5 | | 3 | **0** |
| Boundary and Linear Features | 0 | 5 | | 3 | **0** |
| Bracken | 0 | 5 | | 3 | **0** |
| Broadleaved Mixed and Yew Woodland | 0 | 0 | | 0 | **0** |
| Calcareous Grassland | 0 | 5 | | 3 | **0** |
| Coniferous Woodland | 2 | 5 | | 3 | **0** |
| Dwarf Shrub Heath | 0 | 5 | | 3 | **0** |
| Fen, Marsh, Swamp | 0 | 5 | | 3 | **0** |
| Improved Grassland | 25 | 10 | | 18 | **15** |
| Inland Rock | | 5 | | 5 | **0** |
| Littoral Rock | 0 | 5 | | 3 | **0** |
| Littoral Sediment | 0 | 5 | | 3 | **0** |
| Montane | 0 | 5 | | 3 | **0** |
| Mosaic | 0 | 5 | | 3 | **0** |
| Neutral Grassland | 0 | 5 | | 3 | **0** |
| No Allocation | 0 | | | 0 | **0** |
| Rivers and Streams | 0 | 3 | | 2 | **0** |
| Road Linear Features | 100 | 3 | | 52 | **30** |
| Sea | 0 | 3 | | 2 | **0** |
| Standing Open Waters and Canals | 0 | 3 | | 2 | **0** |
| Supra-littoral Rock | 0 | 5 | | 3 | **0** |
| Supra-littoral Sediment | 0 | 5 | | 3 | **0** |
| Urban built up areas & gardens | 100 | 10 | | 55 | **30** |
| Woody Linear Features | 0 | 5 | | 3 | **0** |

## 4.5 *Alternative area and distance options*

To investigate different aspects of landscape fragmentation on habitat connectivity a number of alternative area and distance options were created. Alternative options ranged from simple landscapes with no representation of edge impact and only straight-line (Euclidean) distance estimates; to more complex, realistic options which incorporated least-cost measures of distance based on landscape permeability (see Section 4.4.1) and a weighted edge impact (see Section 4.4.2). The area and distance options are explained further in the following sections.

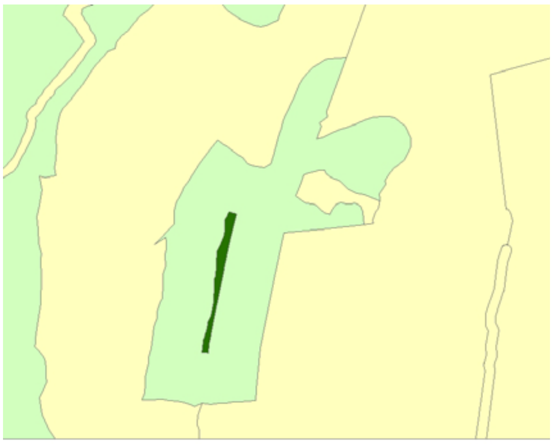
**Table 9** – Combinations of alternative area and distance options.

| | Distance option: | | | |
|---|---|---|---|---|
| **Area options:** | Euclidean distance | | Least-cost distance | |
| | 1990 | 1998 | 1990 | 1998 |
| Normal area – no edge | 1a | 1b | 1a | 1b |
| Core area – fixed edge | 2a | 2b | 2a | 2b |
| Core area – weighted edge | 3a | 3b | 3a | 3b |
| Permanent area | 4a | | 4a | |

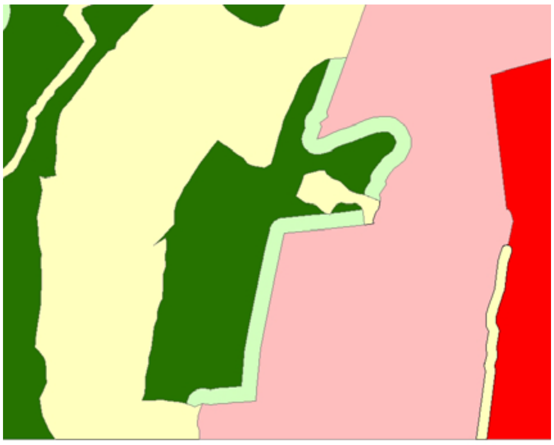
### 4.5.1 *Area options*

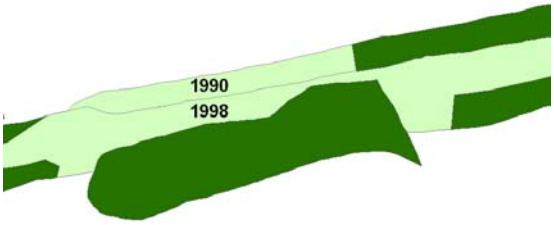
By altering the area of habitat used in the analysis it is possible to consider the relative impact of area, edge and matrix on habitat connectivity. Additionally by determining which areas of habitat are permanent through time, it is possible to examine temporal connectivity as well as spatial connectivity. For this study four habitat area options were created: *normal area* with no edge impact, *core area with a fixed edge* impact, *core area with a weighted edge* impact and *permanent area* for habitat that are persistent through time as illustrated in Figure 7.

Normal area – no edge



Core area – fixed edge






Core area – weighted edge Permanent area.

Habitat is shown as dark green and habitat which has been removed is light green; all other habitats are shown as yellow. For Core area – weighted the darker the red the larger the negative impact on core area, yellow is neutral.

**Figure 7** – Alternative area options.

*Normal area* is the control landscape for this analysis, 'broad-leaved, mixed and yew woodlands', without the inclusion of edge effects caused by the underlying matrix.

*Core area* is linked to deleterious edge impacts from contiguous matrix. The core area reflects the area of remaining habitat unaffected by external edge impacts. Two alternative approaches to assess edge impacts have been used:

1. *Core area fixed edge*. A commonly used internal fixed buffer of 50m. This buffer removes a 50m edge from all habitat patches irrespective of the adjacent land cover/land use types.

2. *Core area weighted edge*, for which the buffer size is dependent on contiguous land cover/land use types as described in Section 4.4.2. This approach allows the negative edge impacts of the matrix to vary. For example, semi-natural habitats are considered to have no negative edge impact; whereas intensive landscapes such as arable and urban have a potentially large negative impact.

*Permanent area* describes those patches or partial patches of habitat that persist through time. This approach allows connectivity to be assessed through time; measuring how connectivity is maintained/improved between more mature habitats.

### *4.5.2 Distance options*

Isolation and the impact of the matrix were investigated using two alternative distance options:

1. *Euclidean* distance is defined as the straight line distance between two patches; it is a direct measure of isolation of patches without accounting for the intervening landscape matrix.

2. *Least-cost* distance is defined as the lowest possible cumulative resistance, based on landscape permeability values, between two patches.

Least-cost approaches have been widely used to calculate the functional distance between patches (Adriaensen *et al.*, 2003). Although more problematic to calculate the method takes account of landscape matrix information within the distance measurement. The landscape was divided into cells, with each cell having a permeability value derived from the Delphi analysis (see Section 4.4.1). For example, a permeability value of 10 incurs a least-cost distance 10 times the Euclidean distance between patches. Using a standard GIS least-cost path calculation the algorithm determines the path of least resistance between patches as illustrated in Figure 8.

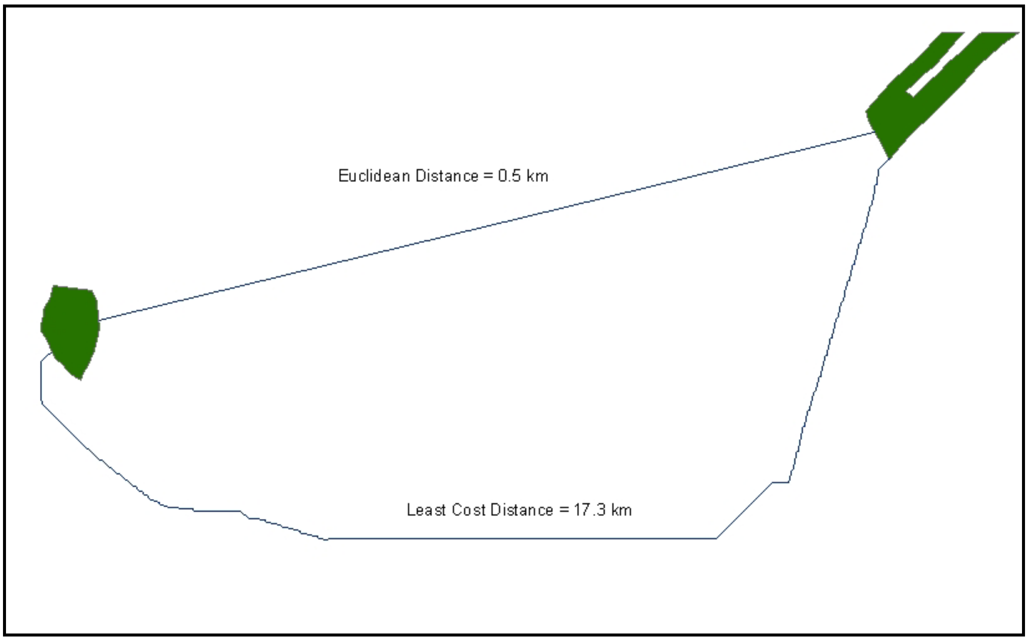



**Figure 8** - Euclidean and least-cost distance calculated between two patches.

### *4.6 Connectivity measures*

A number of indicators to apply to the test data were identified from literature and discussions with landscape and spatial ecologists. Calabrese and Fagan (2004) define different measurements of connectivity based on the level of detail required and the type of data available. They distinguish three classes of connectivity metric (structural, potential, and actual), based on an increasing level of detail (Table 10). Structural connectivity is derived from physical attributes of the landscape, such as size, shape, and location of habitat patches, but does not incorporate dispersal ability. Potential connectivity combines these physical attributes of the landscape with information about dispersal ability to predict how connected a given landscape or patch will be for a species. Actual connectivity relates to the observation of individuals moving into or out of focal patches, or through a landscape, and can provide an empirical estimate of the linkages between landscape elements or habitat patches.

**Table 10** - Classification framework for connectivity metrics (Calabrese and Fagan, 2004).

| *Connectivity metrics* | *Type of connectivity/ level of detail* | *Habitat-level data* | *Species-level data* | *Methodology* |
|---|---|---|---|---|
| Nearest neighbor distance | Structural | Nearest neighbor distance | Patch occupancy | Patch-specific field surveys |
| Spatial pattern indices | Structural | Spatially explicit | None | GIS/remote sensing |
| Scale–area slope | Structural | None | Point- or grid-based occurrences | Occurrence databases, presence/absence sampling |
| Graph-theoretic | Potential | Spatially explicit | Dispersal ability | GIS/remote sensing + dispersal studies |
| Buffer radius, IFM | Potential | Spatially explicit, including patch area | Patch occupancy and dispersal ability | Multi-year, patch-specific field surveys or single-year, patch occupancy study with dispersal study |
| Observed emigration, immigration, or dispersal rates | Actual | Variable, depends on methodology | Movement pathways or location-specific dispersal ability | Track movement pathways (specific methods depend on study organism), mark–release–recapture studies |

The focus of the pilot study was on ‘potential’ connectivity measures that have the ability to combine physical landscape attributes with limited species-based information. The use of these measures offers a pragmatic and implementable solution balancing data availability, model requirements, and output. The selected potential connectivity measures were applied to examine change in habitat connectivity in the selected CS sample squares.

Three groups of connectivity measures were applied to the alternative area and distance options outlined in Table 9:

1. **Graph theory**
2. **Buffer radius**
3. **Incidence Function Model (IFM) connectivity**

The connectivity measures are spatially-explicit and incorporate different degrees of species-level data and provide varying assessments of connectivity. The various measures are described in the next subsection and the inputs and outputs identified. Seven species-based landscape metrics were used to investigate the general change in landscape structure, aiding the interpretation of the connectivity measures.

### 4.6.1 Species-based landscape metrics

A limited number of simple landscape metrics with clear assumptions (Table 1), after Li and Wu (2004), were used to investigate the general change in the structure of the landscape within the CS sample squares and to support the interpretation of the connectivity measures. These metrics are considered as species/habitat-based as they are focussed on a specific habitat type – broad-leaved woodland.

**Table 11** - Summary of selected metrics with underlying ecological assumptions, adapted from Quine and Watts (in press).

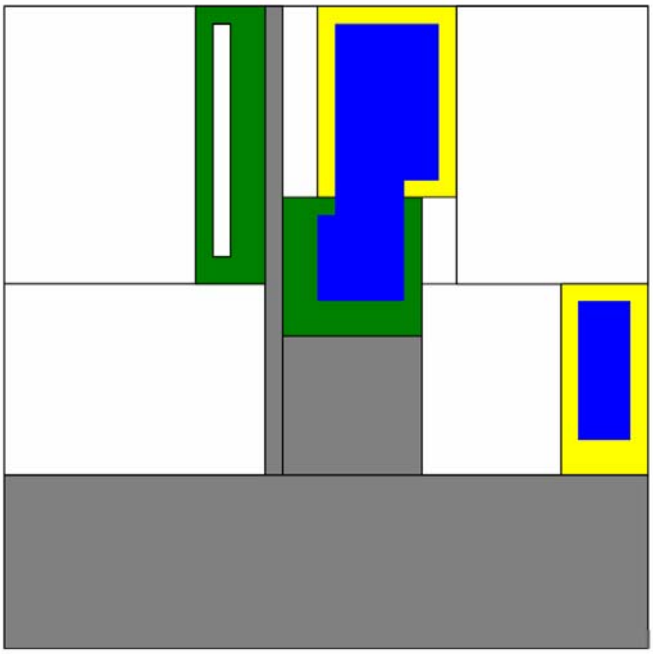
| Metrics | Underlying assumption | Relative increase | Relative decrease |
|---|---|---|---|
| ***Number of patches*** | Habitat composition | Unfavourable – more fragmented | Favourable – less fragmented |
| ***Area*** | Habitat availability | Favourable – more habitat | Unfavourable – less habitat |
| ***Perimeter*** | Edge impacts | Unfavourable – adverse effect on core species | Favourable – beneficial effect on core species |
| ***Nearest neighbour*** | Habitat configuration | Unfavourable – greater isolation | Favourable - reduce isolation |
| ***Core habitat – fixed edge*** | Core habitat – edge impact | Favourable – more core habitat | Unfavourable – less core habitat |
| ***Core habitat – weighted edge*** | Core habitat – edge impact | Favourable – more core habitat | Unfavourable – less core habitat |

Quine and Watts (in press) demonstrated the use of landscape metrics to assess the relative impact of two different woodland grant schemes (untargeted and targeted) in improving structural connectivity of woodlands. These metrics are simple, requiring minimal inputs, and provide outputs limited to the composition and configuration of the landscape rather than functional, connectivity (Table 12).

**Table 12** – Inputs and outputs for species-based landscape metrics.

| Inputs | Outputs |
|---|---|
| • Spatial land cover data<br>• Habitat preference – broad-leaved woodland<br>*Optional:*<br>• Edge impacts (none, fixed, weighted) | • Various landscape metrics |

The cumulative core area (CCA) of semi-natural habitat was also proposed as an additional 'landscape structure' metric to include in the pilot study (Woodland Trust, 2000, 2002). CCA is the 'contiguous area of woodland and semi-natural habitat not significantly affected by negative edge effects associated with intensive land use'. The indicator is a simple metric of the area of contiguous semi-natural habitat. Matrix information is incorporated using a negative edge effect in the same way as core area – weighted is calculated. The method to calculate CCA is illustrated in Figure 9.



Green = Habitat, Yellow = Low-intensity or semi-natural habitats, White = Arable or intensive habitats, Grey = Urban and artificial, Blue = CCA

**Figure 9** – Illustration of Cumulative Core Area (Woodland Trust, 2000, 2002).

### *4.6.2 Connectivity measures - Graph theory approaches*

Recent advances in Graph theory have provided robust and meaningful connectivity measures (Pascual-Hortal and Saura, 2006, 2007; Saura and Pascual-Hortal, 2007b). In a basic form, graph theory requires the construction of a mathematical graph of nodes (representing habitat patches) and edges (linkages between nodes) based on the spatial arrangement of habitat patches and species-specific characteristics (Figure 10).

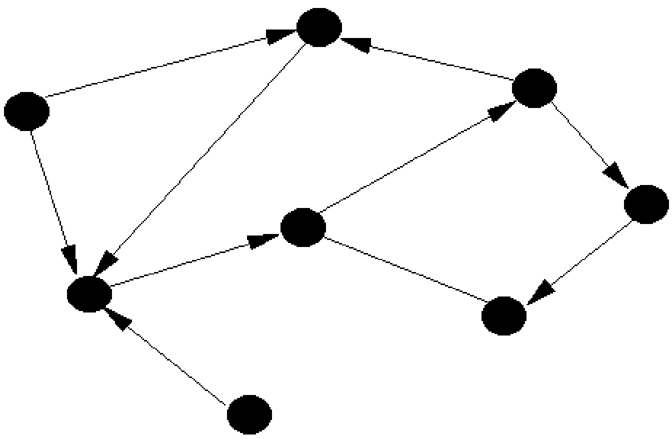


**Figure 10** – Illustration of graph theory with patches defined as nodes and links between them as edges.

The approach in the pilot was based on the work of Saura and Pascual-Hortal, and used their Sensinode software (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007b). The inputs and outputs for the calculation of graph theory connectivity measures are detailed in Table 13. It is also possible to incorporate inputs to account for landscape permeability through the use of least-cost approaches to generate the edges between nodes.

**Table 13** – Inputs and outputs for graph theory connectivity measures.

| Inputs | Outputs |
|---|---|
| • Spatial land cover data<br>• Habitat preference – broad-leaved woodland<br>• Patch level species/area information (e.g. population, carrying capacity)<br>• Dispersal distance (binary)<br>• Dispersal curve (probabilistic)<br>*Optional:*<br>• Edge impacts (none, fixed, weighted)<br>• Permeability values | *Binary and probabilistic measures:*<br>• Graph metrics |

Specific inputs to the Sensinode software contain information on the nodes and edges of the graph. Each node was given a unique ID and patch area. A connection file gives information on the distances between nodes; both Euclidean and least-cost distances were used. Where appropriate, a maximum landscape attribute was included with a value set to equal the total area for a single CS sample square (1,000,000m$^2$). For all sample squares a maximum dispersal distance or threshold was set at 1000m with a probability of 5% of individuals being able to disperse this distance. The software program Sensinode computed the chosen indices, as described in the following paragraphs (adapted from Saura and Pascual-Hortal (2007a)).

**Binary indices**

- **Number of Links (NL)** - As a landscape is more connected, the total number of links will increase.

- **Number of Components (NC)** - A component is a set of nodes in which a connection exists between every pair of nodes; there is no path connecting nodes belonging to different components. A single isolated node can be considered as a component. As a landscape becomes more connected, it will present fewer components.

- **Harary Index (H)** - The Harary index will increase in value as the landscape becomes more connected.

$$H = \frac{1}{2}\sum_{i-1}^{n}\sum_{j-1,i\neq j}^{n}\frac{1}{nl_{ij}}$$

where:
$n$ is the total number of nodes in the landscape
$nl_{ij}$ is the number of links in the shortest path between patches $i$ and $j$

- **Class Coincidence Probability (CCP)** - The CCP index increases with improved connectivity and has a range from 0 to 1. CCP is defined as the probability that two randomly chosen points within the habitat will belong to the same component.

$$CCP = \sum_{i=1}^{NC}\left(\frac{c_i}{A_C}\right)^2$$

where:
$NC$ is the number of components in the landscape.
$c_i$ is the sum of the attributes of all the nodes belonging to that component
$A_C$ is the sum of the attributes of all habitat nodes in the landscape

- **Landscape Coincidence Probability (LCP)** - LCP can be considered as the probability that two random points in the landscape will either lie in the same patch or have a path between them, i.e. lie within the same component. With improved connectivity LCP will increase, ranging between 0 to 1. Both CCP and LCP can be considered generalizations of the degree of coherence.

$$LCP = \sum_{i=1}^{NC}\left(\frac{c_i}{A_L}\right)^2$$

where:
$NC$ is the number of components in the landscape
$c_i$ is the sum of the attributes of all the nodes belonging to that component
$A_L$ is the maximum landscape attribute

- **Integral Index of Connectivity (IIC)** – The IIC increases with improved connectivity and has a range of 0 to 1. IIC has been seen to outperform other indexes by Saura and Pascual-Hortal and is therefore the recommended binary index. As it is more computationally demanding, problems can be encountered with more complex landscapes.

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

Where:
$n$ is the total number of nodes in the landscape.
$a_i$ and $a_j$ are the attributes of nodes $i$ and $j$.
$nl_{ij}$ is the number of links in the shortest path between patches $i$ and $j$.
$A_L$ is the maximum landscape attribute.

**Probabilistic indices**

- **Flux (F)** and **Area-Weighted Flux (AWF)** - Both Flux and Area Weighted Flux will increase as the nodes become better connected in the landscape. Some authors have described them as equivalent to an incidence function model (IFM) (see Section 4.6.4).

$$F = \sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} p_{ij}$$

where:
$n$ is the total number of nodes in the landscape
$p_{ij}$ is the probability of direct dispersal between nodes $i$ and $j$

$$AWF = \sum_{i=1}^{n} \sum_{j=1, i \neq j}^{n} p_{ij} \cdot a_i \cdot a_j$$

where:
$n$ is the total number of nodes in the landscape.
$p_{ij}$ is the probability of direct dispersal between nodes $i$ and $j$

- **Probability of Connectivity (PC)** – this was recommended by Saura and Pascual-Hortal as the best probabilistic index. The index includes a measure of both inter and intra patch connectivity. PC increases with improved connectivity and ranges from 0 to 1.

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^{*}}{A_L^{\ 2}}$$

where:
$n$ is the total number of habitat nodes in the landscape.
$a_i$ and $a_j$ are the attributes of nodes $i$ and $j$.
$A_L$ is the maximum landscape attribute.
$p^*_{ij}$ is the maximum product probability of all paths between patches $i$ and $j$.

### *4.6.3 Connectivity measures - Buffer radius approaches*

Buffer radius calculations are simple binary-based measures of connectivity related to the amount of habitat within a defined buffer. These measures require limited inputs (Table 14) and are based on either a Euclidean or least-cost buffer, which incorporates matrix permeability based on dispersal distance. The output is the amount of habitat within the defined buffer, thus providing a binary measure of potential connectivity. Least-cost buffer radius approaches, as illustrated in Figure 11, have been used to infer potential connectivity and to define habitat networks within the UK to aid conservation planning (Ray *et al.*, 2004; Watts *et al.*, 2005; Catchpole, 2006; Moseley *et al.*, 2007).

**Table 14** – Inputs and outputs for buffer radius connectivity measures.

| Inputs | Outputs |
|---|---|
| • Spatial land cover data<br>• Habitat preference – broad-leaved woodland<br>• Dispersal distance<br>*Optional:*<br>• Edge impacts (none, fixed, weighted)<br>• Permeability values (least-cost) | *Binary measure:*<br>• Spatial habitat and network data<br>• Habitat and network metrics |

The two main inputs are land cover data to define suitable habitat (e.g. broad-leaved woodland) and dispersal distance to define the size of the buffer. To incorporate functional connectivity, in the form of a weighted least-cost buffer, permeability values for the landscape need to be utilised. The pilot study used a distance of 1000m when a least-cost approach was employed and 100m when using Euclidean distances, due to the small extent of the CS sample square. Outputs consisted of two files, one containing habitat, mirroring the area option used, and the other containing the network buffer. Calculation of buffer radius measures, and associated metrics, were conducted using a GIS buffer radius tool (Handley, pers. com.).

