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1 **Breaking barriers for Hedgehogs in Sheffield, UK:**
2 **The latest findings from habitat connectivity analysis**

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7
8 **Abstract**

9 The Western European hedgehog, a flagship species within the UK's Biodiversity Action Plan,
10 has experienced long-term population decline in Britain. Although it is widespread across urban
11 and rural landscapes, its distribution and movement pathways remain poorly understood due to
12 inconsistent evidence, limiting effective conservation and spatial planning. In particular,
13 existing studies often identify broad drivers of fragmentation but do not pinpoint where
14 connectivity gaps occur and where interventions could be most effective. To support emerging
15 needs in biodiversity-inclusive spatial planning with actionable connectivity evidence, we
16 integrate field observations with high-resolution land-use data and circuit theory modelling to
17 assess hedgehog habitat connectivity across Sheffield, UK. We delineate core habitat patches,
18 parameterise a land-use-based resistance surface, and use Circuitscape to map current flow and
19 identify movement corridors, pinch points, and barrier hotspots that constrain movement across
20 the urban landscape. Results show pronounced spatial heterogeneity in connectivity, with high-
21 current corridors concentrated in key green corridors and recurring pinch points associated with
22 major transport infrastructure, particularly around Attercliffe and several road and rail crossings
23 in Sheffield. These locations represent priority intervention zones where relatively local
24 measures could yield disproportionate connectivity gains. We translate the modelling outputs
25 into a planning-oriented intervention logic that links barrier types to targeted actions (e.g.,
26 crossing enhancements, verge management, and habitat patch reinforcement), providing a
27 transferable workflow for diagnosing connectivity gaps and prioritising urban greening
28 investments. Our findings demonstrate how integrated field evidence and circuit-based
29 modelling can inform implementable strategies to safeguard hedgehog movement pathways in
30 urban landscapes.

31 **Keywords:** Green infrastructure planning, Circuitscape, Hedgehogs, Greenspace,
32 Biodiversity conservation

