A methodology for quantifying and measuring connectivity across Surrey and beyond

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Abstract

The following report documents the methodology used by the Surrey Wildlife Trust in the calculation of a connectivity metric for priority habitats across the county. A circuit theory based approach was taken to incorporate both structural and functional connectivity, and to consider the landscape in its entirety rather than focusing on corridors. Habitat maps were compiled from a variety of sources and landscape resistance was quantified using an expert opinion based analytical hierarchy process. Circuitscape was used to render the final connectivity maps, which were generated for five focal species, each representing a different priority habitat. These maps have potential to be used in a wide variety of applications by the Trust and its partners to target habitat improvement works and enact our part in the national Nature Recovery Network.

1. Introduction

A central theme of Surrey Wildlife Trust's (SWT) Strategic Plan (2018-2023) is to improve the connectivity of priority habitats across Surrey. In order to quantify our progress towards this goal, and set a measurable target for ourselves, SWT required a methodology to analyse existing connectivity between habitats within our prioritised Biodiversity Opportunity Areas (BOAs), in order to establish a monitoring base-line. This methodology needed to be calculable with available data, repeatable and refinable, and widely applicable across multiple habitat types. This report presents our proposed methodology along with our initial set of results and further potential applications.

1.1. Context

Connectivity can be defined as the ability of plants or animals to move through a landscape; put simply - greater connectivity means fewer barriers to dispersal or migration. The importance of a well-connected landscape is well established for both individual species' and long-term ecological resilience (Bennet, 2003). This resilience is vital in order for species to persist in the face of growing and unprecedented anthropogenic disturbance alongside natural perturbations. In alignment with Lawton et al. (2010), to achieve this wildlife sites need to be 'better, bigger, more and joined'. This approach has been the foundation of The Wildlife Trust's Living Landscapes initiative and continues as a fundamental driving force behind the SWT Strategic Plan. In the context of GIS, connectivity describes the degree to which the environment's spatial configuration facilitates biological flows, often in the context of organisms travelling within and between habitat patches (Tischendorf and Fahrig, 2000).

For SWT's current purposes, a modelling tool is required only with a focus of structural connectivity with elements of functional connectivity. Structural connectivity pertains to the underlying landscape geometry, such as corridor width and distance between patches, whereas functional connectivity seeks to consider the specific needs and behaviours of a target species or species group (Uezu et al. 2005). Many tools exist which can be used to quantify structural connectivity, but often limit the analysis output to corridor (least-cost path) detection. In order to ensure the most appropriate tool was chosen, a review was undertaken of potential options. Additionally, the concepts informing the tools were researched thoroughly, as connectivity analysis is generally based on one of three underlying approaches: least cost distance, circuit theory and graph theory.

2. Methodology

The following section briefly describes the methodology of the connectivity analysis. For additional details, please contact the authors. All analyses were run using ArcGIS 10.7.x (ESRI, 2019). In order to calculate connectivity, it is commonly understood that two datasets are required. Firstly, a comprehensive and detailed habitat map of the area of study to provide a base for the analysis. Secondly, a dataset representing the resistance that the landscape presents to the species in question in order to determine where there are barriers to movement. The sections below detail how these were created (2.1, 2.2) and then how they were utilised to generate the final output (2.3, 2.4).

2.1. Core Habitat Areas

As discussed above, accurate and detailed records of the spatial distribution of habitats are required to calculate connectivity for an area. This posed many challenges as there was no single dataset which contained detailed habitat maps for the entire county. A dataset had to be compiled, taking information from various sources, as listed in Appendix 1. Some sources were of finer resolution and hence provided more detailed information about the land cover present, however these were typically spatially limited to the extent of sites within the Surrey Wildlife Trust estate. Other less detailed sources, such as the Natural England Priority Habitat Inventory (PHI), covered other areas of the county, but provided very crude resolution of land cover.

Additionally, it was uncertain how much confidence could be placed in third party data sources. The Land Cover Map (LCM) dataset from the Centre for Ecology and Hydrology (CEH), for example, provides complete coverage at a national scale which is generated through an automated process, deriving land cover from infra-red reflectance of the surface. It is, therefore, likely that there has only been limited local quality checking of this data due to the size and scope of the dataset. It is most likely without local context, which can lead to serious errors. For example, a previously-developed hardstanding area in WG11 was identified by the LCM dataset as "bare rock/littoral" habitat due to its similar colouration in satellite imagery. To combat this where possible, LCM habitat cover maps were distributed to members of staff most familiar with reserves and land cover. They could then provide context and intimate local knowledge of any inaccuracies in the LCM data.