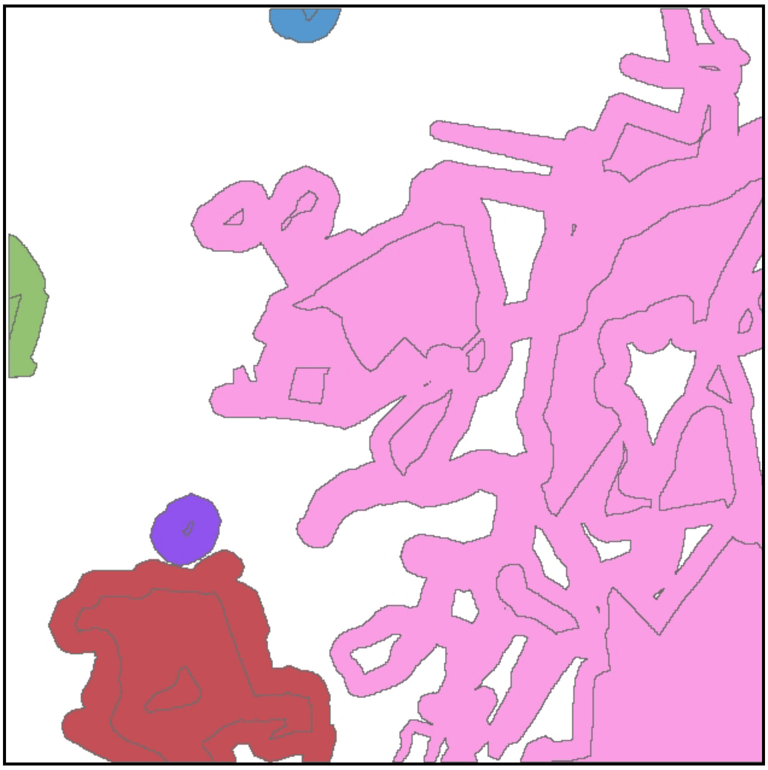


**Figure 11** – Habitats and networks, indicating potential connectivity, generated from a weighted edge (linked to edge impact values) least-cost buffer radius (linked to landscape permeability values). Discrete networks are signified by different colours. Habitat within each network is shown by an inner black line.

### 4.6.4 Connectivity measures - IFM / Connectivity calculation

A more complex, and potentially more realistic, connectivity measures based on the Incidence Function Model (IFM) was identified (Moilanen and Hanski, 2001; Vos *et al.*, 2001; Moilanen and Nieminen, 2002). The IFM calculates the potential number of individuals moving between patches in the landscape, taking into account the area (and even the quality of the patch) as a surrogate for population size, the distance between the patches, expressed as a Euclidean or least-cost function, and a dispersal curve. This is expressed by the following equation (Hanski, 1994):

$$S_i = \sum N_k e^{-\alpha D}.$$

Where:
$N_k$ is the population size in patch k (in this study it is based on area)
e is the natural exponent
D is the distance between patches i and k
α is a species-specific dispersal parameter

Larger high quality patches are assumed to contribute more to connectivity than smaller, lower quality patches with the same functional distance. The IFM approach is analogous to an area-weighted flux in the graph theory calculation (Section 4.6.2). IFM requires more inputs and an increase in parameterisation, but it may yield more informative probabilistic outputs (Table 15).

**Table 15** – Inputs and outputs for IFM connectivity measures.

| Inputs | Outputs |
|---|---|
| • Spatial land cover data<br>• Habitat preference – broad-leaved woodland<br>• Dispersal curve<br>• Patch level species/ area information<br>*Optional:*<br>• Edge impacts (none, fixed, weighted)<br>• Permeability values | *Probabilistic measure:*<br>• Spatial least-cost path data<br>• Connectivity and distance metrics<br>• Patch-based or grid -based connectivity measure |

The calculation of IFM/connectivity was based on a GIS connectivity tool developed by Forest Research (Handley, pers. com.). This tool also creates the necessary inter-patch distances (Euclidean or least-cost) for use in the graph theory calculations. Inputs include spatial habitat patch data (related to the alternative area options in Section 4.5), a raster landscape with permeability values, information on patch area (as a surrogate for population size) and dispersal curve information. The dispersal curve was created using a distance of 1000m with a 5% probability as illustrated in Figure 12.

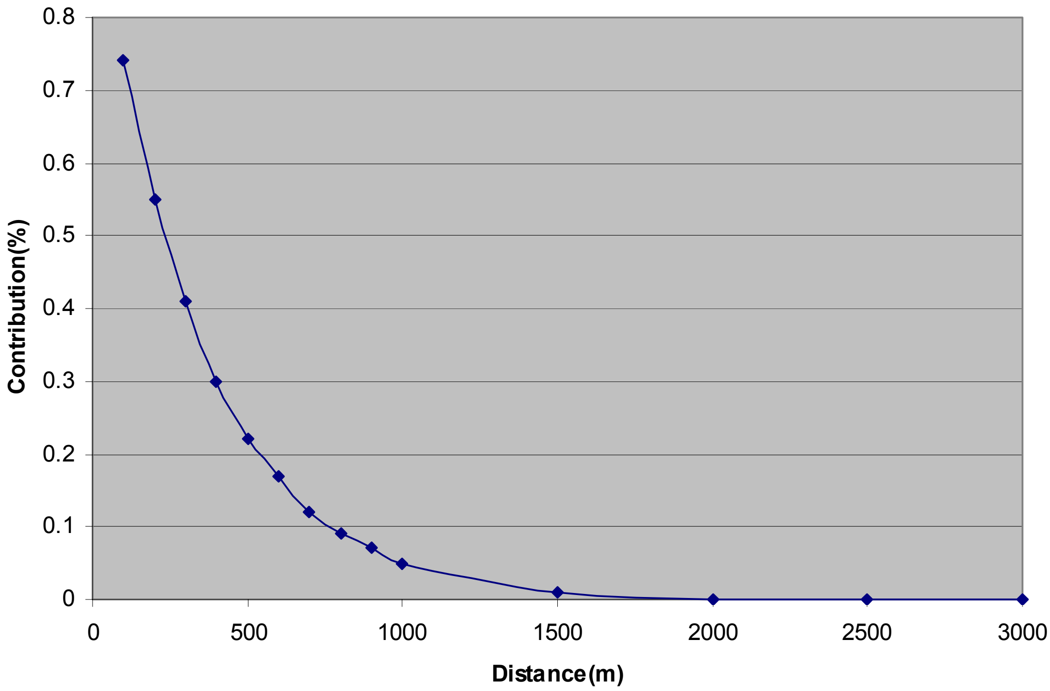



**Figure 12** – Dispersal curve used in IFM connectivity calculation (Hanski, 1994), based on 5% of individuals reaching 1000m.

Outputs from the analysis include the least-cost path between patches (Figure 13), Euclidean and least-cost distance between all patches, the connectivity between all patches (based on Euclidean and least-cost distance measures) as well as the total and mean connectivity for the whole landscape. IFM connectivity can be calculated at a patch or grid -based level.

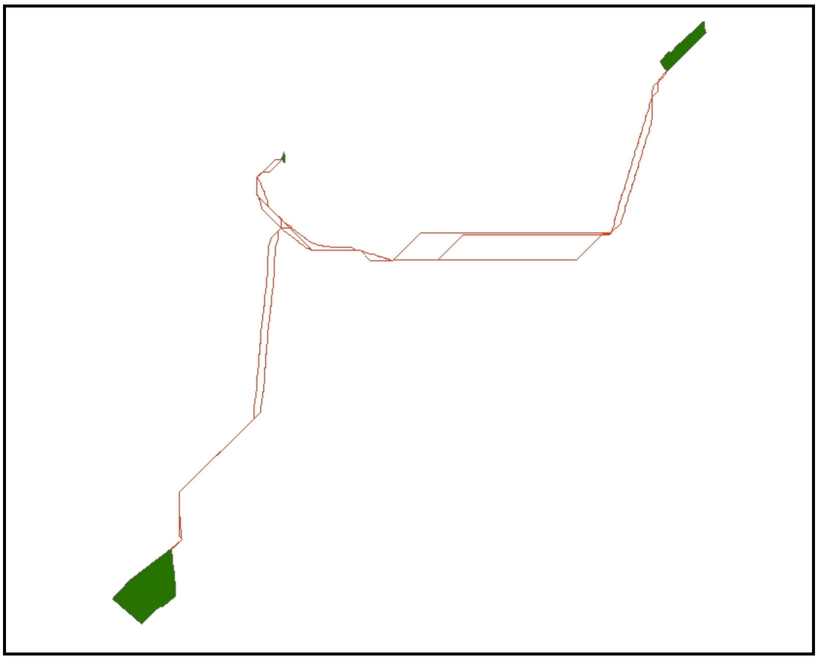


**Figure 13** – Illustration of least-cost paths (red lines) between fragmented woodland patches (green polygons) generated from the IFM tool.

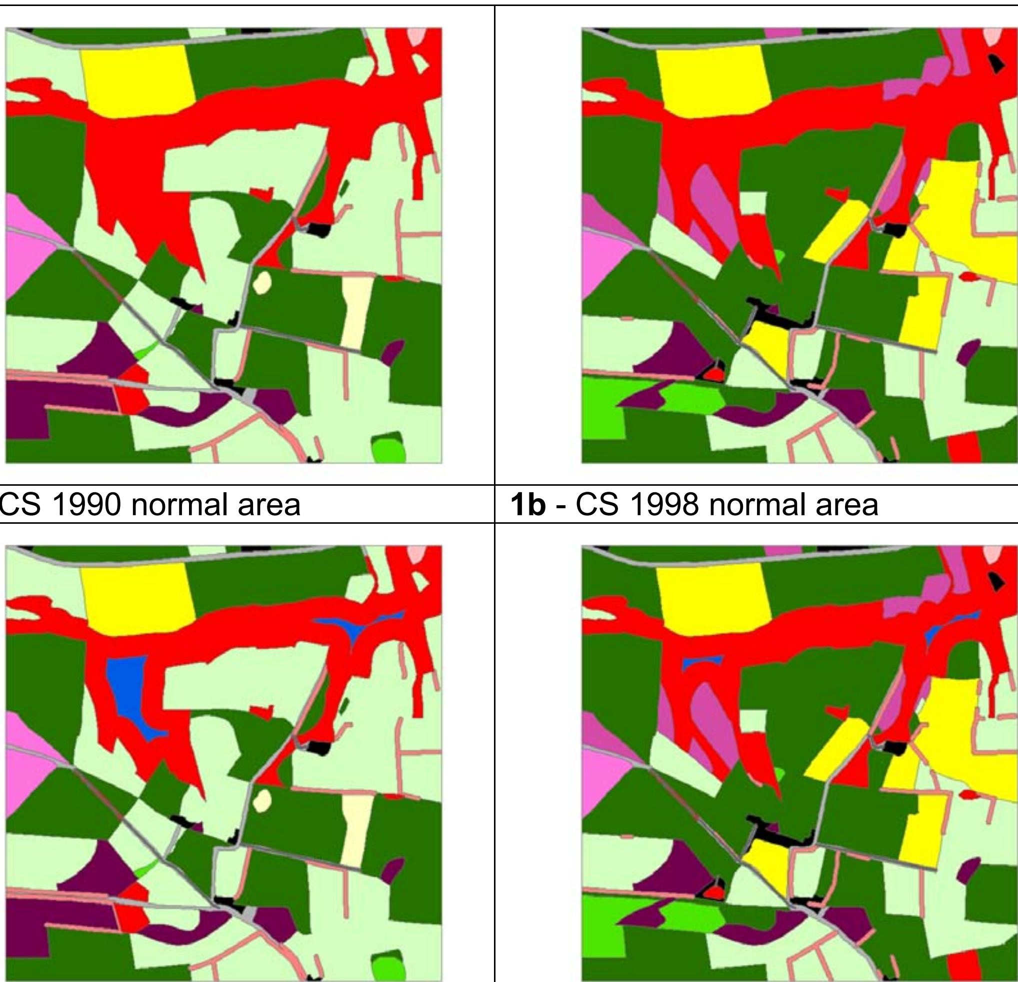
# 5 Results

The Results has been divided into two main sections. Firstly, a detailed examination of all the structural metrics and connectivity measures applied to a single example CS sample square, to identify the most promising connectivity measures (Section 5.1). The chosen CS sample square is considered to be representative of the wider sample. Secondly, key connectivity measures identified by this process were applied to the wider sample of 10 sample squares and the results contrasted (Section 5.3).

## 5.1 Connectivity analysis of a single CS sample square

### 5.1.1 Results for Species-based landscape metrics

Landscape metrics were used to investigate the general change in the structure of the landscape within the CS sample squares, and to assist the interpretation of the suite of connectivity measures. Figure 14 illustrates the land-cover data and alternative habitat area measurement options (see Section 4.5) used to investigate connectivity measures in detail for a single CS sample square (Grid 7 in Appendix 2) (red = original habitat area, blue = habitat area option).



| | |
|---|---|
| **1a** - CS 1990 normal area | **1b** - CS 1998 normal area |
| **2a** - CS 1990 core fixed | **2b** - CS 1998 core fixed |

**3a** - CS 1990 core weighted

**3b** - CS 1998 core weighted

**4a** - CS 1990 permanent


Legend

**Figure 14** – Illustration of the example CS sample square for two time periods with different habitat area options (as described in Section 4.5) applied. Red = original habitat area and Blue = habitat area option.

Changes occurred in the landscape between the two dates (Figure 14: 1a & 1b). The landscape was dominated by a central large habitat patch that was intruded by bracken (pink) in 1998. There was also an expansion of woodland (in the small triangular patch in the centre of the square) and of acid grassland (in the bottom right hand corner). In the bottom left corner, woodland changed (removal of one patch and shrinkage of another) to acid grassland. There was also change within the matrix, with neutral grassland converting to improved grassland and arable (denoted by change in figure from light green to dark green as seen in a large patch below the main woodland and a patch in the top left hand corner of the square). There has also been an apparent change to the length and extent of woodland linear features.

All the structural metrics were able to detect landscape change (Table 16). There were 8 distinct patches of woodland habitat in both 1990 and 1998, although the total and mean area of habitat decreased over the period (Table 16). Perimeter and nearest neighbour metrics increased (both mean and totals) between snapshots, both suggesting a change (increase) in fragmentation and a negative change to biodiversity (Table 11). These metrics are reflecting the loss of clustered woodland patches (in the bottom left corner) and the addition of an isolated patch (bottom right corner).

Figure 14 (2a & 2b) shows that the application of a fixed edge impact of 50m caused an apparent and considerable loss of habitat even where woodland was contiguous with a semi-natural matrix. Only 8% of the original area remained after the application of the fixed edge impact, reflecting the small, fragmented and linear woodland patches. In 1998, the encroachment of bracken (identified in pink) into the woodland habitat increased the habitat perimeter and caused a further reduction of habitat area, with only 2% of the original area remaining identified as habitat. Overall, the application of a fixed edge caused a reduction of habitat area from 14505m$^2$ in 1990 to only 2622m$^2$ in 1998 (Table 16).

The application of a weighted edge buffer (Figure 14 - 3a & 3b) resulted in more of the woodland area remaining identified as habitat, especially where the woodland is contiguous to a semi-natural matrix, and no edge impact is included. Although bracken has no edge impact, a general intensification of land use (as signified by a change in colour form light green to dark green) resulted in an overall reduction in habitat area from 82% in 1990 to 65% in 1998 (Table 16).

Cumulative Core Area (CCA), an additional structural measure, decreased markedly between survey years (Figure 15). This reflects both a decrease in woodland habitat and an increase in the hostility of the matrix. Table 16 details the calculated CCA for the example CS sample square; CCA is represented by the blue areas in Figure 17. The number and area of persistent habitat patches declined slightly between 1990 and 1998, but the proportion was relatively stable compared to the 1990 baseline.

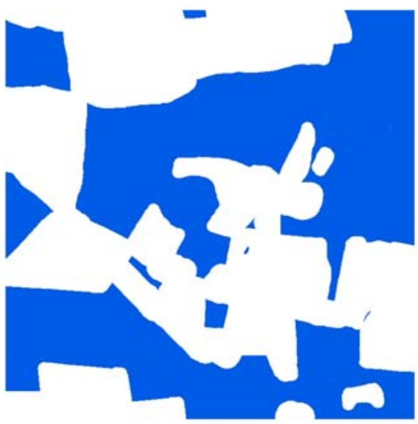
| CCA 1990 | CCA 1998 |
|---|---|
|  |  |

**Figure 15** - Illustration of a Cumulative Core Area (CCA) derived from the example CS sample square.

**Table 16** - Metric outputs for the example CS sample square. Arrows indicate the inferred impact on biodiversity in line with the interpreted outcomes in Table 11.

| **Metric** | | **1990** | **1998** | **Direction of change (see Table 11)** | **Persistent** |
|---|---|---|---|---|---|
| **no of patches** | | 8 | 8 | ↔ | 7 |
| **Area** | **Total** ($m^2$) | 177185 | 161280 | ↓ | 153869 |
| | **Mean** ($m^2$) | 22148 | 20160 | ↓ | 21981 |
| **Perimeter** | **Total** (m) | 6541 | 7016 | ↓ | 6690 |
| | **Mean** (m) | 818 | 877 | ↓ | 956 |
| **Nearest neighbour** | **Total** (m) | 277 | 748 | ↓ | 404 |
| | **Mean** (m) | 35 | 93 | ↓ | 58 |
| **Core – fixed edge** | **no.** | 2 | 2 | ↔ | - |
| | **Total** ($m^2$) | 14505 | 2622 | ↓ | - |
| | **Mean** ($m^2$) | 7252 | 1311 | ↓ | - |
| | **% Area** | 8 | 2 | ↓ | - |
| **Core – weighted edge** | **no.** | 6 | 6 | ↔ | - |
| | **Total** ($m^2$) | 144497 | 104878 | ↓ | - |
| | **Mean** ($m^2$) | 24083 | 17480 | ↓ | - |
| | **% Area** | 82 | 65 | ↓ | - |
| **Cumulative core area** | **Total** ($m^2$) | 493748 | 286122 | ↓ | - |
| | **Mean** ($m^2$) | 49374 | 28612 | ↓ | - |

Further details of the application of these metrics are contained within Appendix 3.

### 5.1.2 Results for Graph theory measures

Not all of the graph theory indices detected change in the example sample square (Table 17 and Table 18). Fewer changes were detected by simple binary indices (NL, NC & Harary). Core fixed habitat measurement options (2a & 2b in Table 17 and Table 18) detected little change between timeframes as both had the same number of woodland patches present.

**Table 17** – Graph theory outputs for alternative area options (as outlined in Figure 14) based on Euclidean distance.

| | 1a<br>Normal area – 1990 | 1b<br>Normal area - 1998 | 2a<br>Core-fixed 1990 | 2b<br>Core-fixed 1998 | 3a<br>Core-weighted 1990 | 3b<br>Core-weighted 1998 | 4a<br>Permanent |
|---|---|---|---|---|---|---|---|
| **NL** | 28 | 28 | 1 | 1 | 15 | 14 | 21 |
| **NC** | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **H** | 28.0 | 28.0 | 1.0 | 1.0 | 15.0 | 14.5 | 21.0 |
| **CCP** | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| **LCP** | 0.03 | 0.0260113 | 1.00 | 0.00 | 0.02 | 0.01 | 0.02 |
| **IIC** | 0.03 | 0.0239038 | 0.75 | 0.00 | 0.02 | 0.01 | 0.02 |
| **F** | 28.55 | 25.09376 | 1.99 | 0.50 | 13.76 | 10.85 | 21.99 |
| **AWF** | 2600047000 | 2618183000 | 498503400000 | 849161 | 2666196000 | 1651169000 | 1631590000 |
| **PC** | 0.03 | 0.0244913 | 1.00 | 0.00 | 0.02 | 0.01 | 0.02 |

Number of Links **(NL)**; Number of Components **(NC)**; Harary Index **(H)**; Class Coincidence Probability **(CCP)**; Landscape Coincidence Probability **(LCP)**; Integral Index of Connectivity **(IIC)**; Flux **(F)**; Area-Weighted Flux **(AWF)**; Probability of Connectivity **(PC)**.

**Table 18** - Graph theory outputs for alternative area options (as outlined in Figure 14) based on least-cost distance.

| | 1a<br>Normal area – 1990 | 1b<br>Normal area - 1998 | 2a<br>Core-fixed 1990 | 2b<br>Core-fixed 1998 | 3a<br>Core-weighted 1990 | 3b<br>Core-weighted 1998 | 4a<br>Permanent |
|---|---|---|---|---|---|---|---|
| **NL** | 3 | 2 | 1 | 1 | 4 | 6 | 2 |
| **NC** | 5 | 6 | 1 | 1 | 3 | 3 | 5 |
| **H** | 3 | 2 | 1 | 1 | 4 | 6 | 2 |
| **CCP** | 0.91 | 0.90 | 1.00 | 1.00 | 0.92 | 0.95 | 0.96 |
| **LCP** | 0.03 | 0.02 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 |
| **IIC** | 0.03 | 0.02 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 |
| **F** | 4.33 | 3.18 | 0.59 | 0.47 | 4.34 | 5.72 | 3.18 |
| **AWF** | 969468400 | 1384817000 | 19364300 | 798868 | 1884283000 | 1483545000 | 851694000 |
| **PC** | 0.03 | 0.02 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 |

Number of Links **(NL)**; Number of Components **(NC)**; Harary Index **(H)**; Class Coincidence Probability **(CCP)**; Landscape Coincidence Probability **(LCP)**; Integral Index of Connectivity **(IIC)**; Flux **(F)**; Area-Weighted Flux **(AWF)**; Probability of Connectivity **(PC)**.

Groups of graph theory indices (simple = NL, NC, H; binary= CCP, LCP, IIC; probabilistic = F, AWF, PC) had similar outcomes for both Euclidean and least-cost measures (Table 17 and Table 18). The direction of change in the graph theory indices is shown in Table 19; it is important to note that this does not adequately represent the strength of change recorded. Positive outcomes only occur where least-cost distances have been used, especially where the impact of the matrix is included in the measure e.g. core weighted.

**Table 19** - Graph theory indices and direction of change for selected CS sample square between 1990 and 1998

| | **Euclidean distance measure** | | | | **Least-cost distance measure** | | | |
|---|---|---|---|---|---|---|---|---|
| | **1a – 1b** | **2a – 2b** | **3a – 3b** | **1a – 4a** | **1a – 1b** | **2a – 2b** | **3a – 3b** | **1a – 4a** |
| | **Normal area** | **Core – fixed** | **Core - weighted** | **Permanent[#]** | **Normal area** | **Core – fixed** | **Core - weighted** | **Permanent[#]** |
| **NL** | ↔ | ↔ | ↓ | ↓ | ↓ | ↔ | ↑ | ↓ |
| **NC** | ↔ | ↔ | ↔ | ↔ | ↑ | ↔ | ↔ | ↔ |
| **H** | ↔ | ↔ | ↓ | ↓ | ↓ | ↔ | ↑ | ↑ |
| **CCP** | ↔ | ↔ | ↔ | ↔ | ↓ | ↔ | ↑ | ↑ |
| **LCP** | ↓ | ↓ | ↓ | ↓ | ↓ | ↔ | ↑ | ↓ |
| **IIC** | ↓ | ↓ | ↓ | ↓ | ↓ | ↔ | ↑ | ↓ |
| **F** | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ |
| **AWF** | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ |
| **PC** | ↓ | ↓ | ↓ | ↓ | ↓ | ↔ | ↓ | ↓ |

Number of Links **(NL)**; Number of Components **(NC)**; Harary Index **(H)**; Class Coincidence Probability **(CCP)**; Landscape Coincidence Probability **(LCP)**; Integral Index of Connectivity **(IIC)**; Flux **(F)**; Area-Weighted Flux **(AWF)**; Probability of Connectivity **(PC)**.

As previously mentioned, simple graph theory indices (NL, NC, H) are shown to have similar outcomes for both Euclidean and least-cost distance as illustrated in Figure 16. The Harary index (H) and the number of links (NL) are strongly correlated because of the structural similarity of the two measures (Section 4.6.2). The number of components (NC) shows little variation due to the small scale of the landscape in relation to the dispersal distance.

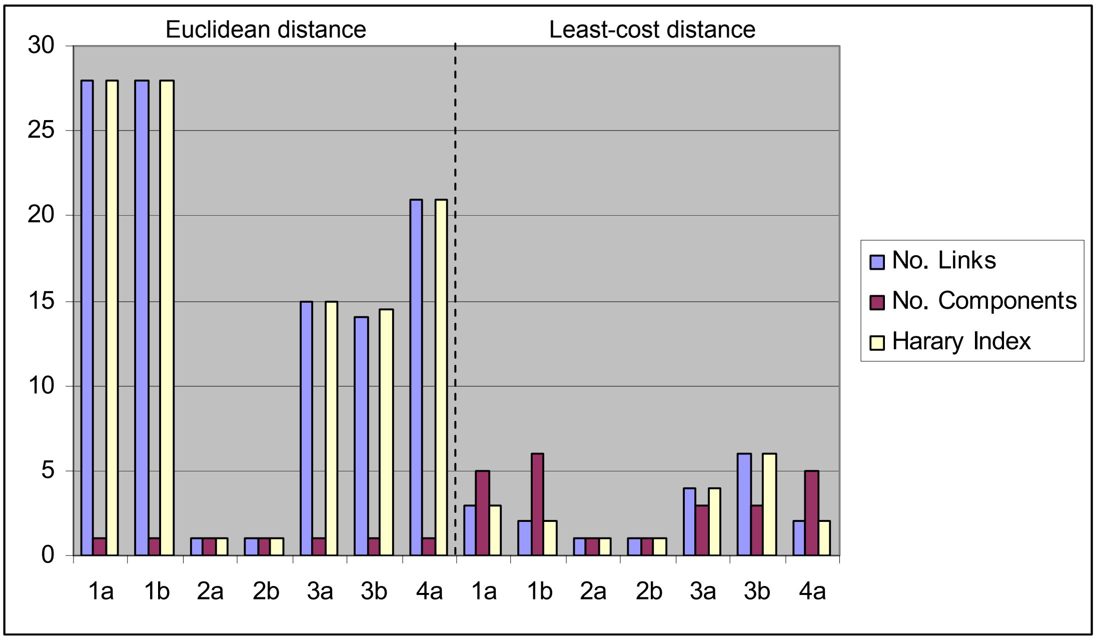



**Figure 16** – Comparison of number of links (NL), number of components (NC) and Harary index (H) for alternative area options (Figure 14) and distance measures.