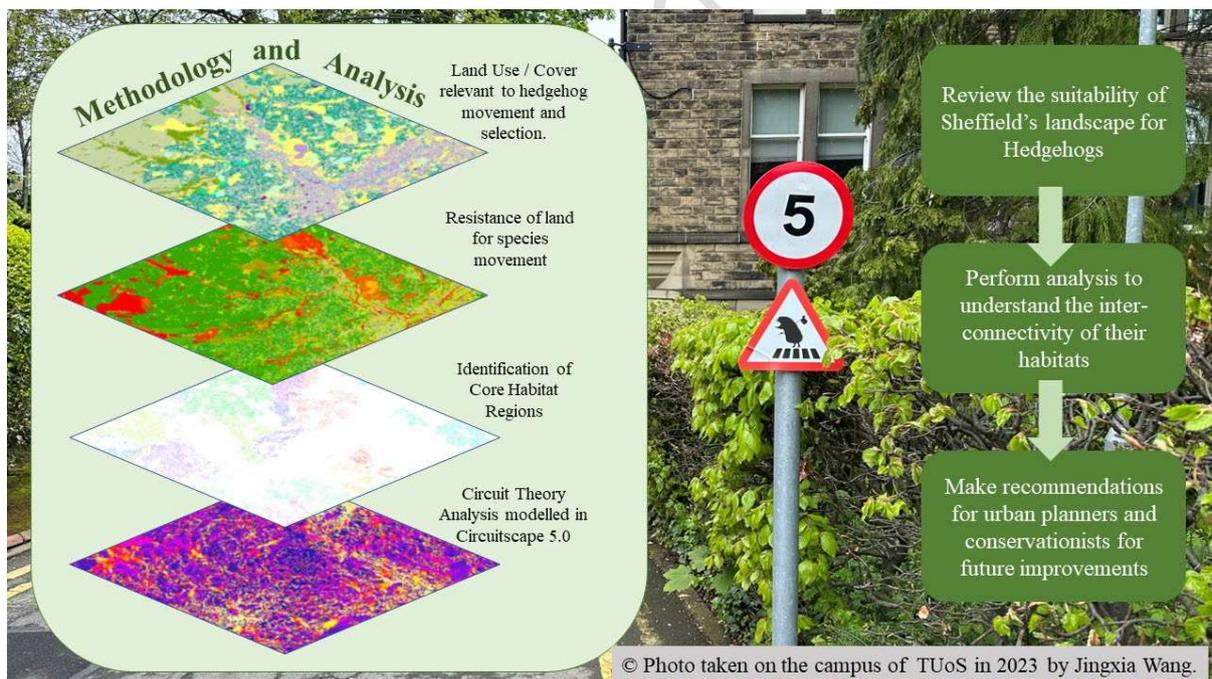
33

34 **Highlights:**

- 35 ● Suburban Sheffield is characterised by relatively well-connected greenspaces
36 supporting hedgehog movement.
- 37 ● Northwest Sheffield is identified as a priority area for monitoring rural–urban
38 hedgehog populations.
- 39 ● Attercliffe is identified as a key barrier area, where species movement is constrained
40 and habitat connectivity is reduced.
- 41 ● Major road and rail infrastructure coincide with key barriers limiting connectivity and
42 represent priority targets for intervention.
- 43 ● Maintaining the quality of core habitats is essential for sustaining connectivity across
44 Sheffield.

45

46 **Graphical abstract:**



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51 1. Introduction

52 Habitat loss and fragmentation pose a threat to the survival of wildlife, particularly in
53 urban environments (Huijser and Bergers, 2000; Jaeger, 2000; Baker and Harris, 2007; Madadi
54 et al., 2017; Almenar et al., 2019). Habitat can be lost completely in the process of land use
55 change or it can be fragmented by infrastructure such as roads, buildings, construction sites, or
56 other species-specific non-suitable land uses, with remaining habitat split into smaller patches
57 reduced in quality and food availability or otherwise left less well-connected (Jaeger, 2000).
58 New infrastructure can create barriers to movement or replace previously connected corridors
59 between patches, leaving remaining patches cut off from each other at a distance greater than
60 a species' maximum dispersal distance – the maximum distance that the species can travel
61 (Scolozzi and Geneletti, 2012). When barriers prevent dispersal between smaller habitat
62 patches within a larger territory, foraging and breeding potential are risky and reduced, limiting
63 or reducing species populations by lowering ecological connectivity (Almenar et al., 2019).

64 For the Western European Hedgehog, *Erinaceus europaeus*, a well-known mammal
65 seen in most of the UK in both rural and urban environments (Baker and Harris, 2007;
66 Doncaster et al., 2008; Hof and Bright, 2009), fragmentation is a risk to their ability to forage
67 and nest successfully. Their habitat can be fragmented and divided by roads, water bodies, and
68 gapless garden boundaries (Rondinini and Doncaster, 2002; Baker and Harris, 2007; Hof and
69 Bright, 2009) leaving them with either reduced pathways between habitats or with higher-risk
70 journeys when foraging.

71 There has been an observed reduction in population density in rural areas in favour of
72 the urban or suburban environments (Van de Poel et al., 2015; Pettett et al., 2017; Williams et
73 al., 2018) where hedgehogs were seen to move away from arable land in favour of rural villages
74 where they experienced less predation by badgers and a slightly warmer microclimate in
75 proximity to buildings (Pettett et al., 2017). Yet, despite the shift in population density toward
76 the urban environment, urban habitat also provides its own challenges; domestic dogs, man-
77 made water features with steep edges, poisoning/pollution, and increased road density and
78 traffic (associated with increased road traffic accidents), are all causes of mortality in
79 hedgehogs (Reeve and Huijser, 1999; Huijser and Bergers, 2000; Hof and Bright, 2009;
80 Taucher et al., 2020).

81 The most recent short-term surveys in British urban landscapes have shown mixed
82 results, the People's Trust for Endangered Species (PTES) Living with Mammals survey

83 showed a recent decrease for hedgehogs between 2003 and 2013 by 3.1% whilst the British
84 Trust for Ornithology (BTO) Garden Birdwatch survey, which included hedgehog sightings,
85 showed a slight increase in species numbers from 2008-2014 for sightings primarily in private
86 urban gardens – a 3.6% increase as analysed in the State of British Hedgehogs 2015 (PTES and
87 BHPS, 2015). According to the most recent 2022 report (Wembridge et al., 2022), the urban
88 hedgehog population appeared to be stabilising somewhat after years of decline with recovery
89 a possibility, however, rural populations remain low and continue to decline. Numbers of
90 hedgehogs have historically decreased over the long term in Britain (Battersby, 2005; Roos et
91 al., 2012; Hof and Bright, 2016) and they are therefore a part of the UK's Biodiversity Action
92 Plan (UK BAP, 2007) which aims to conserve species at risk of permanent decline in the UK
93 and return to a high level of biodiversity within the UK's habitats.