The final hurdle in amalgamating this array of habitat information was how the habitat classification should be expressed. As a result of the range of data sources, the land coverage was expressed in several different, overlapping and inconsistent habitat classification systems. A decision was taken to express all habitat data via the typology offered by the recent UK Habitat Classification (UK Habitat Classification Working Group, 2018) to avoid confusion of varying terminology. The architecture of the UK Habitat Classification sets out five hierarchical levels for habitat designation. At the county level, it was deemed that Level 3 (x20 broad habitat types) was an appropriate level of detail to generate a complete map of Surrey, with internal targets to improve the coverage of this mapping to Level 4 (x80 more specific habitat types) in future.

Despite these challenges, we have achieved a comprehensive map of habitats present across the BOAs, to Level 3 detail in the UK Habitat Classification. With this as a baseline, core areas could be calculated for use in the connectivity analysis, which was achieved using the toolkit Core Mapper (Shirk & McRae, 2013). In addition to habitat type, the calculation required consideration of important metrics for the selected 'focal species' (Lambeck, 1997), such as home ranges, minimum area of habitat required to support a population and dispersal distances (weighted by habitat type; see Table 1). This information was derived both from current literature and expert consensus. See Appendix 2 for additional details on settings used in Core Mapper and their ecological relevance.

2.2. Landscape Resistance

When attempting to incorporate ecological processes, quantifying connectivity becomes far more complex than simply comparing a straight-line distance between suitable habitat patches. To reflect how opposing land-uses will impact movement, a weighted-cost raster surface (also referred to as a resistance surface) is required in order to express the relative difficulty of movement between areas of habitat. Resistance surfaces are traditionally challenging to quantify in an objective way. In a meta-analysis of work in this field, Zeller et al. (2012) categorised studies into 5 core methodologies: expert opinion, detection, relocation, pathway and genetic. Given the lack of available empirical data as well as the practical constraints of gathering it on such large scales, expert opinion was the only option available to us from which to base a resistance model. It is arguably the least quantitatively rigorous approach to quantifying resistance, but does benefit from the ability to incorporate complex ecological processes and relationships into the cost and weighting process.

Table 1: Focal Species per Priority Habitat with additional information to be incorporated into modelling (Appendix 4).

Priority Habitat	Focal Species	Dispersal Distance	Home Range (individual)
Woodland & hedgerows	Dormouse	500m	5100m^2
Heath & acid grassland	Adder	100m	5200m^2
Calcareous grassland	Adonis Blue	250m	5000m^2
Fen, marsh & swamp	Water Vole	1500m	3600m^2
Open standing waters	Great Crested Newt	400m	2500m^2

Zeller's (2012) review makes it clear that expert opinion based approaches have significant limitations and uncertainty associated with them. This approach has generally been shown to provide suboptimal parameterization of environmental variables when compared to empirical approaches (Pearce et al. 2001; Seoane et al. 2005). To improve the robustness of using an expert opinion-based methodology, invited participant experts completed an analytical hierarchy process (AHP) for a suite of selected, relevant focal species. AHP uses pairwise comparisons between each possible pair of land cover types, quantified on a reciprocal 1/9 to 9/1 scale based on their relative permeability (Saaty, 1980). For example, if cover type A is only slightly more impermeable than type B, a value of 2/1 could be assigned to the AB pair, while a 1/7 value would indicate that A is much easier to cross than B. AHP calculates a derived relative cost for each land cover type based on the provided values, as well as a quantitative estimate of consistency across the participant's cumulative responses (Magle et al., 2008).