The more complex binary indices (CCP, LCP, IIC) are shown in Figure 17. These indices have related methodologies, while IIC is the recommended binary index by Saura and Pascual-Hortal. CCP ranges from 0.9 to 1, with little variation through the different area and distance options used. There is also a strong relationship between the scores for LCP and IIC indices.


**Figure 17** – Comparison of class coincidence probability (CCP), landscape coincidence probability (LCP) and integral index of connectivity (IIC) for alternative area options (Figure 14) and distance measures.

To allow comparison of the probabilistic graph theory indices, values were normalised by the normal area option (hence the omission of option 1a and 1b from Figure 18) score to generate a difference from the 'control landscape' in an attempt to illustrate change. Flux and AWF have related methodologies and PC measure is the recommended probabilistic measure. Flux, which includes no area attribute, shows the greatest deviation of the indices (Figure 18), while AWF and PC seem to have closely related scores.

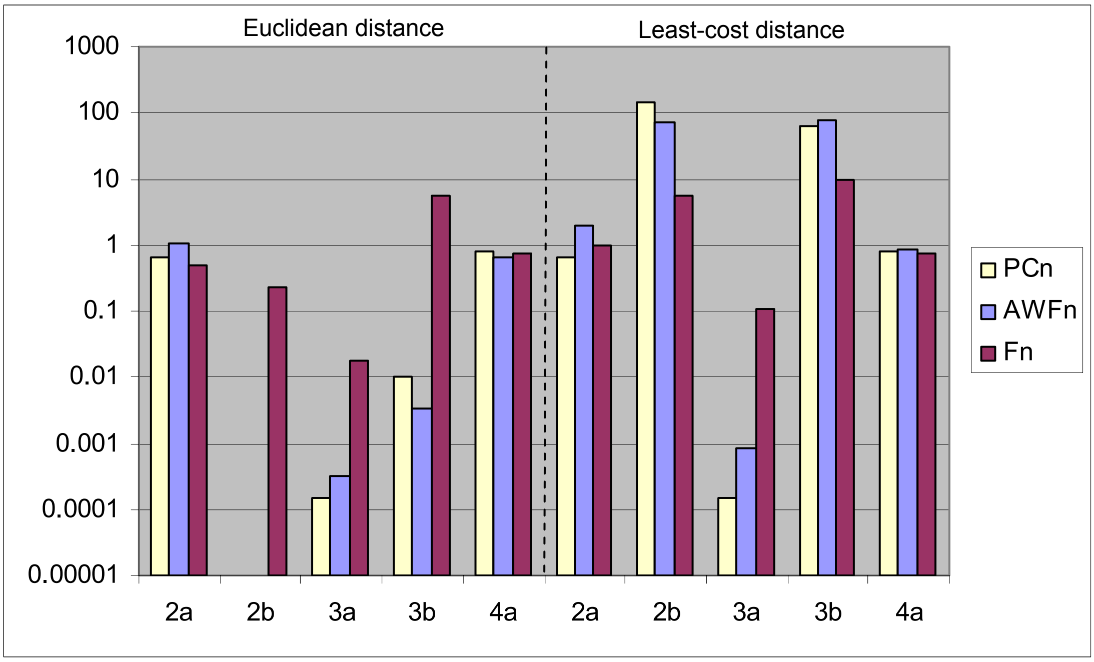
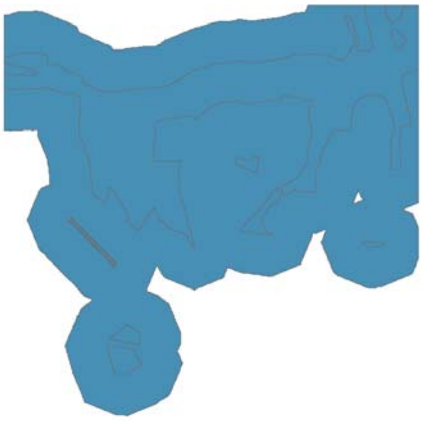
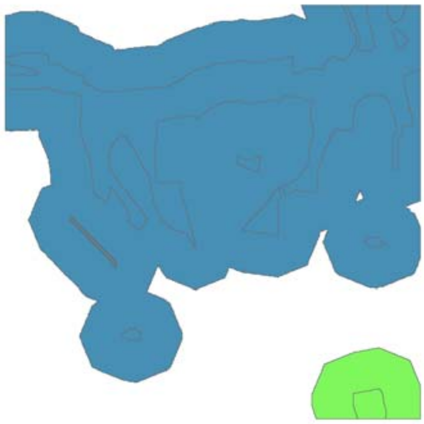
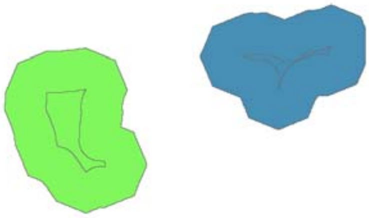
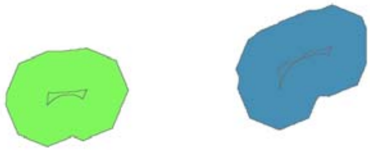
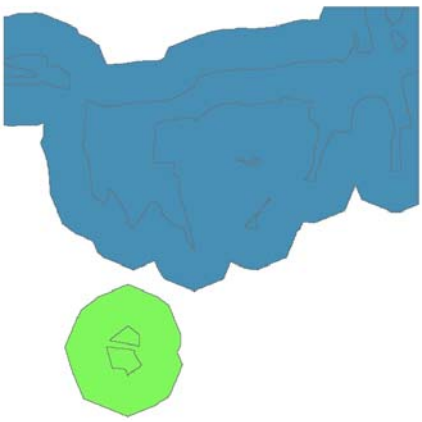
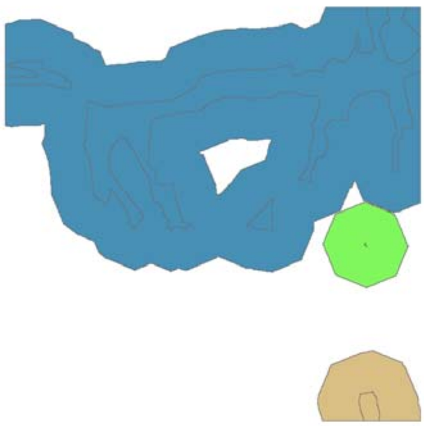



**Figure 18** – Calculation of difference in probability of connectivity (PC), area-weighted flux (AWF) and flux (F) to control landscapes (1a and 1b) for alternative area options (Figure 14) and distance measures.

### *5.1.3 Results for buffer radius measure*

Buffer radius calculations are simple binary-based measures of connectivity related to the area and amount of habitat within a defined buffer, based on Euclidean and least-cost distance measures. The buffer radius (network) outputs for the example CS sample square for the selected habitat area options (Figure 14) are illustrated Figure 19 (Euclidean distance) and Figure 20 (least-cost distance).

| | |
|---|---|
|  |  |
| **1a** – 1990 normal area buffer radius | **1b** – 1998 normal area buffer radius |
|  |  |
| **2a** – 1990 core fixed buffer radius | **2b** – 1998 core fixed buffer radius |
|  |  |
| **3a** – 1990 core weighted buffer radius | **3b** – 1998 core weighted buffer radius |

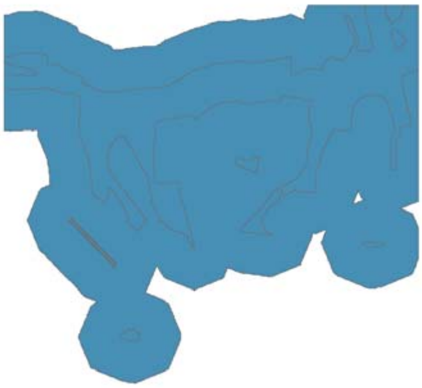
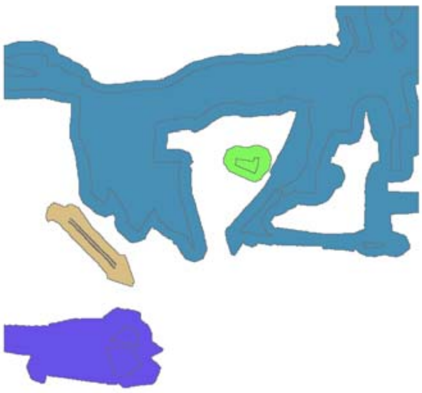
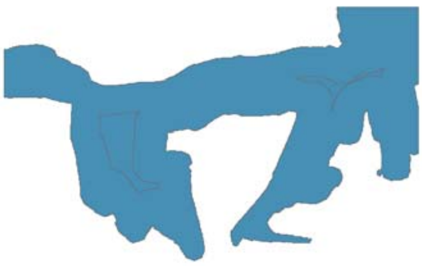
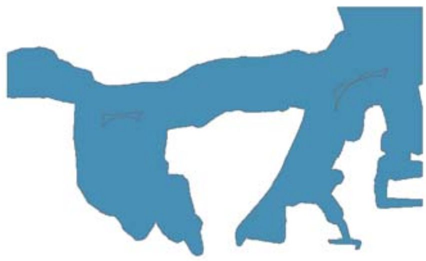
| | |
|---|---|
|  | |
| **4a** – permanent buffer radius | |

**Figure 19** - Buffer Radius analysis using Euclidean distance

| | |
|---|---|
|  |  |
| **1a** – 1990 normal area buffer radius | **1b** – 1998 normal area buffer radius |
|  |  |
| **2a** – 1990 core fixed buffer radius | **2b** – 1998 core fixed buffer radius |

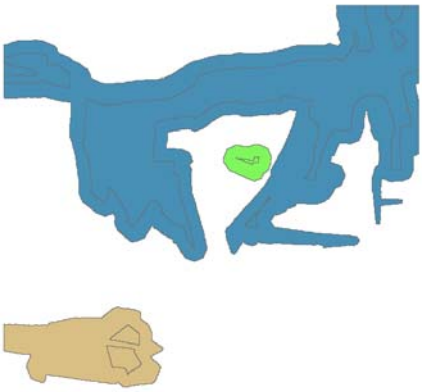
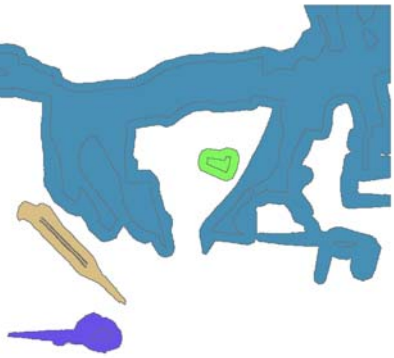
| | |
|---|---|
|  |  |
| **3a** – 1990 core weighted buffer radius | **3b** – 1998 core weighted buffer radius |
|  | |
| **4a** – permanent buffer radius | |

**Figure 20** - Buffer radius analysis using least - cost distance

A buffer based on Euclidean distance (Figure 19) results in a uniform buffer around the habitat patch, which may be unrealistic in a heterogeneous landscape. In contrast, a buffer based on least-cost distance displays a skewed buffer related to the permeability of the surrounding landscape matrix (Figure 20).

An increase in the number of buffer radius networks was detected in all options, apart from the Euclidean distance with fixed core area, and the least-cost, core weighted derived option (see Table 20). In both these exceptions the total network area and mean network area decreased suggesting an overall decrease in connectivity. Only the option derived from Euclidean distance with a normal area shows an increase in total network area and therefore a potential increase in connectivity. Further details of these metrics are contained within Appendix 3.

The Euclidean buffer radius network predicts that there is 1 network in 1a (Figure 19), whereas a least-cost distance approach predicts 4 networks in the same landscape (1a in Figure 20). This demonstrates the impact of the choice of buffer method on the resultant measured outputs.

Between 1a (1990 normal area) and 1b (1998 normal area) in Figure 19 a new habitat patch has been created. This patch is not connected with the existing network; therefore this forms a new network in the bottom right hand corner. Similarly, the least-cost buffer networks in 1b (1998 normal area - Figure 20) have also created an additional network, resulting in an increase from 4 in 1990 to 5 in 1998.

With the application of a fixed edge impact, the core habitat is reduced considerable to form two discrete networks in 1990 and 1998 (2a and 2b in Figure 19), even though this networks lie within woodland patches. A potentially more realistic interpretation is provided by least-cost measures in 2a and 2b in Figure 20, with high connectivity through surrounding woodland habitats, which were removed as habitat by the fixed edge, leading to the creation of a more extensive network.

In 3b (Figure 20) a small habitat patch in the centre of the large network (see 1b Figure 20) has been removed in 1998 as a result of the application of a core weighted buffer. The intensity of the surrounding matrix has changed from neutral and improved grassland to improved grassland and arable (see Appendix 2 – grid 7). This effectively removes the habitat patch and reduces the number of networks from 3 to 2.

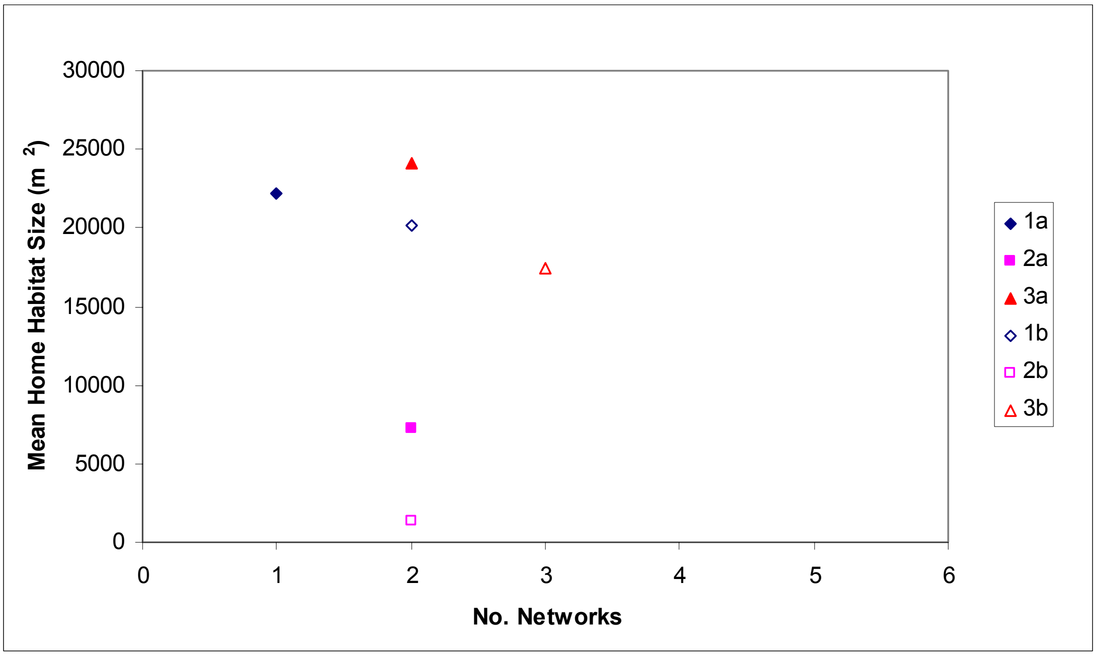
There is little change between the area and networks for permanent habitat (4a) with the 1990 baseline, within both the Euclidean (Figure 19) and least-cost approaches (Figure 20), indicating the temporal persistence of habitat patches.

**Table 20** – Buffer radius outputs for alternative area options based on Euclidean and least-cost distance measures

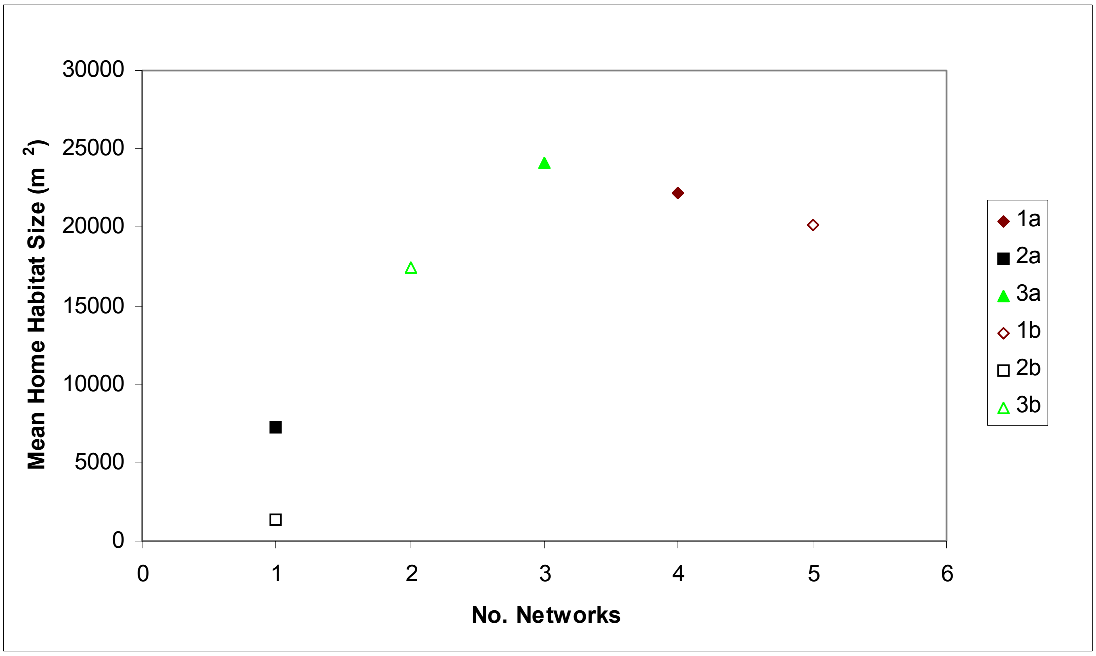
| | | 1990 | | 1998 | | Permanent | |
|---|---|---|---|---|---|---|---|
| | | Habitat | Network | Habitat | Network | Habitat | Network |
| Euclidean[1] | | | | | | | |
| Normal area | no. | 8 | 1 | 8 | 2 | 15 | 1 |
| | Total | 177185 | 652599 | 161280 | 667696 | 153856 | 627746 |
| | Mean | 22148 | 652599 | 20160 | 333848 | 10257 | 627746 |
| Core fixed | no. | 2 | 2 | 2 | 2 | - | - |
| | Total | 14505 | 180352 | 2622 | 118444 | - | - |
| | Mean | 7252 | 90176 | 1311 | 59222 | - | - |
| Core weighted | no. | 6 | 2 | 6 | 3 | - | - |
| | Total | 144497 | 559991 | 104878 | 535539 | - | - |
| | Mean | 24083 | 279995 | 17480 | 178513 | - | - |
| Least –cost[2] | | | | | | | |
| Normal area | no. | 8 | 4 | 8 | 5 | 15 | 4 |
| | Total | 177185 | 394555 | 161280 | 355781 | 153856 | 344835 |
| | Mean | 22148 | 98638.7 | 20160 | 71156.2 | 10257 | 86209 |
| Core fixed | no. | 2 | 1 | 2 | 1 | - | - |
| | Total | 14505 | 282044 | 2622 | 276506 | - | - |
| | Mean | 7252 | 282044 | 1311 | 276506 | - | - |
| Core weighted | no. | 6 | 3 | 6 | 2 | - | - |
| | Total | 144497 | 362360 | 104878 | 322345 | - | - |
| | Mean | 24083 | 120787 | 17480 | 161173 | - | - |

[1] as detailed in Figure 19
[2] as detailed in Figure 20

Figure 21 illustrates the change in the number of buffer radius networks, based on the Euclidean (a) and the least-cost approach (b), against the mean area of habitat contained. A positive change in connectivity may result from a decrease in the number of networks and an increase in the mean area of habitat. All options show a reduction in the amount of woodland habitat contained within the network between 1990 and 1998. Networks with a fixed edge (2a and 2b in Figure 21a) show no change in the number of networks but a decrease in mean habitat area. The least-cost, weighted edge network (3a and 3b in Figure 21b) showed a decrease in the number of networks and mean habitat area.



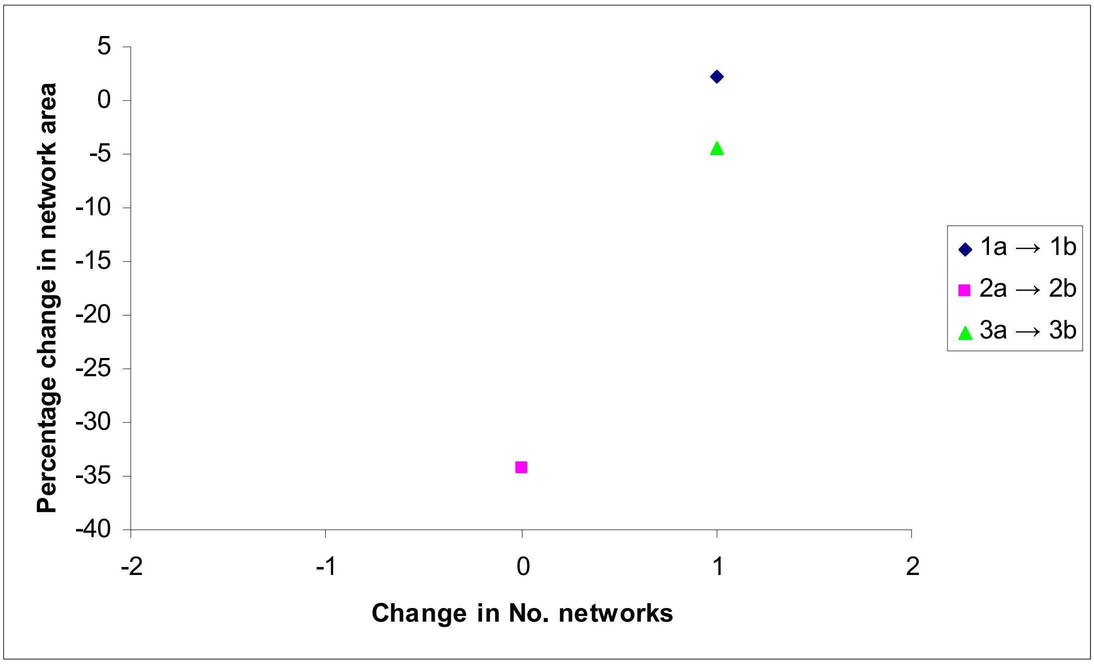

**A** – Euclidean buffer radius networks



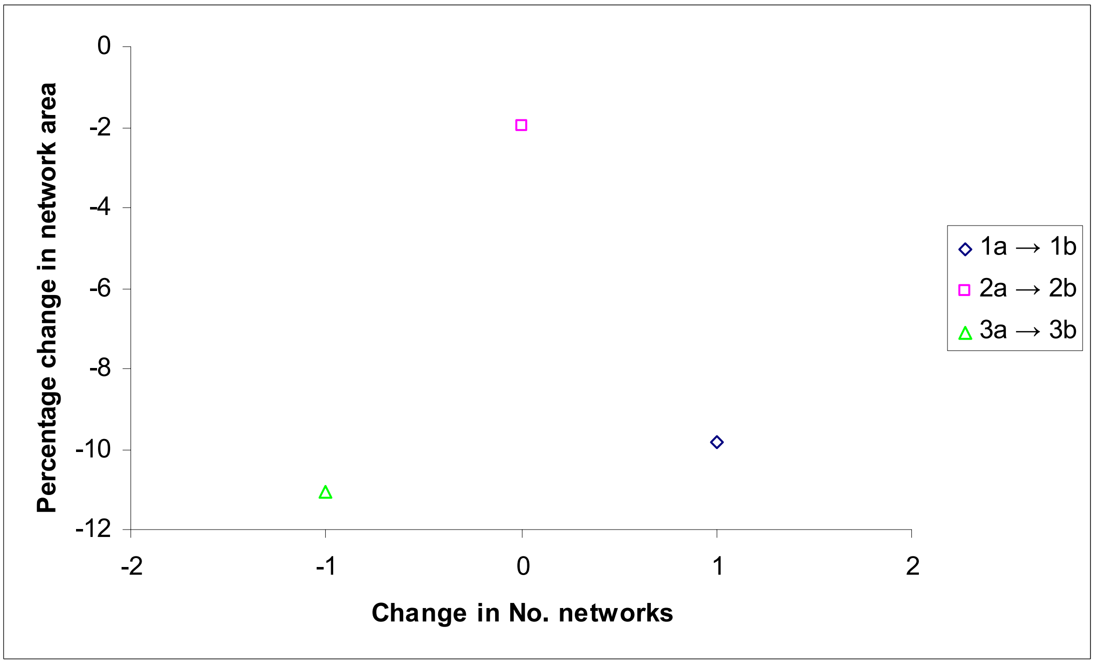

**B** – Least-cost buffer radius networks

**Figure 21** – Number of buffer radius networks using Euclidean (a) and least-cost (b) distance measures against mean area of habitat contained within them (for alternative area options as illustrated in Figure 19 & Figure 20)

Figure 22 illustrates the change in the number of buffer radius networks against the percentage change in network area, as opposed to habitat area. A positive change would result from a decrease in the number of networks and an increase in the network area. One option, Euclidean normal area (1a – 1b in Figure 22a) shows a positive increase (positive change) in network area and an increase in the number of networks (negative change). There is limited change in least-cost, fixed edge networks (2a – 2b in Figure 22b) between 1990 and 1998. Whereas the other least-cost options in Figure 22b normal (1a -1b) and weighted edge (3a – 3b) show a general decline in network area.




**a** – Euclidean buffer radius networks



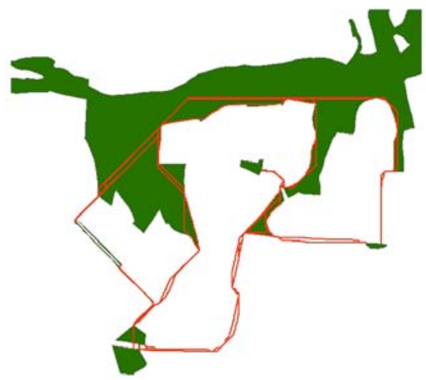
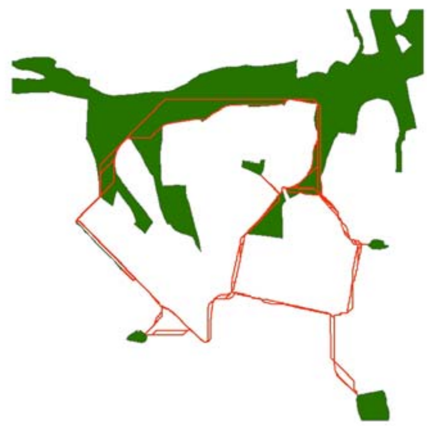
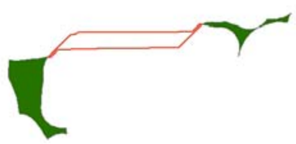

**b** – Least-cost buffer radius networks

**Figure 22** –Change in Euclidean (a) and least-cost (b) buffer radius network area (%) against change in the number of networks

### 5.1.4 Results for IFM connectivity measure

The IFM calculates the potential number of individuals moving between patches in the landscape, taking into account patch area, the distance between the patches, expressed as a Euclidean or least-cost function, and a dispersal curve.

Figure 23 illustrates the IFM connectivity calculation using least-cost paths, and each habitat area option. The habitat patches are represented in dark green and the least-cost paths connecting the different patches in red. IFM values produced using Euclidean and least-cost distances are recorded in Table 21; no illustration of Euclidean connectivity was produced. Further details of the IFM metrics are contained within Appendix 3.

| | |
|---|---|
|  |  |
| **1a** – 1990 normal area IFM | **1b** - 1998 normal area IFM |
|  |  |
| **2a** – 1990 core fixed IFM | **2b** - 1998 core fixed IFM |

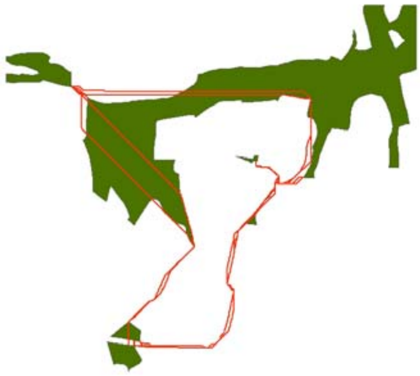
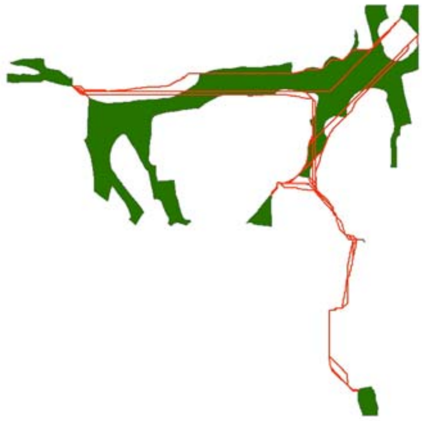
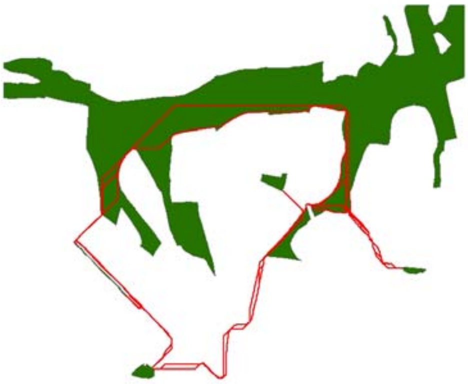
| | |
|---|---|
|  |  |
| **3a** – 1990 core weighted IFM | **3b** - 1998 core weighted IFM |
|  | |
| **4a** – permanent IFM | |

**Figure 23** – Illustration of IFM connectivity calculation using least-cost path lines for the alterative area options.

IFM models detected change in all options for both Euclidean and least-cost methods (Table 21). In normal area options (1a and 1b), both Euclidean and least-cost, there is a slight decrease in IFM values. For core fixed edge (2a and 2b) there is a large decrease in IFM for both Euclidean and least-cost. There is a large reduction in IFM values for core weighted Euclidean (3a and 3b). However, for core weighted least-cost (3a and 3b) there is a slight increase in IFM values. This is possibly due to the enlargement of an existing habitat patch close to the large habitat patch, which allows the potential movement of a large number of individuals. Figure 23 illustrates the importance of the central woodland block for habitat connectivity. Most least-cost paths utilise this low permeability route even if it appears longer geographically.

There is a strong similarity between the patch-based IFM (Table 21) and grid-based IFM and AWF and PC graph theory calculations respectively (Table 17 and Table 18) as predicted by Saura and Pascual-Hortal.

**Table 21** – IFM values for alternative habitat area options and Euclidean and least-cost distance measures (as outlined in Figure 23)

| | | Euclidean distance | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
| | | Norma area - 1990 | Normal area – 1998 | Core-fixed 1990 | Core-fixed 1998 | Core-weighted 1990 | Core-weighted 1998 | Permanent |
| IFM | Total | 853556.15 | 730804.63 | 4630.85 | 659.76 | 451087.31 | 329654.66 | 678818.05 |
| | Mean | 106694.52 | 91350.58 | 2315.42 | 329.88 | 75181.22 | 54942.44 | 96974.01 |

| | | Least-cost distance | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
| | | Normal area-1990 | Normal area- 1998 | Core-fixed 1990 | Core-fixed 1998 | Core-weighted 1990 | Core-weighted 1998 | Permanent |
| IFM | Total | 163147.63 | 142567.88 | 4259.79 | 620.68 | 211027.25 | 243131.67 | 140496.49 |
| | Mean | 20393.45 | 17820.98 | 2129.89 | 310.34 | 35171.21 | 40521.94 | 20070.93 |

## *5.2 Candidate connectivity measures*

From this analysis of a single CS sample square, the preferred habitat area option is based upon the application of a weighted edge and distance is based on the least-cost option, as indicated in Table 22. An interim measure may be based on normal area and Euclidean distance. The most promising connectivity measures would appear to be:

**Graph theory -**

(binary) integral index of connectivity
(probabilistic) probability of connectivity

**Buffer radius -**

(binary) least-cost buffer radius

**IFM -**

(probabilistic) patch and grid-based IFM connectivity

**Table 22** – Selection of habitat area, distance options and potential candidate connectivity measures for further investigation.

| | | Outcome |
|---|---|---|
| **Area options** | *Normal area – no edge* | Possible interim measure. Does not include edge impacts, a feature seen as essential by steering group. |
| | *Core area – fixed edge* | **Rejected**. Removes too much habitat at this scale and can be indiscriminate. |
| | *Core area – weighted edge* | **Accepted**. Preferred option as this account for the surrounding matrix. |
| | *Permanent area* | **Rejected – but may be informative to examine persistence.** Only compares change with original baseline. |
| **Distance Options** | *Euclidean distance* | Possible interim measure. Euclidean is simple and quick to calculate but does not account for matrix permeability. It is a directed measure with limited assumptions. |
| | *Least-cost distance* | **Accepted**. Although more complex and timely to calculate, has the ability to incorporate matrix permeability to assess functional connectivity. Based on a greater number of assumptions. |
| **Candidate connectivity measures** | *Graph theory* | **Accepted** - binary measure of 'Integral Index of Connectivity' and probabilistic measure 'Probability of Connectivity' as recommended |

| | | |
|---|---|---|
| | | by Saura and Pascual-Hortal. These measures are methodologically and ecologically sound and are able to detect change. |
| | *Buffer radius* | **Accepted**. Promising outcome and works well with weighted edge. Indicates connectivity well spatially and provides relatively graphical illustration. Simple approach with limited parameterisation but lacks the ecological robustness of Graph theory and IFM approaches (e.g. area weighting and dispersal curve). |
| | *IFM* | **Accepted**. Methodologically and ecologically robust approach. Requires a high degree of parameterisation. Can be implemented as Patch or grid-based approaches (see below). |

### *5.2.1 Patch and grid based connectivity measures*

Preliminary inspection of the results, and further consultation with experts, identified the need to consider whether connectivity measures such as IFM are implemented in a patch or grid-based approach. Patch-based measures are useful to examine connectivity in static landscapes and to predict inter patch movements. However, when examining change some patch-based measures actually suggest an increase in connectivity with increased fragmentation (Tischendorf and Fahrig, 2000b2000a). This is due to the focus on inter-patch connectivity with no account of the intra-patch connectivity that permits the movement of individuals within adjacent cells of habitat within a patch.

Figure 24 illustrates the difference between patch and grid-based approaches to assess connectivity in a changing landscapes. In landscape (a) *patch connectivity* is 3, with 2 from patch **a** and 1 from patch **b**. Whereas, *grid-based connectivity* is 50. The inter patch contribution is still 3, but each cell (6 in total) in patch **b** receives the 3 inter patch movements and also 5 from contiguous cells in patch **b**. In landscape (b) patch **b** has been fragmented and a new patch **d** formed. As a result patch-based connectivity has increased from 3 to 5, as more patches are created. Whereas the grid-based measure has decreased from 50 to 16, as the intra-patch movements in patch b have reduced considerably.

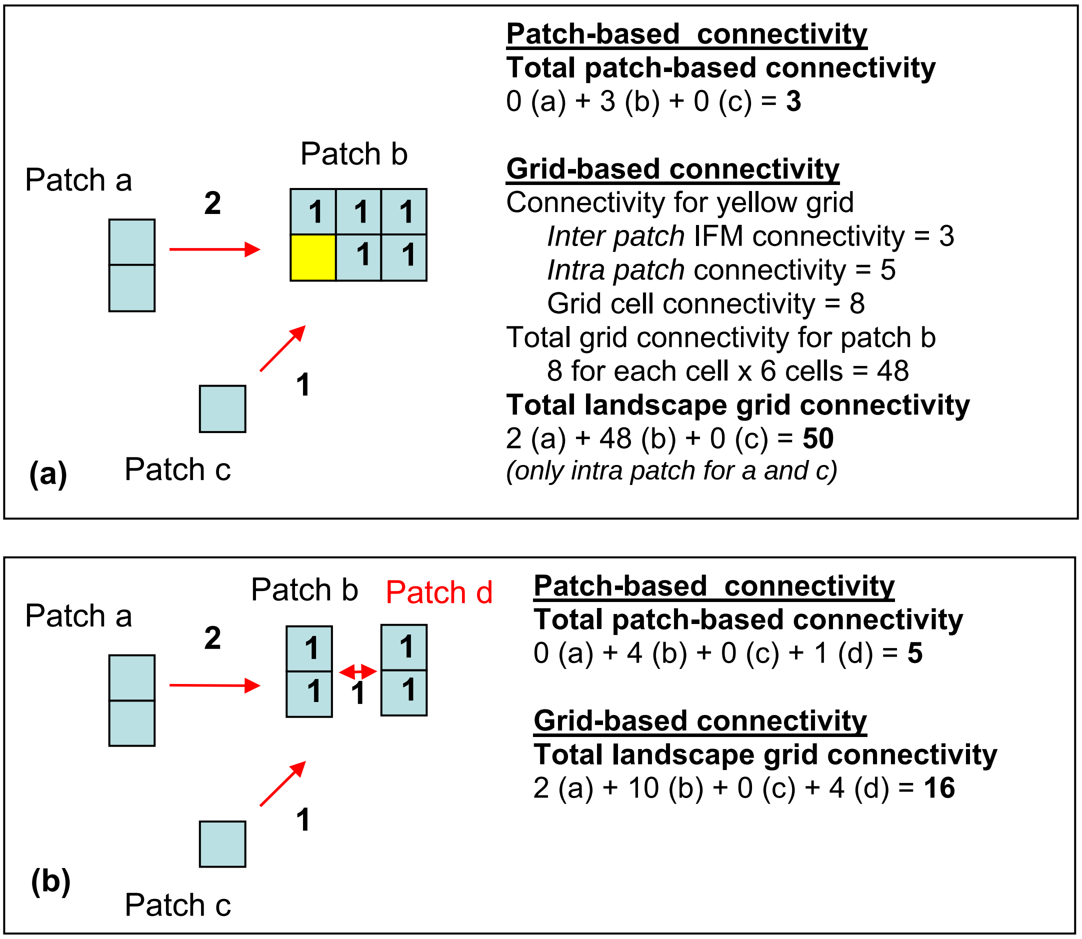



**Figure 24** – Illustration of patch and grid-based approaches to assess connectivity in two landscapes (a & b) with increasing fragmentation.

A grid-based approach takes into account inter and intra-patch connectivity and predicts results consistent with landscape interpretations. Therefore, a grid-based approach will produce maximum connectivity when one patch occupies the whole landscape whereas a patch-based approach would predict zero connectivity.

Assuming full intra patch connectivity within each cell of a habitat patch, intra patch connectivity can be calculated using patch area. As each cell in a habitat patch is consider to be connected to every other cell with the same patch, intra patch connectivity would equal total habitat area squared minus the area of habitat. In addition, Inter patch connectivity is based on the existing patch-based IFM score weighted by patch area. Comparison of the results of this patch/grid hybrid IFM approach to the output from a grid-based IFM (Figure 24) shows them to be equal to one another (Table 23). As a result, the pilot study will utilise a patch/grid hybrid IFM to assess changes in habitat connectivity.

**Table 23** – Comparison of patch/grid hybrid IFM with grid-based IFM

| | | Patch a | Patch b | Patch c | Total |
|---|---|---|---|---|---|
| Inter patch connectivity | Grid-based IFM from Figure 24 | 0 | 18 | 0 | **18** |
| | Hybrid IFM - IFM * area | 0 * 2 = 0 | 3 * 6 = 18 | 0 * 1 = 0 | **18** |
| Intra patch connectivity | Grid-based IFM from Figure 24 | 2 | 30 | 0 | **32** |
| | Hybrid IFM - $(area^2)$ - area | $(2^2) - 2 = 2$ | $(6^2) - 6 = 30$ | $(1^2) - 1 = 0$ | **32** |

## 5.3 Connectivity analysis of ten CS sample squares

The results of the application of the structural metrics and selected connectivity measures (as identified in Table 22) for the 10 CS sample squares (see Appendix 2) between 1990 and 1998 are provided in Table 24. The selected connectivity measures were all able to identify fairly subtle changes in land-cover, over short time periods and in very small (1km) landscapes. Permanent connectivity measures have also been included to give a further indication of the persistence of habitat and connectivity through time. For instance, in Grid 4 (Table 24) there are 6 woodland patches in 1990 and 1998 indicating no change. However there are only 3 permanent patches in 1998, indicating that 3 patches have been destroyed and 3 have been created between 1990 and 1998.

A summary of selected connectivity measures, with potential to provide the basis for a habitat connectivity indicator, are presented Table 25. The connectivity measures in Table 25 are compared against each other and the general description of landscape change and supporting landscape metrics.

**Table 24 –** Outputs for metrics and connectivity measures for 10 CS sample squares. Permanent connectivity measures have also been included to give a further indication of temporal change.

| | | | Grid 4 | | | Grid 5 | | | Grid 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** |
| **Metrics** | | | | | | | | | | | |
| No. Patches | | | 6 | 6 | 3 | 32 | 34 | 32 | 12 | 19 | 18 |
| Area | | Total | 11432.54 | 11228.13 | 7435.37 | 245933.79 | 255290.40 | 243314.87 | 345293.47 | 309294.55 | 293719.57 |
| | | Mean | 1905.42 | 1871.36 | 2478.46 | 7685.43 | 7508.54 | 7603.59 | 28774.46 | 16278.66 | 16317.75 |
| Core -Weighted | | no. | 4 | 5 | - | 22 | 25 | - | 12 | 16 | - |
| | | Total | 3838.63 | 1799.57 | - | 179701.47 | 226886.23 | - | 258032.92 | 241243.12 | - |
| | | Mean | 959.66 | 359.91 | - | 8168.25 | 9075.45 | - | 21502.74 | 15077.69 | - |
| | | % area | 0.34 | 0.16 | - | 0.73 | 0.89 | - | 0.75 | 0.78 | - |
| **Graph theory** | | | | | | | | | | | |
| Core - weighted | euclidean | IIC | 0.0000094 | 0.0000023 | 0.0000386 | 0.019195 | 0.0307994 | 0.0341354 | 0.0428566 | 0.0371122 | 0.0544301 |
| | | PC | 0.0000088 | 0.000002 | 0.0000292 | 0.0220275 | 0.0378953 | 0.043461 | 0.0580332 | 0.0530717 | 0.0813295 |
| Core - weighted | least-cost | IIC | 0.0000052 | 0.0000014 | 0.0000219 | 0.0137747 | 0.0236132 | 0.024783 | 0.035808 | 0.0350588 | 0.0513576 |
| | | PC | 0.0000052 | 0.0000014 | 0.0000219 | 0.0121945 | 0.0228116 | 0.0261776 | 0.0320821 | 0.0271567 | 0.0430427 |
| **Buffer radius networks** | | | | | | | | | | | |
| Core - weighted | euclidean | no. | 3 | 4 | 3 | 4 | 3 | 2 | 1 | 1 | 1 |
| | | Total | 155966.00 | 153743.00 | 159033.00 | 719719.00 | 763775.00 | 897758.00 | 656242.00 | 656317.00 | 667127.00 |
| | | Mean network | 51988.67 | 38435.75 | 53011.00 | 179929.75 | 254591.67 | 448879.00 | 656242.00 | 656317.00 | 667127.00 |
| | | Mean habitat | 1279.54 | 449.89 | 2478.46 | 44925.37 | 75628.74 | 121657.44 | 258032.92 | 241243.12 | 293719.57 |
| Core - weighted | least-cost | no. | 3 | 3 | 3 | 5 | 4 | 6 | 1 | 1 | 1 |
| | | Total | 117544.00 | 84213.00 | 70064.00 | 540392.00 | 590672.00 | 627659.00 | 557160.00 | 561113.00 | 561281.00 |
| | | Mean network | 39181.33 | 28071.00 | 23354.67 | 108078.40 | 147668.00 | 104609.83 | 557160.00 | 561113.00 | 561281.00 |
| | | Mean habitat | 1279.54 | 599.86 | 2478.46 | 35940.29 | 56721.56 | 40552.48 | 258032.92 | 241243.12 | 293719.57 |
| **IFM** | | | | | | | | | | | |
| Core - weighted | euclidean | Total | 4924.34 | 2169.18 | 3886.41 | 1671496.42 | 2624241.45 | 3245436.94 | 1830544.81 | 2403422.52 | 3855471.01 |
| | | Mean | 1231.09 | 433.84 | 1295.47 | 75977.11 | 104969.66 | 101419.90 | 152545.40 | 150213.91 | 214192.83 |
| Core - weighted | least-cost | Total | 1125.95 | 26.64 | 0.04 | 615596.23 | 886166.89 | 1040715.75 | 821071.77 | 1061039.67 | 1668397.04 |
| | | Mean | 281.49 | 5.33 | 0.01 | 27981.65 | 35446.68 | 32522.37 | 68422.65 | 66314.98 | 92688.72 |
| Hybrid IFM | | | 0.0000052 | 0.0000014 | | 0.0111052 | 0.0209317 | | 0.0314613 | 0.0264555 | |

| | | | Grid 7 | | | Grid 9 | | | Grid 12 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** |
| **Metrics** | | | | | | | | | | | |
| No. Patches | | | 8 | 8 | 7 | 3 | 1 | 1 | 10 | 9 | 14 |
| Area | | Total | 177185.00 | 161280.00 | 153869.08 | 12286.41 | 8266.07 | 8266.09 | 320545.55 | 378851.46 | 315558.33 |
| | | Mean | 22148.00 | 20160.00 | 21981.30 | 4095.47 | - | - | 32054.55 | 42094.61 | 22539.88 |
| Core -Weighted | | no. | 6 | 6 | - | 3 | 1 | - | 16 | 15 | - |
| | | Total | 144497.00 | 104878.00 | - | 5497.58 | 3025.88 | - | 228041.89 | 312799.09 | - |
| | | Mean | 24083.00 | 17480.00 | - | 1832.53 | 3025.88 | - | 14252.62 | 20853.27 | - |
| | | % area | 0.82 | 0.65 | - | 0.45 | 0.37 | - | 0.71 | 0.83 | - |
| **Graph theory** | | | | | | | | | | | |
| Core - weighted | euclidean | IIC | 0.0189421 | 0.009798 | 0.0226798 | 0.000025 | - | - | 0.0358023 | 0.066732 | 0.0741144 |
| | | PC | 0.0197424 | 0.0102947 | 0.02332 | 0.0000206 | - | - | 0.0452352 | 0.0901309 | 0.0977729 |
| Core - weighted | least-cost | IIC | 0.0181271 | 0.0095175 | 0.022153 | 0.0000199 | - | - | 0.0356184 | 0.0664609 | 0.0734365 |
| | | PC | 0.0188937 | 0.0101227 | 0.0225356 | 0.0000199 | - | - | 0.0372835 | 0.0742185 | 0.0860983 |
| **Buffer radius networks** | | | | | | | | | | | |
| Core - weighted | euclidean | no. | 2 | 3 | 1 | 3 | 1 | 1 | 2 | 1 | 1 |
| | | Total | 559991.00 | 535539.00 | 627746.00 | 122054.00 | 57012.00 | 75176.00 | 702862.00 | 797290.00 | 807495.00 |
| | | Mean network | 279995.50 | 178513.00 | 627746.00 | 40684.67 | 57012.00 | 75176.00 | 351431.00 | 797290.00 | 807495.00 |
| | | Mean habitat | 72248.50 | 34959.33 | 153869.08 | 1832.53 | 3025.88 | 8266.09 | 114020.95 | 312799.09 | 315558.33 |
| Core - weighted | least-cost | no. | 3 | 2 | 4 | 3 | 1 | 1 | 2 | 2 | 2 |
| | | Total | 362360.00 | 322345.00 | 344835.00 | 64988.00 | 29612.00 | 30168.00 | 580535.00 | 628289.00 | 629762.00 |
| | | Mean network | 120786.67 | 161172.50 | 86208.75 | 21662.67 | 29612.00 | 30168.00 | 290267.50 | 314144.50 | 314881.00 |
| | | Mean habitat | 48165.67 | 52439.00 | 38467.27 | 1832.53 | 3025.88 | 8266.09 | 114020.95 | 156399.55 | 157779.17 |
| **IFM** | | | | | | | | | | | |
| Core - weighted | euclidean | Total | 451087.31 | 329654.66 | 678818.05 | 1497.06 | - | - | 1964919.79 | 2156707.24 | 2606824.12 |
| | | Mean | 75181.22 | 54942.44 | 96974.01 | 499.02 | - | - | 122807.49 | 143780.48 | 186201.72 |
| Core - weighted | least-cost | Total | 211027.25 | 243131.67 | 140496.49 | 0.00 | - | - | 1478217.08 | 1532998.63 | 1905620.54 |
| | | Mean | 35171.21 | 40521.95 | 20070.93 | 0.00 | - | - | 92388.57 | 102199.91 | 136115.75 |
| Hybrid IFM | | | 0.0188889 | 0.0100896 | | 0.0000199 | 0.0000092 | | 0.0351126 | 0.0701630 | |