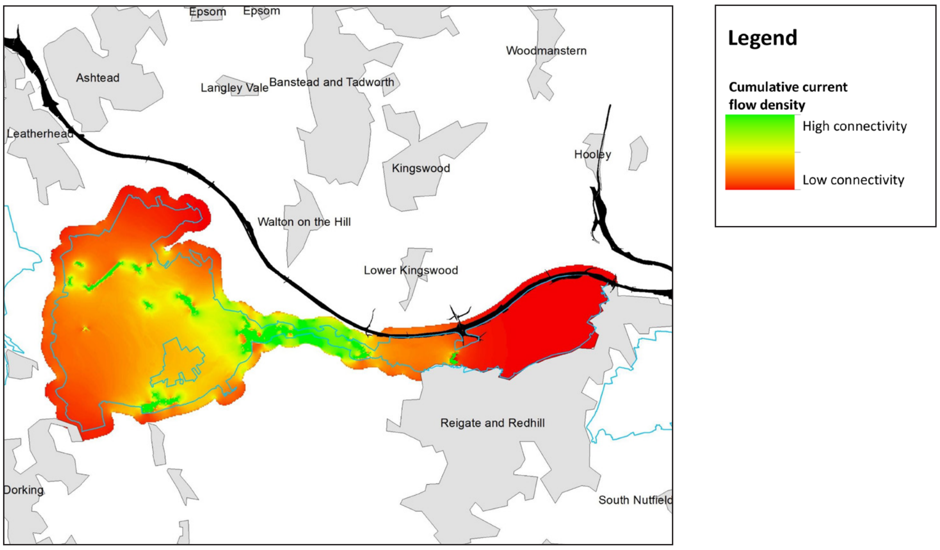
In accordance with the above, the questionnaire was designed as an AHP process which required experts to score all pairs of Level 3 UK Habitat Classification habitats on a reciprocal scale, in terms of which habitat the focal species in question was more likely to use. Expert participants were asked to consider the willingness of organisms to move through a particular environment but also the physiological cost and reduction in survival for the organism from moving across that environment. Often, this came down to the participants' judgement based on their individual experience of observing the natural behaviour of the species in the field. Finally, participants were also asked to assign a value between 0-1 to each Level 3 habitat for the focal species in question (see Appendix 3 for further details). To align the output of these questionnaires in accordance with the SWT Strategic Plan KPI's, five focal species were chosen to represent the characteristics of the key priority habitats within the prioritised BOAs (Table 1). The choices were intended to represent the general specificity for a guild of resident species associated with the priority habitat, including consideration of these species' averaged mobility. The focal representative must also be limited currently in its range (at least in the local Surrey context), and would clearly benefit from increased habitat connectivity.

The information gathered from the AHP was used to input settings into the calculation of the resistance and habitat value layers, generated using Resistance and Habitat Calculator (McRae et al., 2013a). Other relevant information was also weighted and used in the calculation of these layers such as the presence of roads and railways.

2.3 Connectivity Calculation

The Circuitscape toolkit was used to process the above data into an output map representing landscape connectivity (McRae et al., 2013b). ASCII files of the resistance layer and core areas layer (see above for details) were input into Circuitscape and run using pairwise comparison, connecting to four neighbours rather than eight in order to reduce processing time on such large areas. The outputs generated were cumulative current maps, which represent the cumulative connectivity between all pairwise comparisons across the area. An example of the maps generated is below (Figure 1).

Figure 1: Connectivity output map for Dormice (Mixed Deciduous Woodland & Hedgerows) in ND02.



3. Results

Arguably, the most valuable and useful outputs from this process are the connectivity maps themselves, but in order to set targets and track improvements a single numerical value is also required. To obtain a single usable value the output connectivity maps has to be grossly simplified and an average value found for each focal species, for each BOA. To do this a simple model was constructed in ArcGIS to provide an output spreadsheet of values which could then be averaged. The decision was taken to exclude all values from the average that were less than 1, as these areas likely represented "impossible" habitats such as roads, urban areas, etc.. Essentially, the single value was the arithmetic mean of all values over the threshold of 1. These values will serve as the base-line figures for Strategic Plan KPI Bio.05: 'Habitat connectivity significantly enhanced (at least 5% over current) in prioritised Biodiversity Opportunity Areas by FYE 2022-23' (Waite, 2019; see Table 2).

Table 2: Single values per focal species per BOA, baseline and target figures. These outputs of the model provide the baseline levels along with targets for 2023 for enhanced landscape connectivity for wildlife.