| | | | Grid 13 | | | Grid 14 | | | Grid 15 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** | **1990** | **1998** | **Permanent** |
| **Metrics** | | | | | | | | | | | |
| No. Patches | | | 19 | 18 | 19 | 27 | 19 | 27 | 11 | 8 | 11 |
| Area | | Total | 419391.93 | 434885.56 | 413564.80 | 88886.05 | 107792.11 | 87535.46 | 191810.50 | 202768.75 | 190499.18 |
| | | Mean | 22073.26 | 24160.31 | 21766.57 | 3292.08 | 5673.27 | 3242.05 | 17437.32 | 25346.09 | 17318.11 |
| Core -Weighted | | no. | 19 | 18 | - | 27 | 21 | - | 6 | 8 | - |
| | | Total | 383480.35 | 398289.60 | - | 58691.65 | 54073.37 | - | 167269.48 | 174354.47 | - |
| | | Mean | 20183.18 | 22127.20 | - | 2173.76 | 2574.92 | - | 27878.25 | 21794.31 | - |
| | | % area | 0.91 | 0.92 | - | 0.66 | 0.50 | - | 0.87 | 0.86 | - |
| **Graph theory** | | | | | | | | | | | |
| Core - weighted | euclidean | IIC | 0.0932765 | 0.0985287 | 0.1067493 | 0.0022164 | 0.0019456 | 0.0043768 | 0.0243828 | 0.0272456 | 0.0306976 |
| | | PC | 0.1134187 | 0.1248956 | 0.1335355 | 0.0019762 | 0.0017807 | 0.0056039 | 0.0271956 | 0.0293303 | 0.0344242 |
| Core - weighted | least-cost | IIC | 0.0543711 | 0.0564368 | 0.0595561 | 0.0011817 | 0.0011598 | 0.0019256 | 0.0216302 | 0.0241612 | 0.0273945 |
| | | PC | 0.0486205 | 0.0482377 | 0.0525034 | 0.001096 | 0.0010964 | 0.0019277 | 0.0224209 | 0.0242943 | 0.0283175 |
| **Buffer radius networks** | | | | | | | | | | | |
| Core - weighted | euclidean | no. | 1 | 1 | 1 | 2 | 2 | 1 | 2 | 3 | 2 |
| | | Total | 915971.00 | 930658.00 | 938176.00 | 556533.00 | 499149.00 | 710324.00 | 447253.00 | 502098.00 | 558635.00 |
| | | Mean network | 915971.00 | 930658.00 | 938176.00 | 278266.50 | 249574.50 | 710324.00 | 223626.50 | 167366.00 | 279317.50 |
| | | Mean habitat | 383480.35 | 398289.60 | 413564.80 | 29345.83 | 27036.69 | 87535.46 | 83634.74 | 58118.16 | 95249.59 |
| Core - weighted | least-cost | no. | 3 | 3 | 2 | 4 | 3 | 3 | 1 | 2 | 1 |
| | | Total | 670030.00 | 681360.00 | 668549.00 | 294245.00 | 296470.00 | 311608.00 | 300543.00 | 352213.00 | 344411.00 |
| | | Mean network | 223343.33 | 227120.00 | 334274.50 | 73561.25 | 98823.33 | 103869.33 | 300543.00 | 176106.50 | 344411.00 |
| | | Mean habitat | 127826.78 | 132763.20 | 206782.40 | 14672.91 | 18024.46 | 29178.49 | 167269.48 | 87177.24 | 190499.18 |
| **IFM** | | | | | | | | | | | |
| Core - weighted | euclidean | Total | 3727404.13 | 3459564.36 | 3966396.88 | 475533.66 | 358983.24 | 840070.63 | 697187.58 | 831445.67 | 1494425.26 |
| | | Mean | 196179.16 | 192198.02 | 208757.73 | 17612.36 | 17094.44 | 31113.73 | 116197.93 | 103930.71 | 135856.84 |
| Core - weighted | least-cost | Total | 504205.30 | 586429.86 | 751111.97 | 59243.45 | 57894.29 | 187254.35 | 381874.26 | 312955.39 | 967233.42 |
| | | Mean | 26537.12 | 32579.44 | 39532.21 | 2194.20 | 2756.87 | 6935.35 | 63645.71 | 39119.42 | 87930.31 |
| Hybrid IFM | | | 0.0481170 | 0.0473825 | | 0.0010824 | 0.0010811 | | 0.0224176 | 0.0242940 | |

| | | | Grid 16 | | |
|---|---|---|---|---|---|
| | | | **1990** | **1998** | **Permanent** |
| **Metrics** | | | | | |
| No. Patches | | | 8 | 8 | 7 |
| Area | | Total | 16993.09 | 6746.47 | 5793.64 |
| | | Mean | 2124.14 | 843.31 | 827.66 |
| Core -Weighted | | No. | 3 | 1 | - |
| | | Total | 1311.88 | 729.86 | - |
| | | Mean | 437.29 | 729.86 | - |
| | | % area | 0.08 | 0.11 | - |
| **Graph theory** | | | | | |
| Core - weighted | euclidean | IIC | 0.0000013 | - | 0.0000202 |
| | | PC | 0.0000011 | - | 0.0000133 |
| Core - weighted | least-cost | IIC | 0.0000009 | - | 0.0000067 |
| | | PC | 0.0000008 | - | 0.0000067 |
| **Buffer radius networks** | | | | | |
| Core - weighted | euclidean | No. | 2 | 1 | 5 |
| | | Total | 68956.00 | 36249.00 | 260759.00 |
| | | Mean network | 34478.00 | 36249.00 | 52151.80 |
| | | Mean habitat | 655.94 | 729.86 | 1158.73 |
| Core - weighted | least-cost | No. | 2 | 1 | 7 |
| | | Total | 50436.00 | 5429.00 | 92959.00 |
| | | Mean network | 25218.00 | 5429.00 | 13279.86 |
| | | Mean habitat | 655.94 | 729.86 | 827.66 |
| **IFM** | | | | | |
| Core - weighted | euclidean | Total | 1254.15 | - | 8787.30 |
| | | Mean | 418.05 | - | 1255.33 |
| Core - weighted | least-cost | Total | 117.54 | - | 0.02 |
| | | Mean | 39.18 | - | 0.00 |
| Hybrid IFM | | | 0.0000008 | 0.0000005 | |

## 5.4 Assessment of connectivity measures to detect change

Selected connectivity measures from Table 24, with potential to provide the basis for a habitat connectivity indicator, are presented in Table 25. The response of the indicators is discussed in relation to their interpretation, comparison and consistency with general description of landscape change and the supporting landscape metrics:

**CS sample square 4** – all connectivity measures predicted a decline in this CS sample square, in line with the general description of landscape change between 1990 and 1998 (see Table 24) and supporting landscape metrics.

**CS sample square 5** – all connectivity measures predicted a general increase in connectivity consistent with an increase in habitat area and a slight increase in semi-natural habitat with improved permeability.

**CS sample square 6** – 4 of the 5 connectivity measures predicted a decline in habitat connectivity consistent with the decline in habitat area. The buffer radius of total network area predicted an increase in connectivity due to the increase in bracken; a semi-natural habitat with improved permeability.

**CS sample square 7** – patch-based connectivity measures (buffer radius mean habitat & patch-based IFM) predicted an increase in connectivity, as the mean patch size and spatial distribution of patches changed. This is consistent with the observation that patch-based connectivity measures actually increase within increased fragmentation. Other connectivity measures predicted a more realistic decline in connectivity.

**CS sample square 9** – buffer radius mean habitat predicted an increase in this sample square, even though 3 habitat patches were reduced to 1 in 1998. This is due to the removal of 2 smaller habitat patches, leaving 1 larger patch. This is inconsistent with the description of change in this sample square and the supporting metrics. IFM patch-based and PC were unable to detect change as only 1 patch remained in 1998, and they are based on connectivity between patches. Only buffer radius total network area and hybrid IFM predicted the expected decline in connectivity in this sample square.

**CS sample square 12** – all connectivity measures predicted an increase in habitat connectivity in this sample square. This is consistent with the description of the sample square with an increase in habitat and an increase in matrix permeability.

**CS sample square 13** – there are very subtle landscape changes in this sample square. PC and hybrid IFM predict a slight decrease, whereas the other measures predict a slight increase.

**CS sample square 14** - there are also very subtle landscape changes in this sample square, with a very slight increase in woodland cover and matrix permeability. PC and hybrid IFM predict little change, whereas the other measures predict a slight increase.

**CS sample square 15** – patch-based connectivity measures (buffer radius mean habitat & IFM patch-based) predicted an unexpected decrease in connectivity, due to the reduction in the number of patches, even though the total and mean habitat area increased. The other measures predict a positive increase more consistent with the landscape change within the sample square.

**CS sample square 16** – this CS sample square only has 1 area of habitat remaining in 1998 after the application of a weighted edge; therefore PC and patch-based IFM were once again unable to detect change. Buffer radius mean habitat predicted an unrealistic increase, due to the removal of smaller patches. Only buffer radius total network and hybrid IFM were able to detect the expected negative change in habitat connectivity, consistent with the landscape description and supporting metrics.

**Table 25** – General change in 10 CS sample squares (Appendix 2) based on landscape metrics and general description; compared with selected connectivity measures (red down arrow = decrease, green up arrow = increase, grey horizontal arrow = no/minimal change, 0 = no value).

| | **Landscape metrics & general description of landscape change** | | | | **Connectivity measures based on weighted edge and least-cost distance** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *CS grid square* | *Metric - change in number of patches* | *Metric - change in total habitat area* | *Metric - change in mean patch size* | *General description of landscape change within CS sample squares between 1990 and 1998* | *Graph theory - Probability of connectivity* | *Buffer radius - total network area* | *Buffer radius, mean habitat area* | *IFM – patch - based* | *IFM – hybrid* |
| **4** | ↔ | ↓ | ↓ | 6 small woodlands in a fairly homogenous arable landscape. 6 patches within both time frames, only 3 permanent. Loss of some semi-natural habitat and linear features. | ↓ | ↓ | ↓ | ↓ | ↓ |
| **5** | ↑ | ↑ | ↓ | Numerous woodlands within a heterogeneous agricultural/riparian landscape. General shift from intensive grassland to semi-natural habitat. | ↑ | ↑ | ↑ | ↑ | ↑ |
| **6** | ↑ | ↓ | ↓ | Fairly intact large woodland block in riparian landscape surrounded by coniferous woodland. Relatively stable landscape with encroachment of bracken in woodland in 1998. | ↓ | ↑ | ↓ | ↓ | ↓ |
| **7**[1] | ↔ | ↓ | ↓ | Large woodland block within a mixed semi-natural/ agricultural landscape. A general shift to more intensive agriculture in the matrix and encroachment of bracken in woodland. | ↓ | ↓ | ↑ | ↑ | ↓ |
| **9** | ↓ | ↓ | ↓ | 3 small patches of woodland within an intensive agricultural landscape, reduced to 1 woodland patch in 1998. | 0 | ↓ | ↑ | 0 | ↓ |
| **12** | ↓ | ↑ | ↑ | Widespread woodland throughout an arable/urban landscape. Increase in woodland cover and a reduction in agricultural intensity (matrix hostility) in 1998. | ↑ | ↑ | ↑ | ↑ | ↑ |
| **13** | ↓ | ↑ | ↑ | Numerous patches of woodland of varying size within a mixed grassland landscape. Slight increase in woodland area and joining of small | ↓ | ↑ | ↑ | ↑ | ↓ |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | patches in 1998 and slight change to matrix configuration. | | | | | |
| **14** | ↓ | ↑ | ↑ | Numerous linear woodlands around field boundaries within an intensive grassland/arable landscape. Increase in woodland cover in 1998 and joining of smaller patches. | ↔ | ↑ | ↑ | ↑ | ↔ |
| **15** | ↓ | ↑ | ↑ | Large linear band of woodland along coastal fringe with smaller woodlands within a grassland/urban landscape. Slight increase in area of woodland. | ↑ | ↑ | ↓ | ↓ | ↑ |
| **16** | ↔ | ↓ | ↓ | Very small, linear woodland patches within an agricultural, urban, coastal landscape. Loss of woodland and linear features in 1998. | 0 | ↓ | ↑ | 0 | ↓ |

[1]CS sample square used in analysis of single CS sample square in Section 5.1.

The selected indicators detected change in CS landscapes as identified in Table 25 and showed that there is considerable diversity in indicator performance. In particular, the analysis revealed a difference in measures applied to patches as compared to those focussed on a grid or cell-based measures. As a result of this analysis the proposed measures form Table 22, are further refined in Table 26. This identifies core-weighted edge, least-cost distance and a hybrid IFM as the preferred options to take forward. Normal area and Euclidean distance are possible interim options if there are issues with permeability and edge values, although these would fail to capture matrix change.

**Table 26** – Further selection of habitat area, distance options and candidate connectivity measures, following on from Table 22.

| | | **Outcome** |
|---|---|---|
| **Area options** | *Normal area – no edge* | Possible interim measure. Does not include edge impacts, a feature seen as essential by steering group. |
| | *Core area – weighted edge* | **Accepted**. Preferred option as this account for the surrounding matrix. |
| **Distance Options** | *Euclidean distance* | Possible interim measure. Euclidean is simple and quick to calculate but does not account for matrix permeability. It is a directed measure with limited assumptions. |
| | *Least-cost distance* | **Accepted**. Although more complex and timely to calculate, has the ability to incorporate matrix permeability to assess functional connectivity. Based on a greater number of assumptions. |
| **Candidate connectivity measures** | *Graph theory* | **Rejected**. Probability of Connectivity (PC) outputs appear to be consistent with the proposed hybrid IFM connectivity indicator. Issue with calculating PC for single patch landscapes. Limited flexibility within Sensinode software, and requires outputs from other GIS tools (area and distance measures). |
| | *Buffer radius* | **Rejected**. Patch-based measure - Buffer radius mean habitat area - increased with increasing fragmentation.<br><br>**Rejected**. Grid-based measure - total buffer network radius – increases with increased |

| | | |
|---|---|---|
| | | permeability. Identifies binary connectivity in the wider landscape rather than between patches. Lacks the ecological robustness of Graph theory and IFM approaches (e.g. area weighting and dispersal curve). |
| | *IFM* | **Rejected**. Patch-based IFM as this increased with increasing fragmentation.<br><br>**Accepted**. Hybrid IFM as it is methodologically and ecologically robust, and it captures inter and intra patch connectivity and predicts change consistently. Approach based on existing GIS tool. |

# 6 Discussion

## 6.1 Data limitations

This pilot study has had to rely on a single spatial data set to assess habitat connectivity. CS field survey accurately captures land cover data at high spatial and temporal resolution. However, there is concern that the limited spatial extent may not accurately capture changes in the wider landscape. Many species of conservation concern may be able to traverse a 1km square with relative ease. The pattern of landscape structure within a CS sample square may also be related to the manner in which the boundaries of the sample square dissect larger patches beyond, as shown in Figure 25.

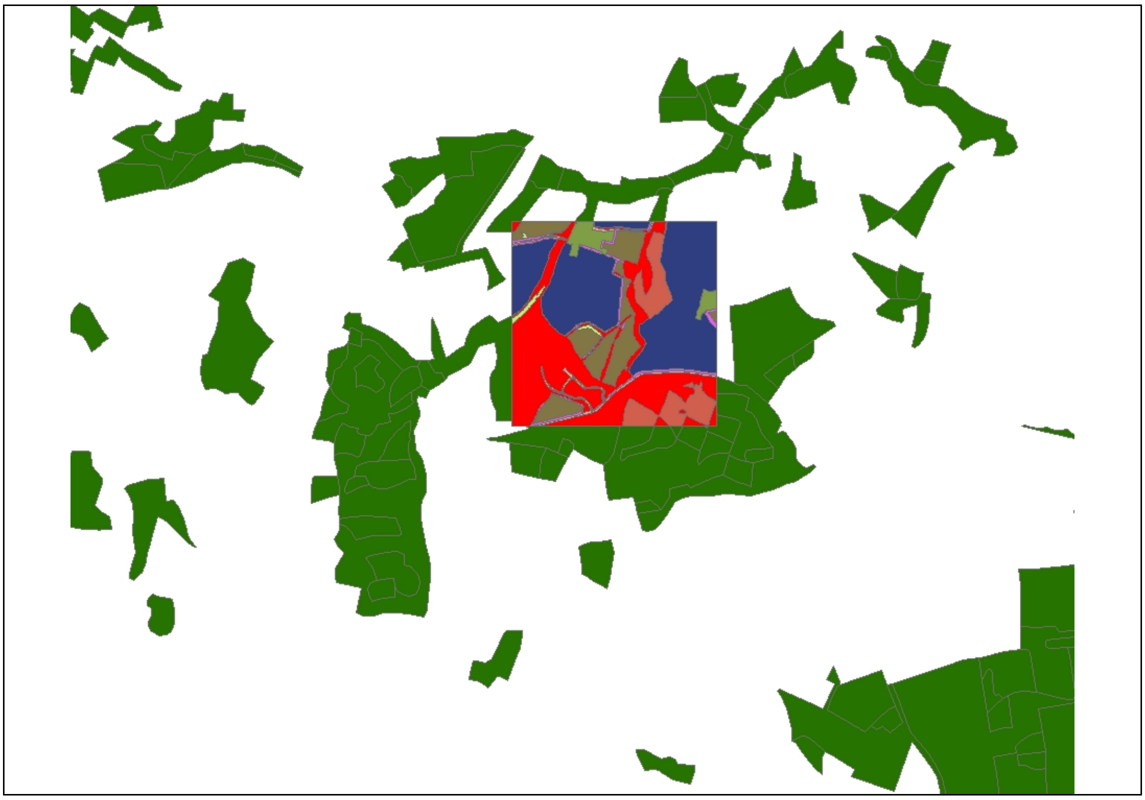


**Figure 25** – Comparison of woodland within a CS (red) with woodland within the wider landscape (green)

The original intention had been to investigate some of these scale issues with LCM data; however, the available data were not suitable for analysis (See Appendix 1). Outputs assessing habitat connectivity at the scale of CS sample squares may provide an acceptable interim measure but may not reflect connectivity change at a larger extent. The use of future LCM data should provide an opportunity to address this problem.

A significant amount of work was required to add linear features, in a form suitable for analysis, to the CS data. However, there seems to be a lack of consensus over the value of linear features for species movement (Davies and Pullin, 2007; Eycott *et al.*, 2008). Within this study woodland linear features were considered as highly permeable due to the species and structural similarity to woodland habitat (Section 4.4.1). There was also some concern over the reliability of the mapping of linear features and whether they represented real change or different surveyor interpretation.

As the data within CS are mapped as Broad Habitats there is little opportunity to distinguish between certain landscape features. There seemed to be an apparent high species similarity between urban areas (probably gardens), and woodlands. Unfortunately there was no opportunity to separate out gardens from the buildings within the urban classification.

### *6.2 Permeability and edge values*

There appears to be a growing realisation that the surrounding matrix may have an impact on habitat connectivity (Eycott *et al.*, 2008). In addition, many discussions of connectivity suggest the use of alternative distance measures to account for matrix permeability and provide a more realistic measure (Calabrese and Fagan, 2004; Fagan and Calabrese, 2006; Pascual-Hortal and Saura, 2006) . For example, approaches that account for landscape permeability have been shown to be a better predictor of genetic similarity between fragmented populations than Euclidean distance measures (Storfer *et al.*, 2007).

It is difficult to define the relative degree of matrix permeability as it is species specific, and there is little supporting evidence (Eycott *et al.*, 2008). Even if there were considerable empirical data on permeability and edge impacts for a number of species, there would still be a degree of subjectivity in assimilating all the data into a single measure. Therefore, this study gathered expert opinion on landscape permeability for a conceptual woodland focal species through a Delphi analysis (MacMillan and Marshall, 2006). Improvements could be made to the Delphi analysis process to collect knowledge from a larger number of experts on potential landscape permeability and edge values, perhaps through a one day workshop. The advantage of the Delphi approach is that it is structured to build consensus, and when conducted anonymously should not be open to bias from peer pressure. The Delphi method of information gathering also provides a mechanism for the inclusion of empirical evidence, since evidence-based assertions carry considerable weight in the evaluation of knowledge gathered in an anonymous procedure.

# 7 Conclusion and recommendations

There is a fundamental trade-off in landscape-scale modelling approaches between simplicity and data availability. On the one hand, very simple indicators based on metrics can be readily calculated from available land-cover data but do not realistically report on the processes inherent in landscape ecology. On the other hand relatively complex mechanistic-type models such as the detailed IFM connectivity approaches, which more adequately portray ecological processes, are more difficult to parameterise. The implementation of these models is hampered by the lack of data about species interactions with habitat and matrix mosaic. Between these extremes are relatively simple heuristic analyses such as Euclidean or least-cost-distance approaches that provide very broad guidance from a set of readily available and updateable information and data. The application of these often uses expert opinion to help parameterise the model, but this process is relatively easily repeated and can be quickly updated as new information becomes available.

The urgency to implement conservation policy means that the there is often little time to wait until more complete data have been assembled on species and their interaction with the environment, even if the resources are available to acquire the necessary data. The pace of both land-use and climate change requires that policy and action must be based on acceptable principles, albeit subject to change in the light of emerging research. An adaptive modelling approach is a very practical response to the need for adaptive management, where one informs the other and vice-versa. The development of models based on a combination of empiricism and heuristics conveys the reality of the situation, where expert opinion provides the missing link of empirical evidence, and the incorporation of empirical data into the model reflects the importance assigned to particular species, guilds, and habitats in terms of conservation effort.

## *7.1 Indicator and spatial data recommendation*

As a result of this study, it is concluded that the proposed indicator should comprise an area option with a weighted edge, a least-cost distance option and a hybrid (patch/grid-based) Incidence Function Model (IFM) (see Table 26) applied to the Countryside Survey: Field Survey (CS) spatial data set; [note the caveat regarding the limited extent of the spatial data (see Section 6.1)]. A normal area option, without edge impacts, and Euclidean distance option, without matrix impacts, may provide an interim measure if there are issues with permeability and edge values.

A grid -based or hybrid IFM calculates (Moilanen and Hanski, 2001; Vos *et al.*, 2001; Moilanen and Nieminen, 2002; Early *et al.*, 2008) (Section 4.6.4) the potential number of individuals moving between grids/cells within the landscape and captures information on both inter and intra patch connectivity. The approach captures information on habitat area (also habitat quality if available), isolation, edge and matrix permeability, through the use of least-cost approaches and dispersal curves. The inputs and outputs for such an approach are listed in Table 27.

**Table 27** – Inputs and outputs for proposed habitat connectivity indicator.

| Inputs | Outputs |
|---|---|
| • Spatial/temporal land cover data – CS data<br>• Habitat preference – selected habitat<br>• Dispersal curve<br>• Patch level species/ area information<br>*Optional:*<br>• Edge impacts (weighted)<br>• Permeability values | *Probabilistic measure:*<br>• Grid -based connectivity measure |

In order to assess the suitability of the proposed spatial data and connectivity indicators, each is compared with the original indicator selection criteria (introduced in Section 3.3) in Table 28. This confirms that both the data and proposed connectivity measure are highly suitable for indicator development, with the only concern being the limited extent of the CS data. The application of the recommended connectivity indicator to the 10 CS sample squares is summarised in Table 29.