BASELINE	WG11	ND02	ND03	TBH1 & 2	TBH3 & 4	TBH6
Adder	5.062978564	2.76225786	3.053039637	14.25839	29.84963	6.361333
Adonis Blue	N/A	4.12272844	4.178999012	N/A	N/A	N/A
Dormouse	1.544325268	13.5116455	28.43159544	N/A	N/A	N/A
GCN	7.796400656	N/A	N/A	N/A	N/A	N/A
Water Vole	TBC*	N/A	N/A	4.068178	3.545387	3.906334

TARGET	WG11	ND02	ND03	TBH1 & 2	TBH3 & 4	TBH6
Adder	5.316127	2.900371	3.205692	14.97131	31.34211	6.6794
Adonis Blue	N/A	4.328865	4.387949	N/A	N/A	N/A
Dormouse	1.621542	14.18723	29.85318	N/A	N/A	N/A
GCN	8.186220689	N/A	N/A	N/A	N/A	N/A
Water Vole	TBC*	N/A	N/A	4.271587	3.722656	4.101651

N/A = where there is no/negligible habitat within the BOA, and no target is therefore applicable.
* Due to an unforeseen issue with water vole model in WG11 values are TBC

3.1. Application to SWT Strategic Plan Targets

Under KPI Bio.03 of the SWT Strategic Plan (Waite, 2019), the Trust has set itself targets for priority habitat creation and/or restoration within the prioritised BOAs. The priority habitats highlighted in this KPI also require a value for their base-line connectivity as established to primarily inform KPI Bio.05. Table 3 shows how the modelling will inform monitoring of the KPI Bio.03 priority habitat targets in relation to KPI Bio.05

Table 3: Relevance to SWT target terminology

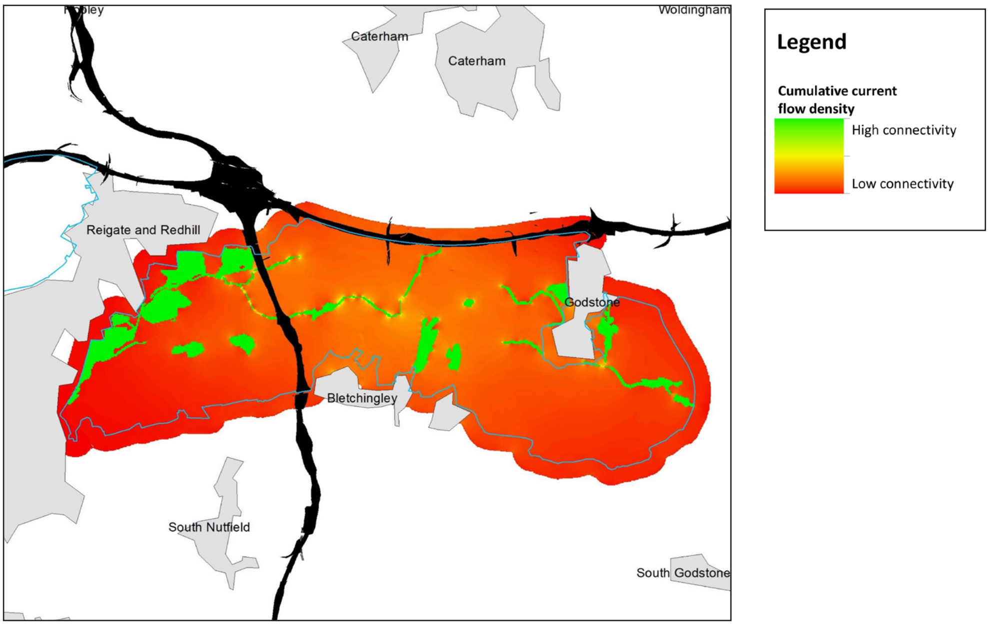
Priority Habitat	Prioritised BOAs	Connectivity Model
Acid grassland & heathland	TBH1, 2, 3, 4, 6; ND02, 03; WG11	Adder
Wet woodland	TBH1, 2, 3, 4, 6; WG11	N/A; see below*
Fen	TBH1, 2, 3, 4, 6;	Water Vole
Calcareous grassland	ND02, 03	Adonis Blue
Beech & yew woodland	ND02, 03	Dormouse
Mixed deciduous woodland	ND02, 03; WG11	
Hedgerows	ND02, 03; WG11	
Standing open water	WG11	Great crested newt
Floodplain grazing marsh	WG11	Water Vole
Reedbeds	WG11	

*Wet Woodland has not currently been assigned a connectivity model, due to its ecological incompatibility with other, drier woodland and hedgerow habitats covered in UK Habitat Classification W1 (using the Dormouse model). There is a Level 4 category for wet woodland, but this would require further field data to extend the model to the habitat detail of Level 4.

3.2 Application to Potential Projects

The following are two examples of how this work may be used to inform the Trust's future projects. Crucially, for any specific project applications the model is capable of incorporating additional relevant parameters. This process would provide a more accurate representation of real ecological processes and makes the model both flexible and relevant to a great variety of applications. In particular this is important for looking at individual species and certain parameters they may be affected by, for example, a model looking at connectivity for bats could incorporate information about artificial lighting and noise pollution.
The water vole is now functionally extinct in Surrey. The Trust aims to initiate its recovery with a reintroduction project in the Holmesdale BOA (WG11). This is still very much in its infancy as a project, but our connectivity and habitat-suitability mapping work will be used to inform potential locations for the most effective reintroduction sites (Figure 2). These must be places which are well-connected to the surrounding landscape, so that the reintroduced population is able to efficiently disperse and colonise

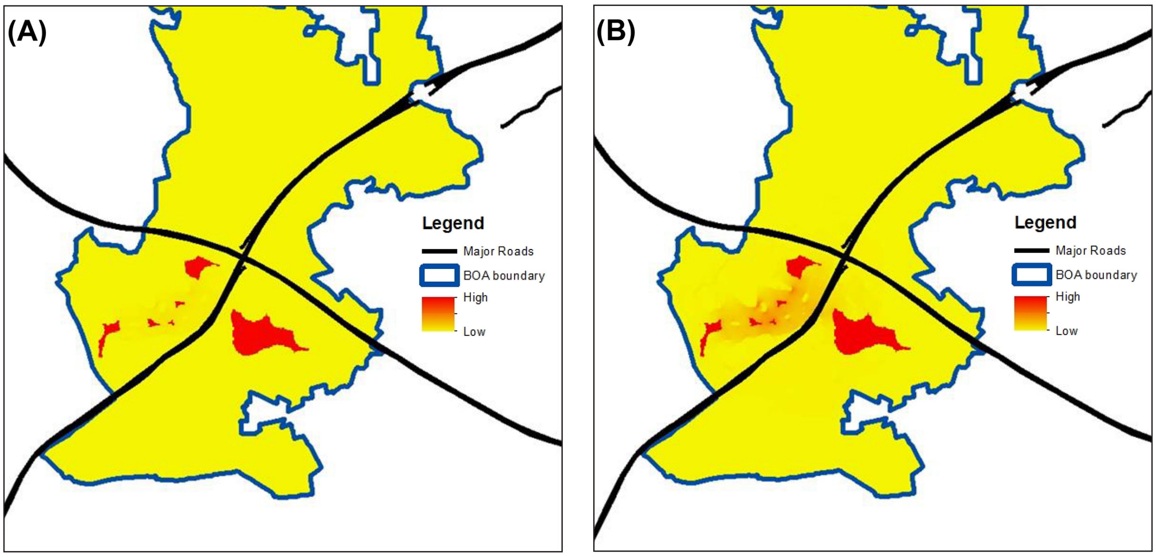
Figure 2: Open water connectivity in WG can be used to locate sites for potential water vole reintroduction



areas beyond the immediate project boundaries. Habitat connectivity is particularly important for water voles because they live colonially within a metapopulation structure, supported by migration between connected sub-populations.

Another potential project for which Surrey Wildlife Trust could use connectivity maps to evidence the ecological benefits is the construction of a wildlife passage/'green bridge' across the A3(T) at Wisley, near M25 Junction 10. This junction was built in the 1980's on a heathland SSSI (now also SPA), dividing it into quadrants. This presents an obvious opportunity to reconnect a key priority habitat that is clearly indicated in Figure 3A. A modelled inclusion of a green bridge (Figure 3B) shows the impact that this could have for target species dispersal (specialist terrestrial invertebrates and reptiles) within the site.