**Table 28** - Assessment of selected spatial data and connectivity indicator against EEA and CBD indicator criteria (SEBI2010 Expert Group, 2005)

| No. | Criteria | CS data | Hybrid IFM indicator |
|---|---|---|---|
| 1 | Policy relevant and meaningful | | ✓ Measure of functional connectivity addresses area, isolation, edge & matrix |
| 2 | Biodiversity relevant | | ✓ Species-based indicator |
| 3 | Scientifically sound and methodologically well founded | | ✓ Underpinned by strong scientific theory & evidence |
| 4 | Progress towards 2010 targets | | ✓ Indicator linked to drivers and conservation actions in landscapes |
| 5 | Broad acceptance and easy to understand | | ✓ Easy to interpret |
| 6 | Affordable monitoring, available and routinely collected data | ✓ Use of existing CS data | |
| 7 | Affordable modelling | | ✓ tools for indicator analysis developed |

| | | | |
|---|---|---|---|
| **8** | Spatial and temporal coverage of data | ✗ Issues of small extent with CS data, good consistent temporal coverage | |
| **9** | National scale and representativeness of data | ✓ CS data collected across | |
| **10** | Sensitive to detect change | | ✓ detected subtle change consistently in small landscapes |
| **11** | Representative of DPSIR framework | | ✓ State, impact indicator |
| **12** | Small number – low complexity | | NA – for assessment of groups of indicators |
| **13** | Aggregation and flexibility – range of scales | | NA – for assessment of groups of indicators |

**Table 29** – Proposed habitat connectivity indicator output for the 10 Cs sample squares used in the pilot study

| ***CS grid square*** | ***General description of landscape change within CS sample squares between 1990 and 1998*** | ***Connectivity indicator*** |
|---|---|---|
| **4** | 6 small woodlands in a fairly homogenous arable landscape. 6 patches within both time frames, only 3 permanent. Loss of some semi-natural habitat and linear features. | ↓ |
| **5** | Numerous woodlands within a heterogeneous agricultural/riparian landscape. General shift from intensive grassland to semi-natural habitat. | ↑ |
| **6** | Fairly intact large woodland block in riparian landscape surrounded by coniferous woodland. Relatively stable landscape with encroachment of bracken in woodland in 1998. | ↓ |
| **7** | Large woodland block within a mixed semi-natural/ agricultural landscape. A general shift to more intensive agriculture in the matrix and encroachment of bracken in woodland. | ↓ |
| **9** | 3 small patches of woodland within an intensive agricultural landscape, reduced to 1 woodland patch in 1998. | ↓ |
| **12** | Widespread woodland throughout an arable/urban landscape. Increase in woodland cover and a reduction in agricultural intensity (matrix hostility) in 1998. | ↑ |
| **13** | Numerous patches of woodland of varying size within a mixed grassland landscape. Slight increase in woodland area and joining of small patches in 1998 and slight change to matrix configuration. | ↓ |
| **14** | Numerous linear woodlands around field boundaries within an intensive grassland/arable landscape. Increase in woodland cover in 1998 and joining of smaller patches. | ↔ |
| **15** | Large linear band of woodland along coastal fringe with smaller woodlands within a grassland/urban landscape. Slight increase in area of woodland. | ↑ |
| **16** | Very small, linear woodland patches within an agricultural, urban, coastal landscape. Loss of woodland and linear features in 1998. | ↓ |

## 7.2 Indicator implementation

The possible means of implementing the recommended indicator, and a number of risks associated with such implementation, are now described.

Calculation of a hybrid IFM (using weighted edge and least-cost distance) can be calculated by a software refinement to an existing habitat connectivity tool (within the BEETLE toolbox – Biological and Environmental Evaluation Tools for Landscape Ecology) developed by Forest Research. Hybrid IFM connectivity calculations can already be determined from existing tool outputs; however this requires some manual intervention **RISK 1**.

The existing connectivity tools are based on using a single polygon shape file for each individual CS sample squares, any deviation from this will require further development of the connectivity analysis tool **RISK 2**.

There are technical challenges to the inclusion of linear features in a useable form within CS data **RISK 3**. An option is to exclude linear features from the analysis if the issue cannot be resolved within the time available for indicator derivation.

In order to utilise landscape permeability and edge impacts, through least-cost approaches, there is a heavy reliance on a very limited number of expert-based judgements. A priority should be to conduct a fuller Delphi analysis **RISK 4**. If this risk cannot be overcome in the short term, Euclidean distance and normal edge values could be used as an interim measure.

The proposed connectivity indicator can be presented fairly easily, as it can be normalised (between 0 and 1) for each landscape and is comparable between years and between landscapes. Indicator outputs could include mean, median, change, confidence limits for each CS sample square, landscape types or time periods.

The proposed connectivity indicator should be evaluated further by applying conceptual changes (as proposed in Appendix 1) to a larger landscape area, perhaps the final version of LCM 2007 or similar. Although the approach is well founded it would be prudent to further evaluate indicator performance **RISK 5**. See Section 7.3 for further details.

This indicator outputs are only relevant to the 1km scale of CS sample squares – see Section 7.2 about the use of larger extent data. Therefore there needs to be a strong caveat that the indicator outputs are based on 1km CS sample squares, and change at this level may not reflect wider landscape change **RISK 6**.

## 7.3 Further development

Further development of the indicator project should aim to tackle the specific risks identified in Section 7.2.

**Risk 1** – Provide for the further development of the habitat connectivity tool and allow reasonable time for testing (~4 weeks).

**Risk 2** – Ensure all CS data is in the required format (CEH) or further refine the habitat connectivity tool (~2 weeks).

**Risk 3** – Consider whether and how to include linear features in original data set (~2 weeks).

**Risk 4** - Refine permeability and edge values with revised Delphi analysis (~8 weeks).

**Risk 5** – The use of scenarios, as proposed in Appendix 1, to explore possible change options and validate indicator response (~12 weeks). Isolate positive and negative changes in area and connectivity, where there is a combination of the two, as in real landscape, it can be difficult to identify overall effect on connectivity. Examine the relationship between intra and inter patch connectivity. Identify potential thresholds i.e. where adding/removing patches starts to have a significant effect on connectivity.

In order to report on habitat connectivity in the short term, Figure 26 provides a Gantt chart detailing the potential implementation of the connectivity indicator based on the use of existing CS data.

In the longer term, there would be a need to tackle **Risk 6** by utilising larger extent data (LCM) when available and to examine the impact of scale. There is also an ongoing need to validate connectivity with empirical evidence for selected focal species.

| | Task Name | Start | Finish | Duration |
|---|---|---|---|---|
| 1 | Inclusion of linear Features (Risk 3 - CEH) | 29/09/2008 | 10/10/2008 | 2w |
| 2 | Getting data in the correct format (Risk 2 - CEH) | 13/10/2008 | 24/10/2008 | 2w |
| 3 | Further development of the habitat connectivity tool (Risk 1 - FR) | 27/10/2008 | 21/11/2008 | 4w |
| 4 | Calculation of the indicator | 24/11/2008 | 02/01/2009 | 6w |
| 5 | Revised Delphi Analysis (Risk 4 - FR & Stakeholders) | 29/09/2008 | 21/11/2008 | 8w |
| 6 | Validation and testing (Risk 5 - FR & Stakeholders) | 29/09/2008 | 19/12/2008 | 12w |

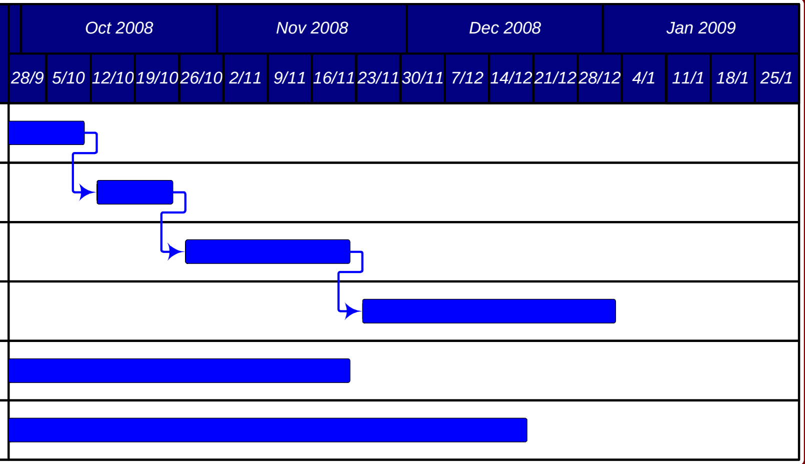



**Figure 26** – Gantt chart detailing potential implementation of habitat connectivity indicator.

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# 9 Appendix 1 – Analysis of suitability of Land cover Map data for habitat connectivity indicator pilot project

## 9.1 Land Cover Map

LCM is a pixel/parcel-based spatial dataset which accurately represents real world features. It was developed by the Centre for Ecology and Hydrology (CEH) using satellite imagery and, more recently, Ordnance Survey MasterMap polygons to form a digital map describing different types of land and vegetation cover across the UK (Comber *et al.*, 2003). The LCM project thereby creates a framework for analysis of landscapes within the UK.

The original project specification suggests using LCM at two date points: 1990 and 2000 to investigate environmental change. Refinements and changes to the method of producing LCM between survey years meant that the two time points were not directly comparable. The knowledge-based correction procedure had been changed between the two studies, using a parcel based classification rather than one based on pixels as used in 1990. The minimum mapable unit had been changed and the class names had also altered in meaning, in interpretation or been changed completely (Comber *et al.*, 2003).

The comparison between earlier LCM data and LCM2007 also identified problems due to changing data collection and interpretation standards. Previously, the geometry used in mapping (pre-2007) was derived from image segmentation of Earth observation data. The geometry used in LCM2007 uses a generalised version of OS MasterMap, supplemented by other digital cartography (i.e. agricultural land parcel dataset) and then segmented by 20-35m resolution Earth observation data. The resulting dataset has a minimum mapable unit of 0.5 ha and a minimum feature width of 20m.

Changes in data collection and interpretation methodologies make direct comparison between LCM2007 and previous datasets unworkable at present. The improvement in the collection techniques and the possibility of a rolling update made LCM2007 the best candidate for investigating environmental change.

### 9.1.1 LCM2007 pilot data

The final version of LCM2007 is not due for release until mid 2009. Therefore, LCM2007 pilot data was supplied by CEH and utilised for this study. The pilot data is currently available for two areas of the Berwyn Hills in north Wales and an area of Hampshire. The pilot data does not represent a final product, instead it is an early stage in the iterative process used to develop and test methods and user requirements. The data therefore has some limitations and caveats associated with early stage data.

**Removal of voids**

The pilot data contained numerous voids within the data; these were identified using standard GIS techniques. Voids over 10,000 $m^2$ in extent were manually classified using a combination of aerial photography and the surrounding polygons to determine a 'best guess' classification. Large linear features were reclassified where they could be clearly identified; otherwise they were left to be corrected in a subsequent correction phase. Finally, minor/small unclassified polygons were assigned to the same classification as the polygon sharing the longest border.

**Reclassification to Broad Habitats**

The data within LCM2007 was reclassified to the Broad Habitat classification used in CS by means of a reclass table (Table 30). The reclass methodology provided consistency between the two data sets; and Broad Habitat categories provided greater clarity in understanding and interpretation.

**Table 30** - Table showing reclassification from LCM to CS Broad Habitats

| LCM General Classification | LCM Description | Broad Habitat Classification |
|---|---|---|
| *Arable:* | Wheat | Arable and Horticultural |
| | Barley | Arable and Horticultural |
| | Oil seed rape | Arable and Horticultural |
| | Potatoes | Arable and Horticultural |
| | Sugar beet | Arable and Horticultural |
| | Field beans | Arable and Horticultural |
| | Linseed | Arable and Horticultural |
| | Arable oats | Arable and Horticultural |
| | Horticulture | Arable and Horticultural |
| | Carrots | Arable and Horticultural |
| | Peas | Arable and Horticultural |
| | Maize | Arable and Horticultural |
| | Mustard | Arable and Horticultural |
| | Arable bare | Arable and Horticultural |
| | Cereal stubble | Arable and Horticultural |
| | Set-aside | Arable and Horticultural |
| | Set-aside (sprayed) | Arable and Horticultural |
| | Set-aside (bare) | Arable and Horticultural |
| | Set-aside (vegetated) | Arable and Horticultural |
| *Grass:* | Ley | Neutral Grassland |
| | Neutral | Neutral Grassland |
| | Improved | Improved Grassland |
| | Unimproved | Neutral Grassland |
| | Acid | Acid Grassland |
| | Calcareous | Calcareous Grassland |
| | Rough / unmanaged | Neutral Grassland |
| | With dominant Juncus | Neutral Grassland |
| | Moor (Nardus/Molinia) | Neutral Grassland |
| | Grass moor molinia | Neutral Grassland |
| | Grass moor nardus | Neutral Grassland |
| | Hay | Improved Grassland |
| *Wood:* | Conifer | Coniferous Woodland |
| | Larch | Coniferous Woodland |
| | Recent (<10yrs) | Coniferous Woodland |
| | Mixed | Broadleaved Mixed and Yew Woodland |

| | | |
|---|---|---|
| | Recent (<10yrs) | Broadleaved Mixed and Yew Woodland |
| | Deciduous | Broadleaved Mixed and Yew Woodland |
| | Poplar | Broadleaved Mixed and Yew Woodland |
| | Recent (<10yrs) | Broadleaved Mixed and Yew Woodland |
| | Rhododendron | Dwarf Shrub Heath |
| | Evergreen | Coniferous Woodland |
| | Scrub | Dwarf Shrub Heath |
| | Orchard | Arable and Horticultural |
| | Orchard (new) | Arable and Horticultural |
| | Vineyard | Arable and Horticultural |
| | Hop | Arable and Horticultural |
| | Felled | Broadleaved Mixed and Yew Woodland |
| *Heath / Marsh:* | Heather & dwarf shrub | Dwarf Shrub Heath |
| | Dry heath | Dwarf Shrub Heath |
| | Wet heath | Dwarf Shrub Heath |
| | Gorse | Dwarf Shrub Heath |
| | Arctic heath | Dwarf Shrub Heath |
| | Burnt heather | Dwarf Shrub Heath |
| | Burnt heather now grass | Dwarf Shrub Heath |
| | Heather grass | Dwarf Shrub Heath |
| | Bracken | Bracken |
| | Fen / swamp | Fen, Marsh, Swamp |
| | Fen marsh (grass) | Fen, Marsh, Swamp |
| | Fen & willow | Fen, Marsh, Swamp |
| | Bog | Bog |
| | Bog (Heather dom.) | Bog |
| | Bog (Grass dom.) | Bog |
| | Blanket bog | Bog |
| | Montane habitats | Montane |
| *Coastal:* | Littoral sand | Littoral Sediment |
| | Littoral mud | Littoral Sediment |
| | Littoral rock | Littoral Sediment |
| | Saltmarsh | Littoral Sediment |
| | Saltmarsh grazing | Littoral Sediment |
| | Sub littoral rocks | Littoral Rock |
| | Sand dune | Supra-littoral Sediment |
| | Sand dune with shrubs | Supra-littoral Sediment |
| | Shingle | Supra-littoral Sediment |
| | Shingle vegetated | Supra-littoral Sediment |
| | Sea | Sea |
| | Water estuary | Sea |
| *Urban / Other:* | Urban | Built-up Areas, Gardens |
| | Suburban | Built-up Areas, Gardens |
| | Industrial urban | Built-up Areas, Gardens |
| | Despoiled land | Built-up Areas, Gardens |
| | Bare | Inland Rock |
| | Water | Standing Open Waters and Canals |
| | Water flooded | Standing Open Waters and Canals |

**Addition of roads and rivers**
In the creation of the LCM2007 pilot data, road and river objects were not included. The polygons containing the road and river information had been shared between adjoining polygons. The steering group identified the need to include these important landscape features in the analysis since roads and rivers could act as barriers or corridors for species movement. As a result, rivers and roads were extracted from the OS MasterMap and combined with the LCM2007 pilot data to produce a single data set.

**Selection of LCM 10km x 10 km squares**
Two 10km squares were extracted from each pilot study area in the Berwyn Hills and Hampshire, taking account of the limited size of the study areas and their irregular data coverage. The final decision was based on the best coverage of spatial data.

### *9.1.2 Modelling landscape change*

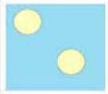
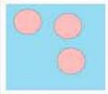
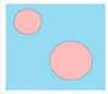
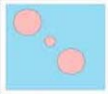
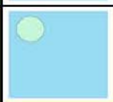
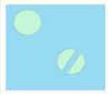
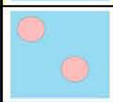
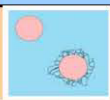
To address the lack of temporal data with which to investigate landscape change (a key requirement for indicator application – see Section 3.3), the connectivity indicator sub-group identified the need to develop conceptual, but plausible, landscape change scenarios. Once agreed, these conceptual changes were applied to the landscapes within the LCM2007 pilot data areas. Conceptual changes in connectivity could then be identified in a methodical approach to create a series of paired comparisons.

In order to develop conceptual landscape change scenarios it was necessary to identify the different ways landscape change may impact on connectivity. A number of distinct elements of change were described:

- Change in the area of habitat or the number of distinct patches.
- Change the isolation of patches.
- Impact on the edge of habitats, i.e. by changing patch shape.
- Change patch persistence through time, i.e. the area may be constant, but a patch may have been destroyed and another created. This will impact on temporal connectivity.
- Landscape change may also alter the matrix surrounding the habitat patches. This may impact on the elements above by increasing/decreasing isolation or changing edge impacts.

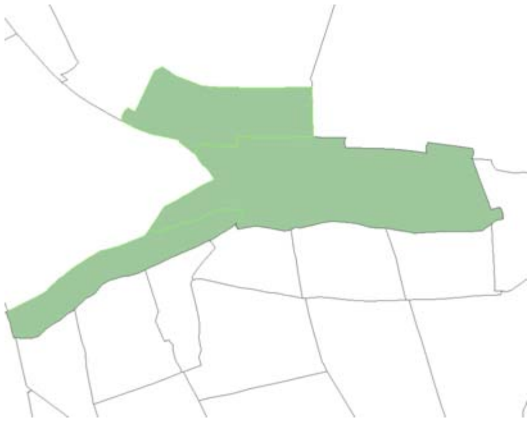
Changes were applied to one patch at a time, i.e. only one patch can be added, removed or altered between each conceptual change. Complex changes were produced by applying iterations of change. As a result, specific actions (e.g. add patch) were identified along with their spatial application (e.g. random or buffer existing patch), as outlined in the Table 31. These actions were assessed in terms of their potential impact on habitat connectivity. Spatial illustrations of the landscape change scenarios are provided in Table 31.

**Table 31** – Potential landscape change scenarios

| Action | Application | | Illustration | | | conceptual change |
|---|---|---|---|---|---|---|
| CONTROL | | |  | | | |
| Add patch | random | *1* |  | | | add patch |
| | to existing patch/shape | *2* |  |  |  | enlarge patch<br>change shape<br>filll perforation (*where they exist - not in control*) |
| | to form join/link | *3* |  | | | add joining patch - increase core area, decrease edge |
| | as stepping stone | *4* |  | | | add stepping stone |
| Remove patch | random | *5* |  | | | remove patch |
| | to existing patch/shape | *6* |  |  |  | shrink patch<br>change shape<br>perforate patch |
| | to break join/link | *7* |  | | | remove joining patch<br>split patch - decrease core area, increase edge |
| | acting as stepping stone | *8* |  | | | remove stepping stone<br>(*where they exist - not in control*) |
| Persistence in time<br>(*affected by to add/remove actions*) | Constant | *9* |  | | | patches constant in time |
| | Changing | *10* |  | | | patch removed/added |
| Matrix | increase permeability (*outlined area*) | *11* |  |  | | decrease matrix hostility<br>decrease edge impacts |
| | decrease permeability (*dark area*) | *12* |  |  | | increase matrix hostility<br>increase edge impacts |

## Problems with the approach

Although the conceptual approach was robust, systematic and well founded, problems with the underlying pilot data prevented this approach from being utilised. After reworking the data and applying connectivity measures a number of anomalies were identified. It became apparent that many small, false fragmentation slivers were artificially created through the intersection of habitat with roads and rivers. In the original data set there were 205 discrete woodland patches with a mean size of 4.2 ha in the Berwyn square, however, when roads and rivers were added there were 631 patches with a mean size of 1.3 ha. Further examination revealed that nearly 300 of these woodlands were less than 100 $m^2$, 200 were less than 10 $m^2$ (below the minimum mapable unit of 25 $m^2$) and 140 were less than 1 $m^2$. This problem is illustrated in Figure 27, where the effect of adding road and river information to woodland, clearly shows false fragmentation of the habitat. While it is expected that the number of patches would increase from dissection by roads and rivers; Figure 27 seems to indicate that many patches created may be false. The relatively small size of some of the patches suggests that the GIS created sliver polygons due to unmatched polygon boundaries. This issue has a fundamental impact on the assessment of landscape connectivity, as the number of patches will be too high, mean patch size too low and the inter patch distance incorrect.



LCM 2007 Pilot data, the woodland is shown in green

OS MasterMap data, the roads are shown in red

The two dataset overlying each over, showing how they will intersect with each other

After the two datasets are combined, numerous small patches/slivers have been produced (highlighted in blue)

**Figure 27** - Effect of adding OS MasterMap information to woodland in LCM2007 Pilot data

## *9.2 LCM suitability for indicator pilot project*

Due to the combination of errors in the LCM pilot study data combined with the amount of processing time required to remove voids, adding roads and rivers, the investigation of LCM pilot data was terminated. A further very significant constraint for indicator development was the lack of a consistent time series within LCM. This might in the future be overcome by applying methods used in LCM2007 retrospectively to historical satellite data. The full potential of LCM2007 for assessment of habitat connectivity should be reviewed when final data products are available. The project steering group for pragmatic reasons decided to focus the pilot study on the 1 km CS data. Although this has meant that the conclusions of this assessment can only be valid at this scale given the previously discussed difficulties.

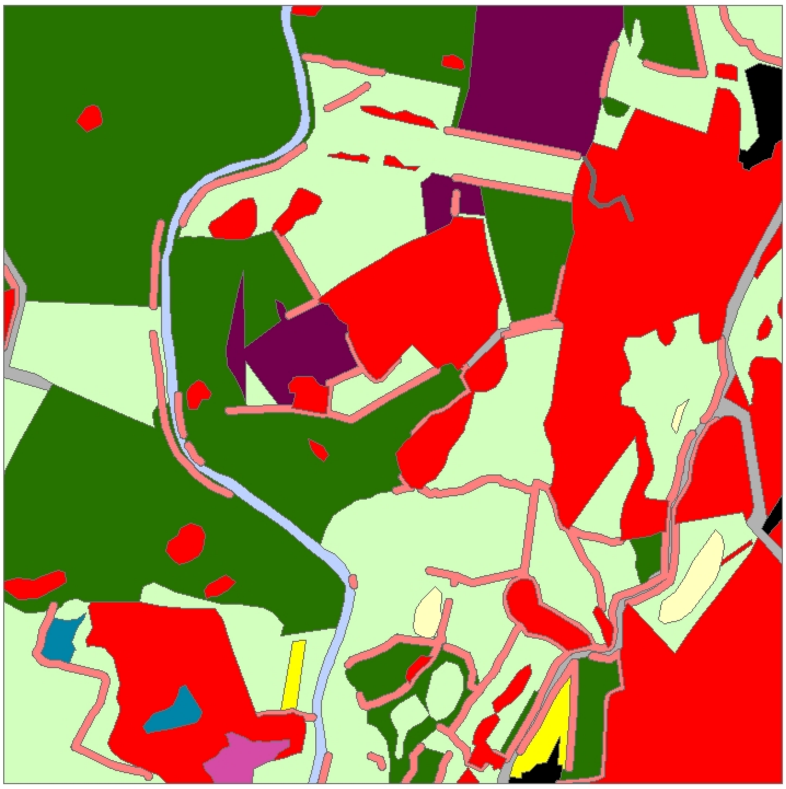
# 10 Appendix 2 – Images of Countryside Survey sample squares used in the habitat connectivity analysis for 1990 and 1998


Legend for CS images

Grid 4 1990

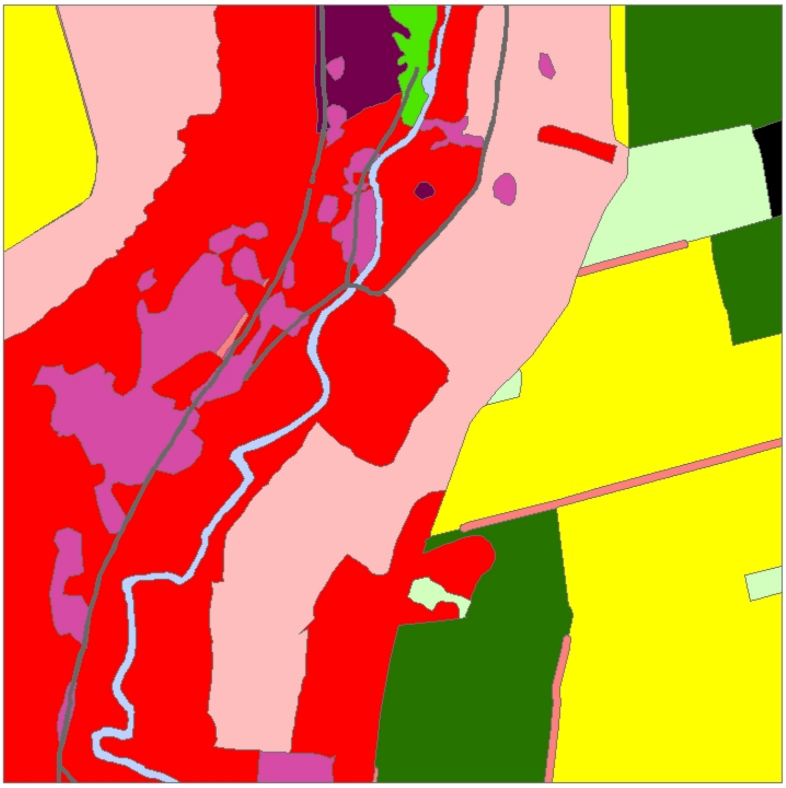
Grid 4 1998

Grid 5 1990



Grid 5 1998

Grid 6 1990

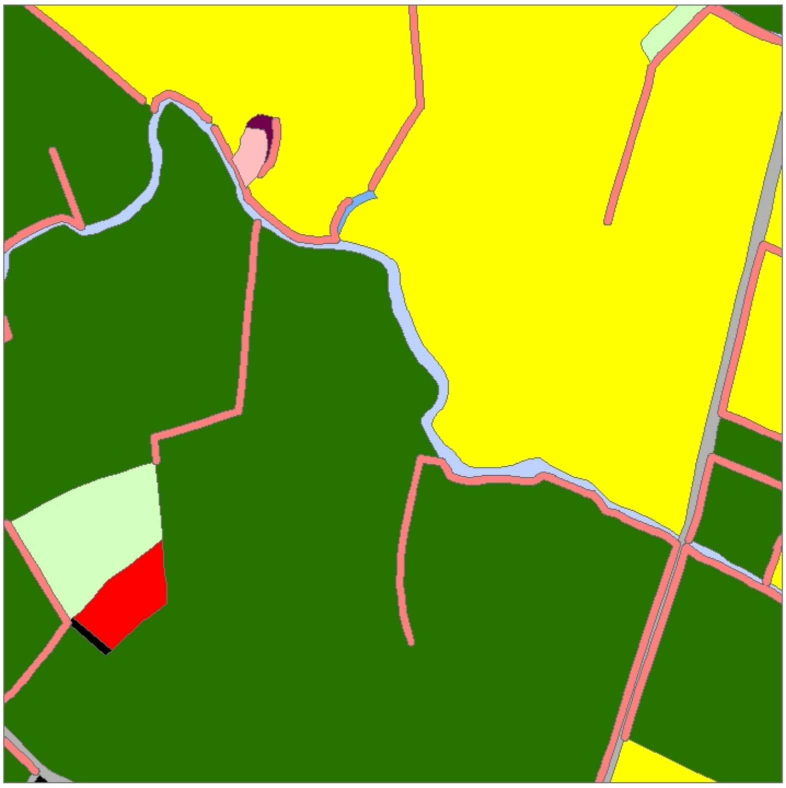


Grid 6 1998

Grid 7 1990

Grid 7 1998

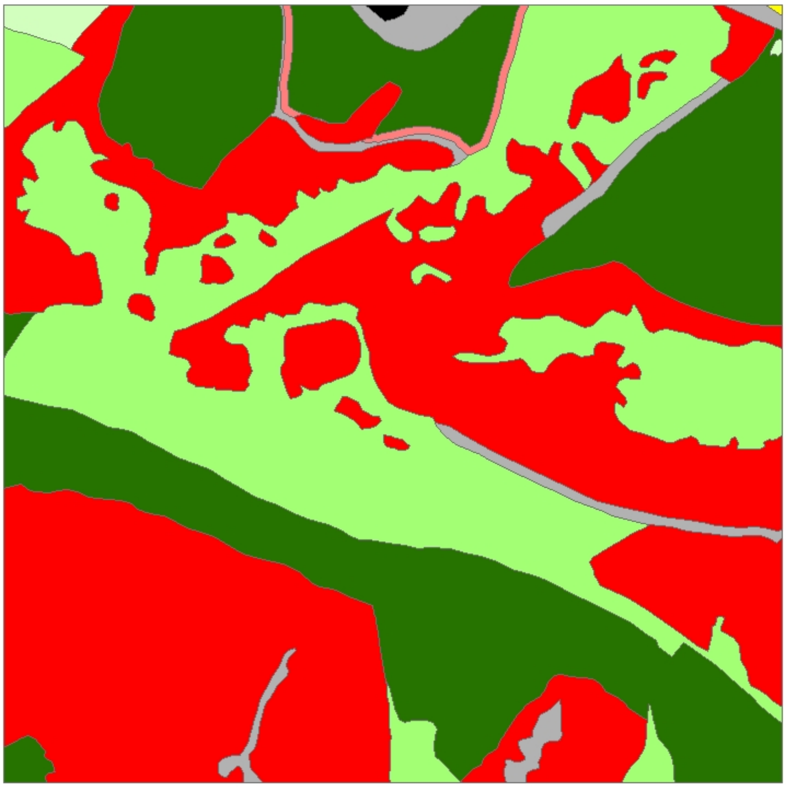
Grid 9 1990



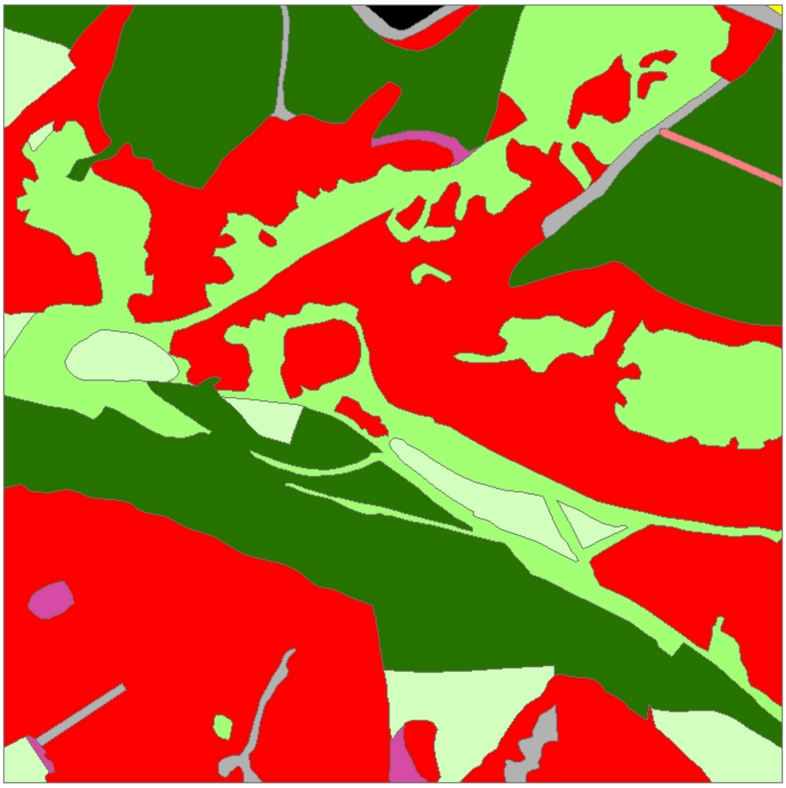
Grid 9 1998

Grid 12 1990

Grid 12 1998

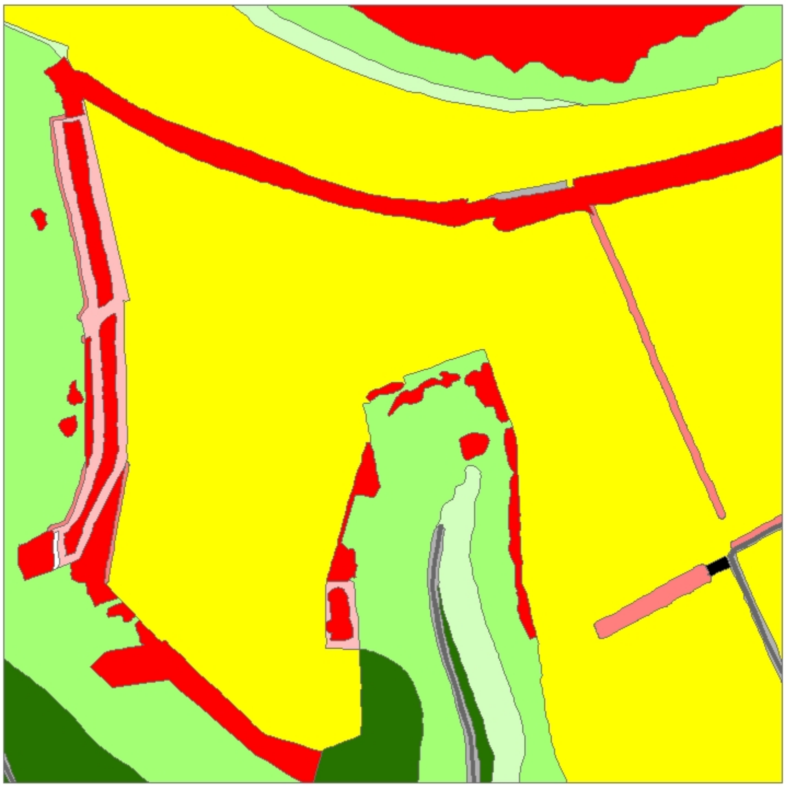


Grid 13 1990

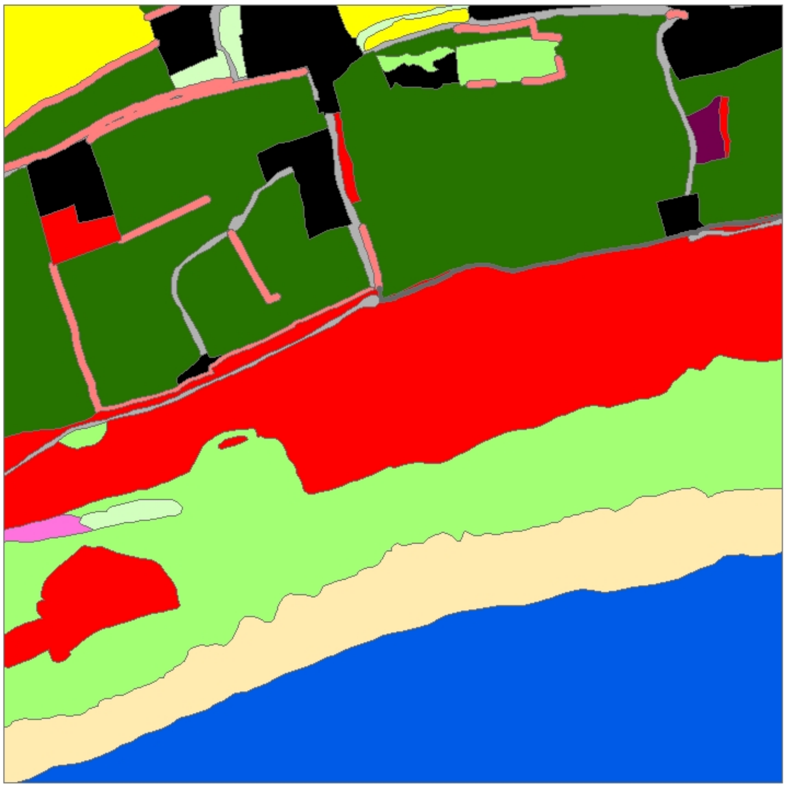


Grid 13 1998

Grid 14 1990

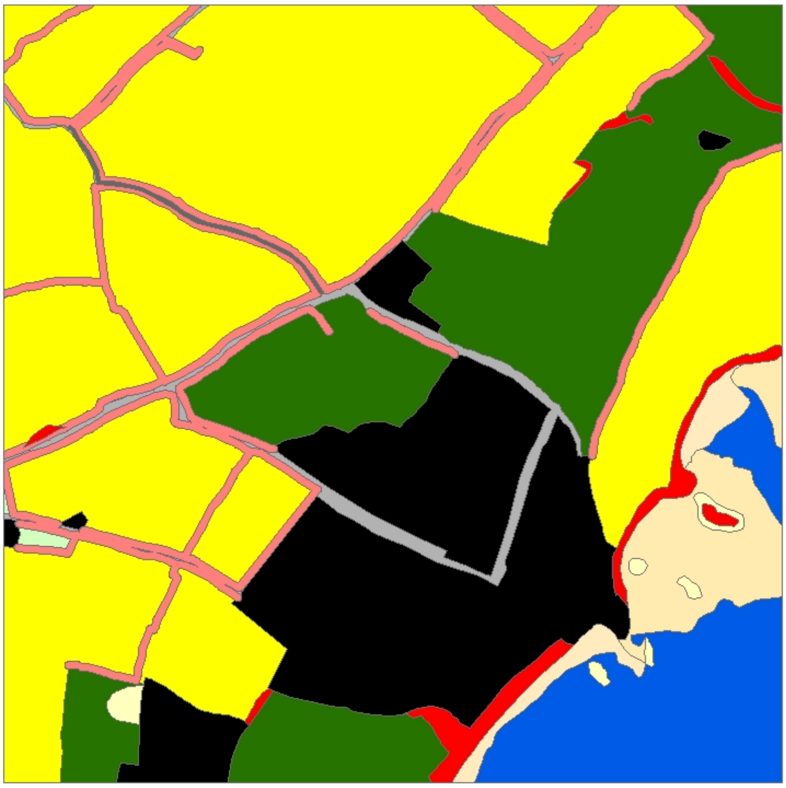


Grid 14 1998

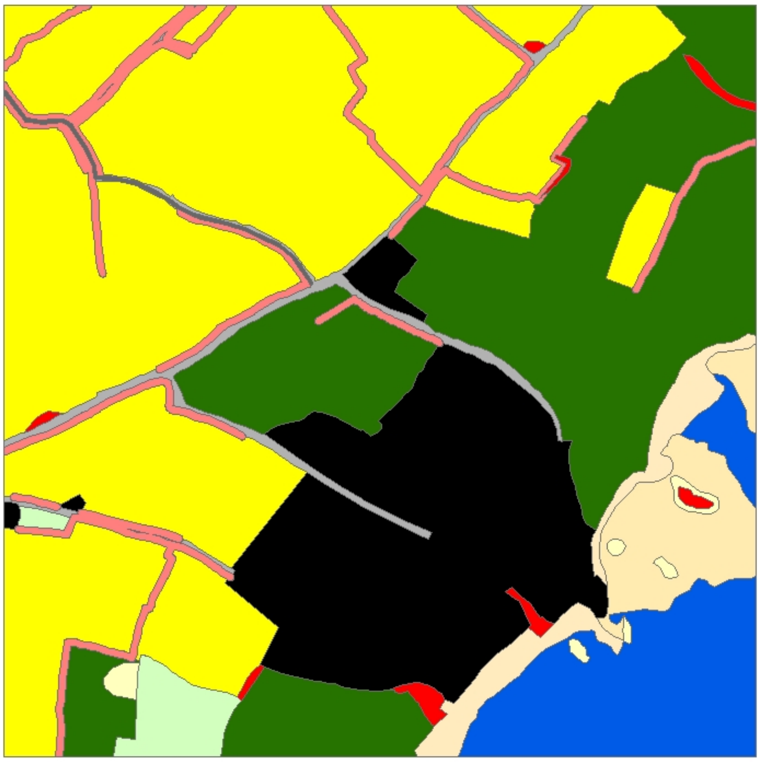


Grid 15 1990

Grid 15 1998



Grid 16 1990

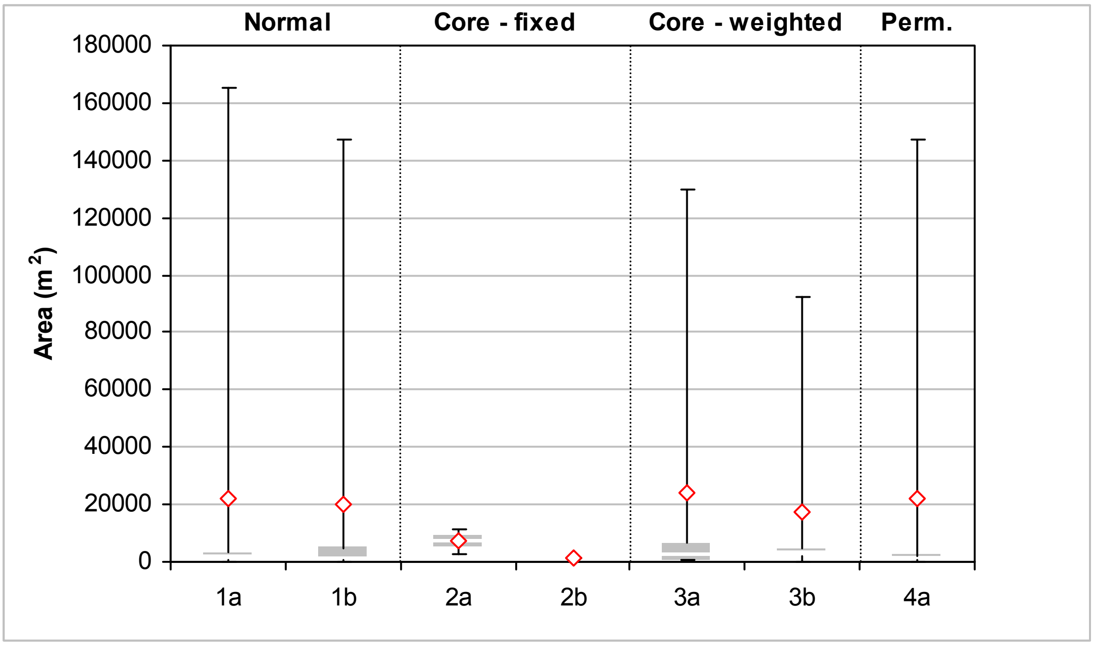


Grid 16 1998

# 11 Appendix 3 – supporting data and box whisker plots for analysis of single CS sample square

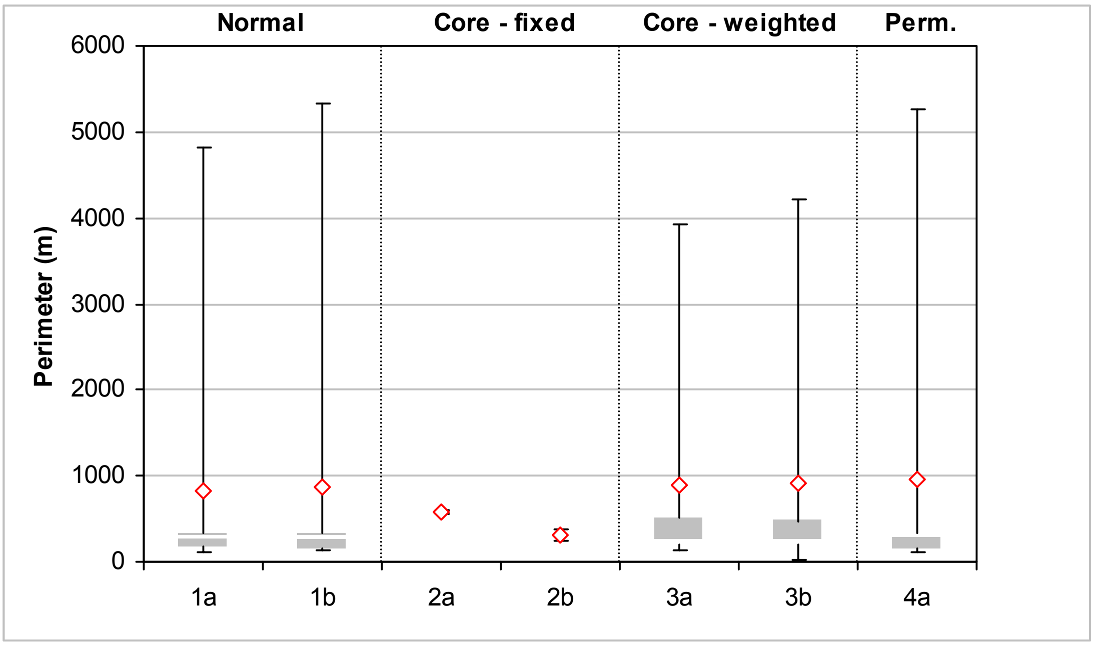
## *11.1 Metrics*

### *11.1.1 Area*



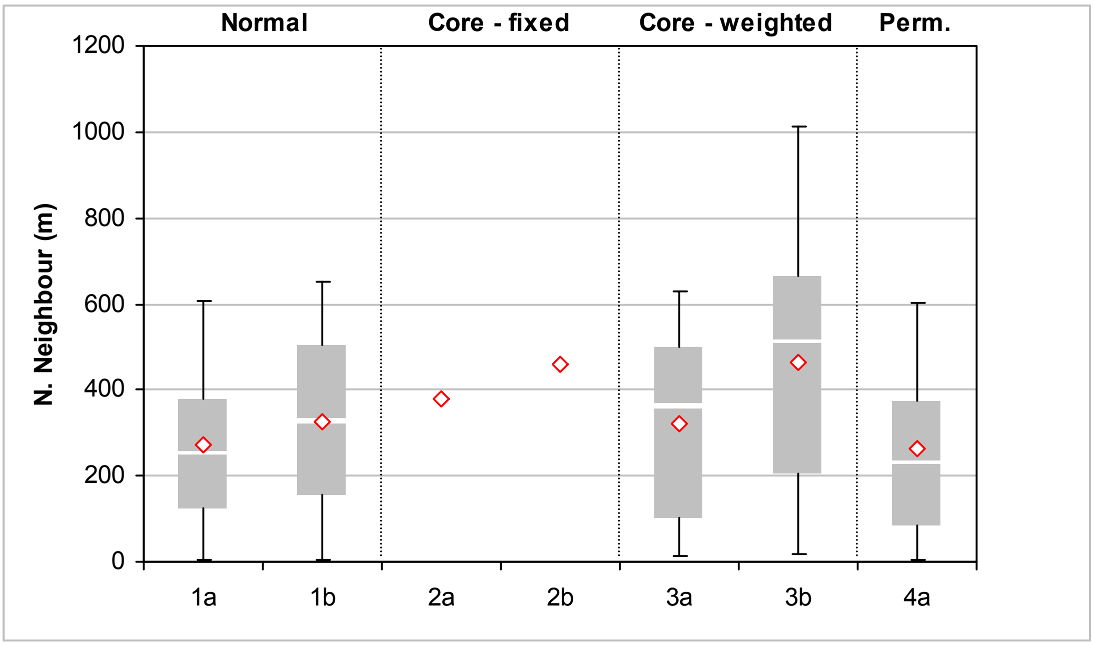

| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 8 | 8 | 2 | 2 | 6 | 6 | 7 |
| Min | 321 | 321 | 2822 | 1134 | 364 | 16 | 321 |
| $25^{th}$ | 471.3775 | 684.57 | 5037.148 | 1222.365 | 914.6225 | 2097.873 | 430.255 |
| Median | 1616 | 1146 | 7252 | 1311 | 2750 | 2550 | 1032 |
| $75^{th}$ | 3387.623 | 4966.005 | 9467.583 | 1399.835 | 6864.685 | 4601.175 | 2222.935 |
| Max | 165594 | 147452 | 11683 | 1489 | 130094 | 92530 | 147209 |
| Mean | 22148 | 20160 | 7252 | 1311 | 24083 | 17480 | 21981 |
| SD | 57976.54 | 51471.09 | 6265.581 | 250.9805 | 52009.39 | 36804.69 | 55229.31 |