Figure 3: Heathland connectivity in TH6, as present (A), and with the proposed habitat creation and resto



3.3 Concluding Remarks

Many conservation bodies are currently interested in connectivity modelling and its methodology. As the aspirations of organisations vary, so does the complexity and ambition of the models. For Surrey Wildlife Trust, an ambitious model such has much potential for a variety of applications. It will enable us to work towards proactive, evidence based decision making rather than being led by resource opportunities in a more reactive way. Alongside the applications described above, we envision that this model will play a key role in evidencing biodiversity net-gain, and therefore securing project funding to underwrite a long-term vision for Surrey's wildlife.

This methodology is a work in progress, and we recognise that there remain limitations which we hope to address in the future. Fundamentally, any model chosen is a tool, and the quality of inputs and effective use of the tool are the most important factors in determining the output. Therefore, work will continue on internal and external (partner) verification of our inputs, and incorporation of additional relevant parameters and features into future iterations of the model.

Ultimately, this work will more accurately inform the existing connectivity of habitat patches as well as enable us to better measure the effects of habitat enhancement and creation projects across the county; progressing our role in the national Nature Recovery Network. We will use the model to influence our landscape scale conservation advocacy with future partners by evidencing the barriers to wildlife. We also hope this work will be useful to other Trusts and conservation bodies engaged in similar endeavours, both in Surrey and elsewhere.

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6. Appendices

Appendix 1 – Priority Habitat Mapping report

Please refer to "Priority Habitat Creation and Restoration in BOAs" report accessible by contacting Research & Monitoring Dept. This report contains details of the sources used for the compilation of the habitat maps used in this modelling, as well as calculation of priority habitat area in relation to KPI Bio.03 targets.

Appendix 2 – Core mapper settings

Setting	Choice & Justification
Moving window radius	The smallest possible value was used for this parameter, as it directly dictates resolution of output. In all cases, the best possible resolution was preferable. The value was calculated from the cell size of input raster + 1. This minimum was used in all cases.
Minimum average habitat value	The value had to fall between 0-1, and a mid-point of 0.5 was chosen to ensure consistency throughout the modelling. This would exclude any areas that fell below 0.5 average value within the moving window radius from being considered as core areas. Thereby including the most valuable areas, without immediately excluding other areas of potential value.
Minimum habitat value per pixel	The value had to fall between 0-1, and a low-mid point of 0.3 was chosen to ensure consistency throughout the modelling. This would exclude any areas that scored below 0.3 from being in a core, effectively removing the lowest value habitats.
Optional CWD (cost weighted distance) core expansion	This setting was selected as it is important to incorporate potential dispersal from core areas, but whilst considering the differentiation in that dispersal across difference land cover types. This parameter was set as the focal species dispersal distance, taken from literature (see Table 1 & Appendix 4). This would expand core areas by the maximum dispersal distance of the species, but after that distance was weighted by the resistance values of each habitat type (e.g. a resistance of 2 uses up the allotted distance twice as fast as a resistance of 1).
Trim back expanded cores	This setting was selected to remove any areas of poor habitat quality gained during the previous step. Setting this to 'yes' deletes any areas of < 0.5 (minimum average habitat value) value habitat from the newly expanded core. This, for example, would mean that if an unsuitable habitat (i.e. a road) was included through the expansion, it would then be removed.
Minimum core area size	The home ranges for an individual of the focal species were used to decide upon the values for this parameter, rather than range area of an entire metapopulation. The information was taken from literature (see Table 1 & Appendix 4). This eliminated any cores which were too small to support an individual of the species in question.
Exclude nonhabitat from core size calculations	This was set as "No" as we were working with fairly small areas of habitat so did not want to eliminate any cores which had lower amounts of suitable habitats. This provides scope to use the cores as focal points for applications of the model.
Append core stats	No – because this adds extra processing time, particularly with a large number of cores.
Delete temporary files	Yes – to save disk space.

Appendix 3 – AHP Questionnaire Results

The following table documents the processing of questionnaire results and reports on the consistency checking done for each response. Table is correct as of May 2019. Please contact Shadi Fekri for queries on this.