### *11.1.2 Perimeter*




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 8 | 8 | 2 | 2 | 6 | 6 | 7 |
| Min | 113.0844 | 124.1265 | 565.5013 | 250.9547 | 132.0203 | 21.55435 | 113.084 |
| 25th | 186.2656 | 159.081 | 576.1425 | 285.6181 | 197.2713 | 207.5865 | 151.1585 |
| Median | 286.322 | 293.4569 | 586.7838 | 320.2815 | 233.584 | 222.3588 | 317.2654 |
| 75th | 333.4931 | 331.4156 | 597.425 | 354.9448 | 504.7259 | 468.223 | 342.6099 |
| Max | 4810.573 | 5325.444 | 608.0662 | 389.6082 | 3932.393 | 4210.258 | 5271.896 |
| Mean | 817.6516 | 876.9641 | 586.7838 | 320.2815 | 885.3091 | 904.8951 | 955.6832 |
| SD | 1615.651 | 1799.694 | 30.09795 | 98.04282 | 1501.402 | 1628.112 | 1905.897 |

### 11.1.3 *Nearest Neighbour - Euclidean*

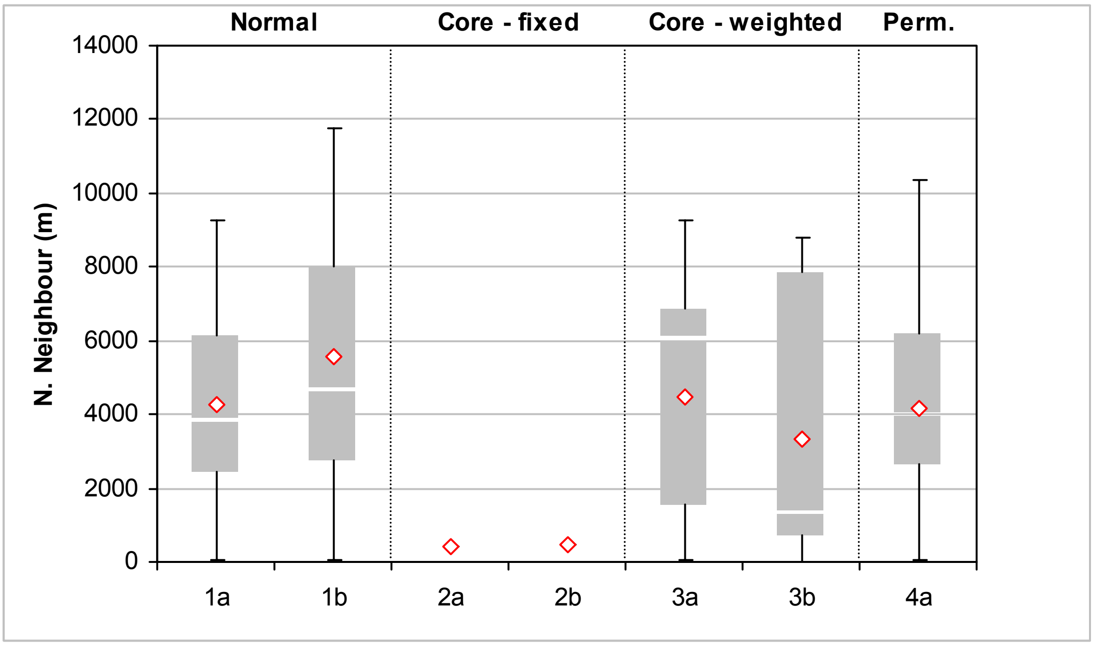



| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 28 | 28 | 1 | 1 | 15 | 15 | 21 |
| Min | 5 | 5 | 381 | 461 | 12 | 20 | 5 |
| 25th | 126.6225 | 157.0225 | 381.12 | 460.62 | 104.525 | 204.95 | 84.24 |
| Median | 253 | 328 | 381 | 461 | 363 | 512 | 233 |
| 75th | 380.945 | 502.9425 | 381.12 | 460.62 | 500.795 | 665.92 | 375.13 |
| Max | 606 | 651 | 381 | 461 | 628 | 1012 | 600 |
| Mean | 273 | 328 | 381 | 461 | 321 | 463 | 262 |
| SD | 191.1826 | 207.5396 | #DIV/0! | #DIV/0! | 211.3399 | 312.9885 | 189.7076 |

N. Neighbour permanent is between 1990 and 1998, but by definition must be worst connected than either.

### *11.1.4 Nearest Neighbour – least-cost*

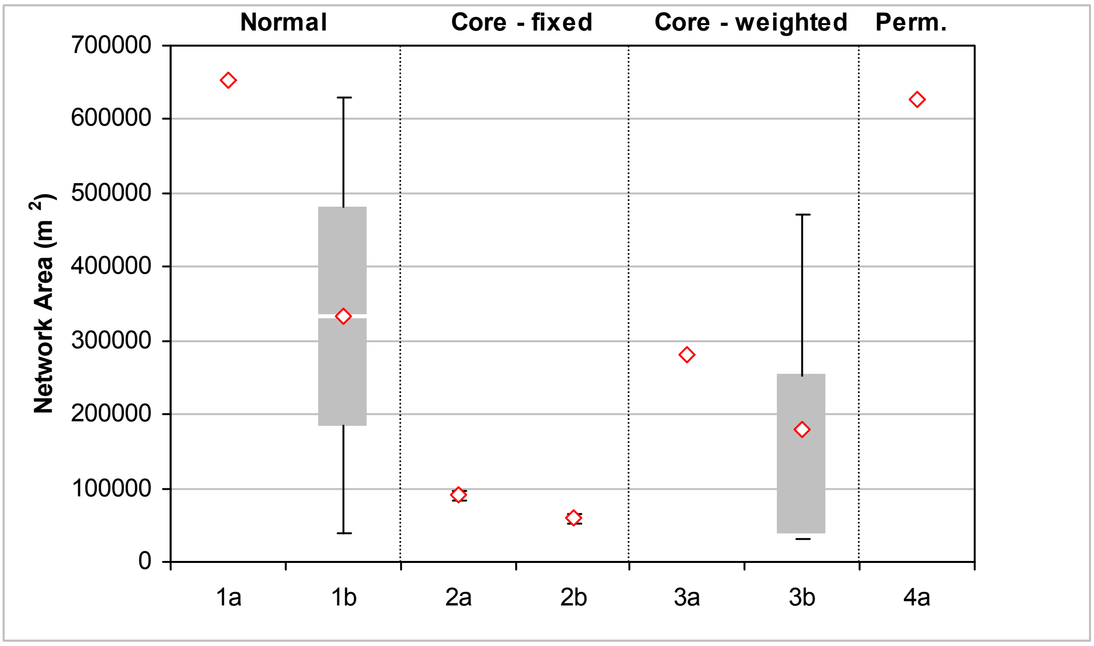
This out of order as it was calculated from the outputs from the Incident Function Modelling, but it makes more sense to include it here with the other metrics.




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 28 | 28 | 1 | 1 | 15 | 15 | 21 |
| Min | 34 | 34 | 409 | 481 | 52 | 24 | 34 |
| 25th | 2423 | 2756 | 409 | 481 | 1558 | 728 | 2641 |
| Median | 3853 | 4683 | 409 | 481 | 6057 | 1363 | 4016 |
| 75th | 6116 | 7991.5 | 409 | 481 | 6853 | 7837 | 6205 |
| Max | 9271 | 11751 | 409 | 481 | 9284 | 8798 | 10363 |
| Mean | 4289 | 5545 | 409 | 481 | 4453 | 3329 | 4185 |
| SD | 2684.938 | 3435.793 | #DIV/0! | #DIV/0! | 3328.899 | 3625.525 | 2707.899 |

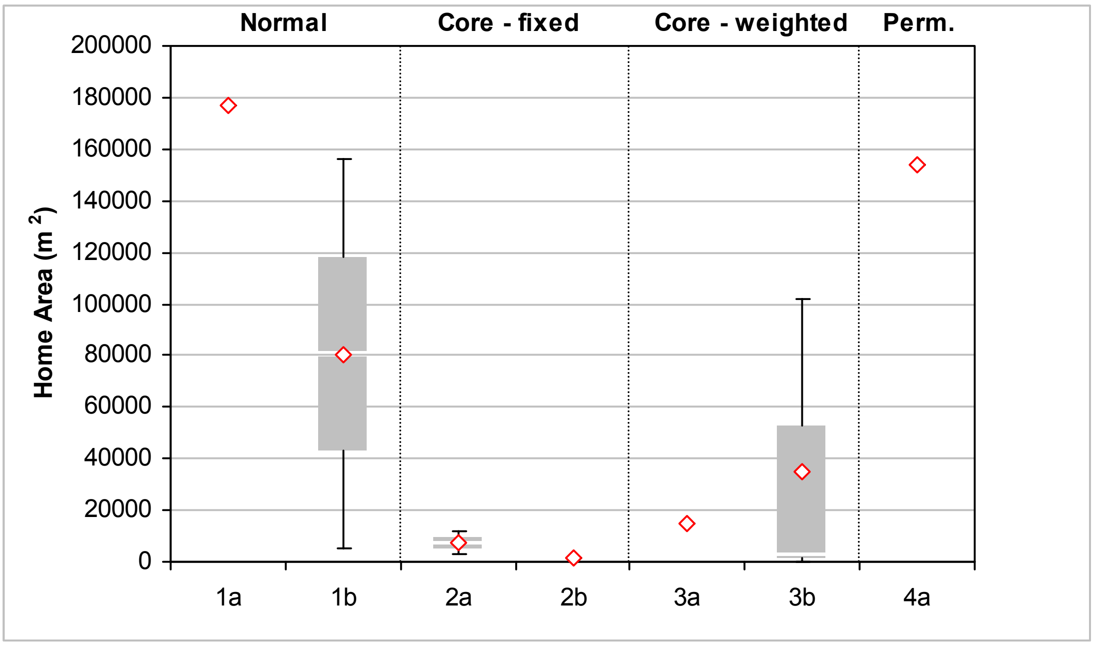
## 11.2 Buffer radius

### 11.2.1 Euclidean – network area



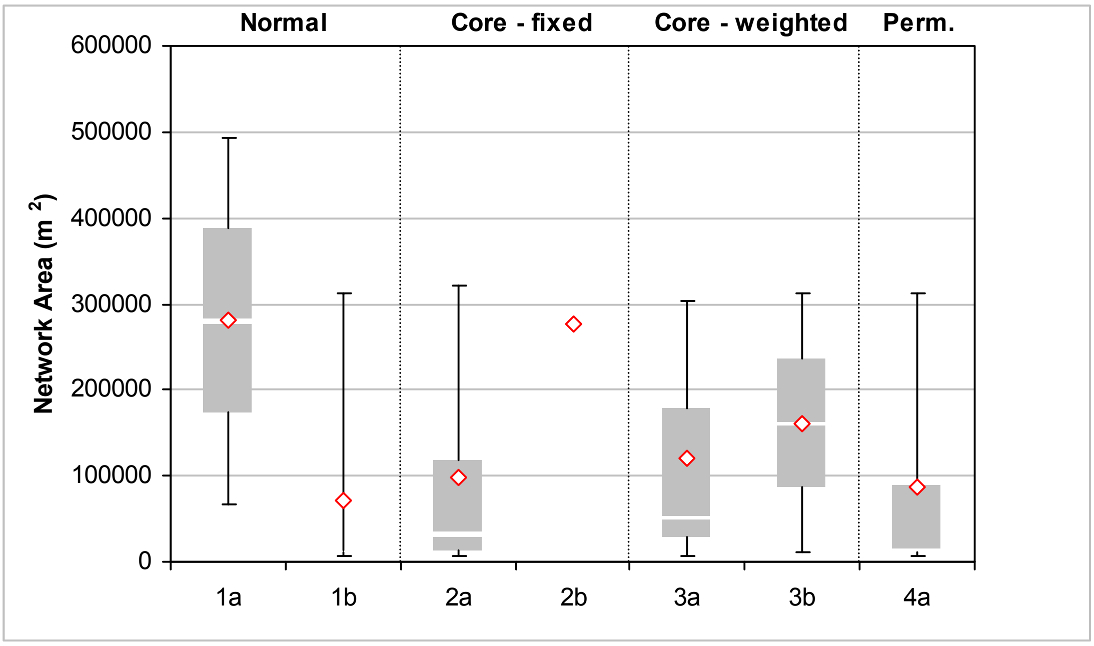

| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 1 | 2 | 2 | 2 | 1 | 3 | 1 |
| Min | 652599 | 37853 | 82794 | 52943 | 282044 | 30025 | 627746 |
| 25th | 652599 | 185850.5 | 86485 | 56082.5 | 282044 | 31809 | 627746 |
| Median | 652599 | 333848 | 90176 | 59222 | 282044 | 33593 | 627746 |
| 75th | 652599 | 481845.5 | 93867 | 62361.5 | 282044 | 252757 | 627746 |
| Max | 652599 | 629843 | 97558 | 65501 | 282044 | 471921 | 627746 |
| Mean | 652599 | 333848 | 90176 | 59222 | 282044 | 178513 | 627746 |
| SD | #DIV/0! | 418600.1 | 10439.72 | 8879.847 | #DIV/0! | 254105 | #DIV/0! |

### 11.2.2 *Euclidean – habitat area*



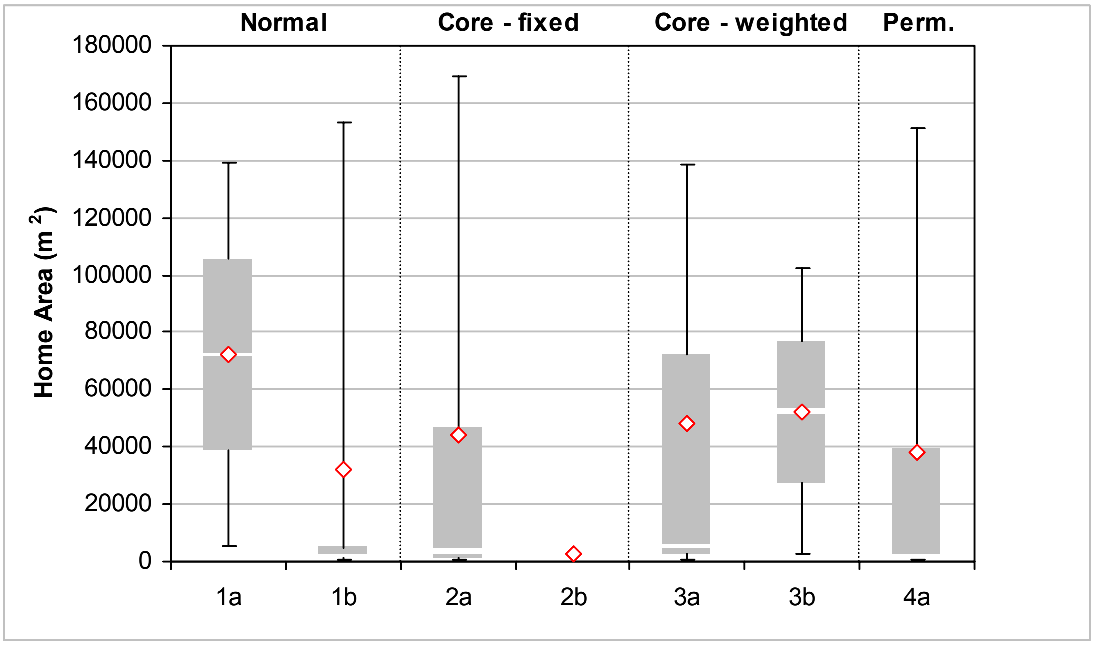

| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 1 | 2 | 2 | 2 | 1 | 3 | 1 |
| Min | 177193 | 4895 | 2842 | 1137 | 14524 | 14 | 153856 |
| 25th | 177193 | 42771 | 5052 | 1227.75 | 14524 | 1396.5 | 153856 |
| Median | 177193 | 80647 | 7262 | 1318.5 | 14524 | 2779 | 153856 |
| 75th | 177193 | 118523 | 9472 | 1409.25 | 14524 | 52435 | 153856 |
| Max | 177193 | 156399 | 11682 | 1500 | 14524 | 102091 | 153856 |
| Mean | 177193 | 80647 | 7262 | 1318.5 | 14524 | 34961.33 | 153856 |
| SD | #DIV/0! | 107129.5 | 6250.824 | 256.6798 | #DIV/0! | 58152.43 | #DIV/0! |

### 11.2.3 Least-cost – network area




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 2 | 5 | 4 | 1 | 3 | 2 | 4 |
| Min | 65996 | 5926 | 7547 | 276506 | 7495 | 10954 | 5940 |
| 25th | 172995.7 | 11025 | 12301.25 | 276506 | 29229 | 86063.25 | 10268.25 |
| Median | 279995.5 | 11719 | 32440.5 | 276506 | 50963 | 161172.5 | 13073.5 |
| 75th | 386995.2 | 14401 | 118778 | 276506 | 177432.5 | 236281.8 | 89014 |
| Max | 493995 | 312710 | 322127 | 276506 | 303902 | 311391 | 312748 |
| Mean | 279995.5 | 71156.2 | 98638.75 | 276506 | 120786.7 | 161172.5 | 86208.75 |
| SD | 302641 | 135067.5 | 150219.5 | #DIV/0! | 160064.9 | 212441 | 151067.7 |

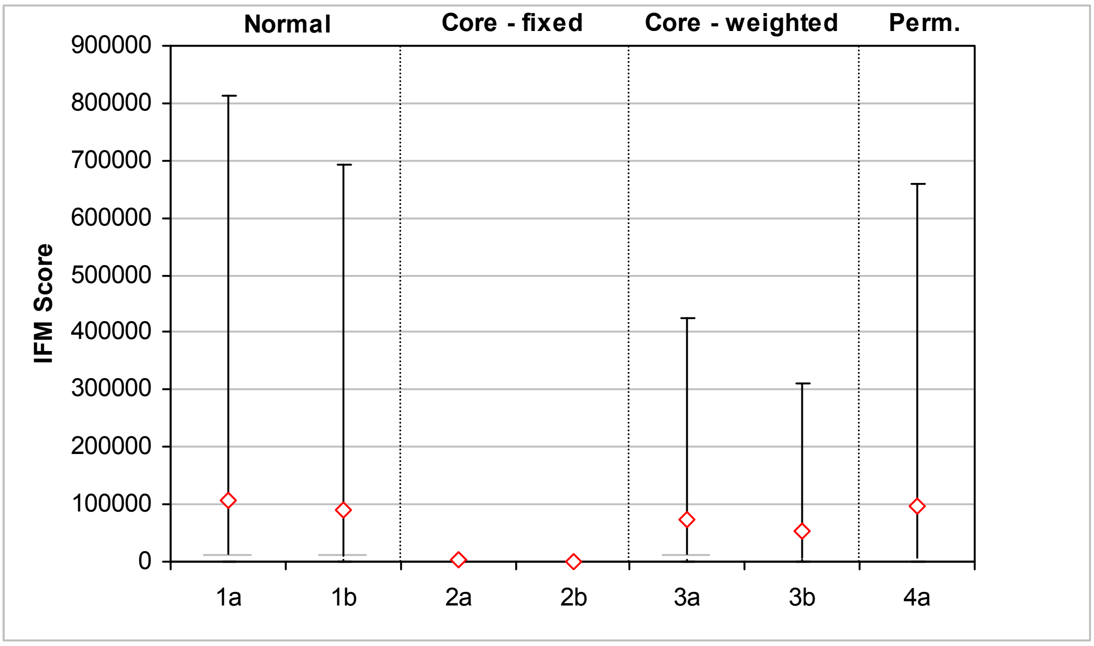
### 11.2.4 Least-cost – habitat area




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 2 | 5 | 4 | 1 | 3 | 2 | 4 |
| Min | 5501 | 672 | 668 | 2637 | 361 | 2779 | 669 |
| 25th | 38873.75 | 1033 | 1112.75 | 2637 | 2931 | 27610.5 | 940.5 |
| Median | 72246.5 | 1261 | 3612.5 | 2637 | 5501 | 52442 | 1147 |
| 75th | 105619.2 | 4895 | 46798 | 2637 | 72066 | 77273.5 | 38670.5 |
| Max | 138992 | 153433 | 169300 | 2637 | 138631 | 102105 | 150893 |
| Mean | 72246.5 | 32258.8 | 44298.25 | 2637 | 48164.33 | 52442 | 38464 |
| SD | 94392.39 | 67759.88 | 83368.17 | #DIV/0! | 78388.57 | 70234.09 | 74953.07 |

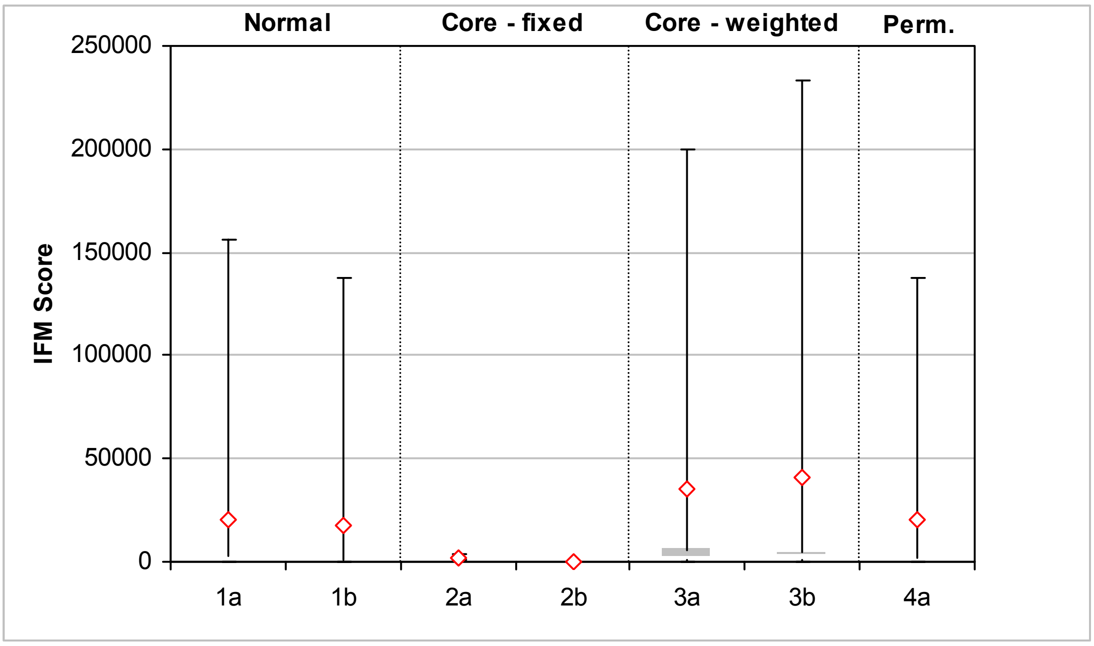
## 11.3 IFM connectivity

### 11.3.1 Euclidean distance




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 8 | 8 | 2 | 2 | 6 | 6 | 7 |
| Min | 1126.56 | 1102.69 | 900.94 | 285.23 | 796.89 | 27.47 | 1043.22 |
| 25th | 1318.7 | 1738.645 | 1608.183 | 307.555 | 2086.558 | 2729.215 | 1097.78 |
| Median | 5484.3 | 3366.995 | 2315.425 | 329.88 | 5,812.95 | 3829.025 | 2611.28 |
| 75th | 12258.25 | 10494.78 | 3022.668 | 352.205 | 11795.85 | 6216.105 | 7364.59 |
| Max | 813953 | 692877.3 | 3729.91 | 374.53 | ######## | 312594.7 | 658238.8 |
| Mean | 106694.5 | 91350.58 | 2315.425 | 329.88 | 75,181.22 | 54942.44 | 96974.01 |
| SD | 285814.6 | 243129.8 | 2000.384 | 63.14464 | 170961.6 | 126243 | 247519.8 |

### *11.3.2 Least-cost distance*




| | 1a | 1b | 2a | 2b | 3a | 3b | 4a |
|---|---|---|---|---|---|---|---|
| Count | 8 | 8 | 2 | 2 | 6 | 6 | 7 |
| Min | 4.04 | 0 | 828.75 | 268.33 | 1.01 | 0 | 0.01 |
| 25th | 161.3575 | 0.52 | 1479.323 | 289.335 | 593.545 | 563.8075 | 12.035 |
| Median | 667.48 | 120.82 | 2129.895 | 310.34 | 1552.03 | 2326.57 | 205.28 |
| 75th | 2425.405 | 1359.23 | 2780.468 | 331.345 | 6007.413 | 4487.013 | 1579.99 |
| Max | 156377.6 | 137333 | 3431.04 | 352.35 | 200155.6 | 233295.2 | 137107.2 |
| Mean | 20393.45 | 17820.99 | 2129.895 | 310.34 | 35171.21 | 40521.95 | 20070.93 |
| SD | 54956.96 | 48318.14 | 1840.097 | 59.41111 | 80869.68 | 94458.62 | 51619.12 |