Species	Attendee	Consistency Rate		Result
		Original	Revised	
Adder	Mike Waite	0.096		Consistent
	Steve Langham	Not following Standard value (e.g. 3/4 inacceptable)	Waiting for the reply	TBC
Adonis Blue	Fiona Haynes	0.13		Consistent
	Simon Saville	0.27	0.17	Consistent
	Mike Waite	0.016		Consistent
Dormouse	Mike Waite	0.04		Consistent
	Elizabeth Burtenshaw	Empty cells	0.13	Consistent
	Ian White	Negative scores and terms n/a not acceptable	0.17	Consistent

Great Crested Newt	Mike Waite	0.02		Consistent
	James Caldwell	0.52	0.18	Consistent
	Gareth Matthes	0.12		Consistent
Water Vole	Mike Waite	0.27	0.044	Consistent

Appendix 4 – Dispersal distances and home range references

The authors are open to discussion and input from any species specialists on the below values, if they believe there are more accurate alternatives that should be used.

		Value	References
Adder	Minimum Core	5200m^2	1. There is an "absence of any published values for home ranges of adders in the UK", but a 2018 paper by Nash and Griffiths provided some data from radio-tagged individuals, which suggested that non-translocated male snakes (which typically travel further) had a 0.52Ha home range.
	Dispersal Distance	100m	1. The distance of 100m was suggested by Steve Langham, Chairman of SARG. 2. This is supported by a statement in ARG UK's 2018 habitat management advice that "although some adders can move over distances of up to 2km through the year, other animals may move no more than a few tens of metres, and can be very site faithful".
Adonis Blue	Minimum Core	5000m^2	1. Various sources (including publications from Butterfly Conservation) state that "colonies can coexist on sites with a wide range of butterfly species that require taller or variable swards as long as there are patches (0.5-1 ha) of suitably short vegetation" based on research by Thomas (1983). The lower 0.5Ha figure was used as the minimum core size.
	Dispersal Distance	250m	1. The most commonly cited work for this species is by Thomas et al., who undertook detailed autecological research on the Adonis Blue between 1976-1980 (published as multiple papers in 1983, 1984, 1990 and 1991). "The work demonstrated that the Adonis Blue was a colonial, highly sedentary species with no adult movement detected between sites separated by small barriers, such as scrub, also movements within sites were rarely above 250 metres for both sexes".
Dormouse	Minimum Core	5100m^2	1. Goodwin et al. found that Mean dormouse home range size was 0.51 Ha (±0.07 SE, n = 16) and did not vary between sexes or among sites in their 2018 paper "Habitat preferences of hazel dormice Muscardinus avellanarius and the effects of tree-felling on their movement".
	Dispersal Distance	500m	1. PTES cite the use of a juvenile dispersal rate of 500m in the mapping of dormouse populations in Ireland in their summer 2015 publication of "The Dormouse Monitor". 2. Buchner found that the maximum dispersal distance in treeless areas was 500m in his 2008 paper "Dispersal of common dormice Muscardinus avellanarius in a habitat mosaic".
Great Crested Newt	Minimum Core	2500m^2	1. This was another figure which there were not clear answers for. Discussion between specialists on hereptofauna.co.uk suggested that a "250 m radius around a pond is accepted as the extent of a 'typical' home range" by consultants. However, they also reported that "by far the most captures were recorded within 50m of ponds and few animals were captured at distances greater than 100m" from Cresswell et al. (2004) report ENRR576. Therefore, an assumed 50m x 50m area was used as the minimum core.
	Dispersal Distance	400m	1. Joly et al. report that "400 m corresponds to the average migration distance of newts (Dolmen 1980; Griffiths 1984; Cooke 1986; R. Jehle, unpublished results)" in their 2001 paper "Habitat Matrix Effects on Pond Occupancy in Newts". 2. Additionally, DEFRA state in report WC1108 that dispersal distance is "around 400 m while rare long range dispersal has been recorded up to 1000 m".
Water Vole	Minimum Core	3600m^2	1. PTES cite that "males have home ranges of 60-300m that overlap several females" which is taken from a 2006 study by Strachan & Moorhouse. It is understood that this is "strongly influenced by overall population density, season and habitat quality", which is explored in a doctoral thesis by Neyland (2011). For simplicity, the minimum of 60m was used to assume a 60m x 60m area.
	Dispersal Distance	1500m	1. National Water Vole Database and Mapping Project (2006-2015) reported that in lowland areas dispersal distance was on average 1.5km (+/- 0.25 SE) for males, and slightly lower (1.04km) for females. 2. The same report states that in other projects, "2km, as measured from water vole records, has been used to capture dispersal distance"