94 This inconsistency in distribution data presents a significant knowledge gap,
95 particularly when trying to prioritise conservation actions in urban landscapes. Specifically,
96 there is limited spatially explicit evidence on where within-city connectivity is constrained and
97 where interventions could be prioritised to support hedgehog movement across urban
98 landscapes. While our study does not resolve the population-level controversy directly, it
99 contributes to addressing this gap by identifying spatial connectivity barriers and movement
100 patterns, such as critical ecological factors that underpin hedgehog presence, survival, and
101 long-term viability in fragmented habitats.

102 The UK Biodiversity Action plan details areas of improvement that are necessary to
103 keep up with national and international nature preservation targets to improve the natural
104 environment. Their monitoring is necessary to provide further estimations of population
105 density and assess the progress of conservation projects aiming to restore their numbers
106 (Wembridge et al., 2022), and analysis of the connectivity between their habitats is needed to
107 understand their movement - identifying areas that are key to their population's survival or
108 preventing their growth. Existing studies monitoring hedgehog habitat connectivity have
109 established the importance of domestic gardens and green infrastructure for the species in
110 Zurich, Switzerland, (Braaker et al., 2014) and in Braunschweig, Germany, (App et al., 2022)
111 and located habitat corridors and 'pinch points' – areas where hedgehogs were forced to travel
112 as alternate routes were limited by barriers to movement and land unsuitable to hedgehogs. The
113 results of a connectivity analysis can be used by both city planners and in conservation efforts
114 (Almenar et al., 2019; Velázquez et al., 2022), focusing resources on where hedgehogs are

115 more active and restoring where their habitats have been, or risk potentially being, disconnected
116 by future infrastructure.

117 Several methods have been developed to evaluate habitat connectivity and green
118 infrastructure (GI) connectivity. To quantify connectivity, methods such as landscape metrics
119 using Fragstats (Kuttner et al., 2013, Lynch, 2016), least-cost analysis (Wang et al., 2022),
120 and Morphological Spatial Pattern Analysis (Wang et al., 2019) have been widely utilised in
121 the landscape planning field for analyses at multiple scales, given their advantages of being
122 user-friendly and their convenience of interpretation. Circuit theory builds on the
123 aforementioned least-cost analysis by considering multiple pathways simultaneously rather
124 than only the path of least cost, utilising the mathematical equations of electrical circuit theory
125 to determine where current would flow when there are multiple pathways of differing levels of
126 resistance in a circuit (McRae et al., 2008). With current flow representing paths of species
127 movement, results reveal multiple paths with varying amperage of current flow which in
128 ecological terms can indicate routes that are more likely to be used by the species and routes
129 where species density will be lower (McRae et al., 2008). It is significant for pathway analysis,
130 particularly for animals such as hedgehogs, as several paths should be taken into account before
131 giving a reliable suggestion about route change. The Julia programme Circuitscape 5.0
132 (Anantharam et al., 2020) is a model which uses circuit theory to produce raster outputs of
133 current or voltage flow by inputting a resistance layer representing ease or difficulty of
134 movement through a landscape and core habitat nodes for the current to run between. It has
135 been used successfully in many studies of ecological connectivity, for species movement and
136 for gene flow (McRae et al., 2008). Specifically, in the context of hedgehogs, Circuitscape has
137 been used to produce city-scale outputs of connectivity in Zurich, Switzerland (Braaker et al.,
138 2014) and in Braunschweig, Germany (App et al., 2022). The Circuitscape model provides
139 intuitive visualisation for connectivity analysis which may make the communications of our
140 findings with stakeholders such as planners and local conservation experts more effective. It is
141 thus a suitable choice for assessing connectivity in Sheffield and was selected as the method
142 and model for this study.

143 In Sheffield, the presence of hedgehogs has been confirmed through sightings and
144 roadkill data observations (Alcock and Johnson, 1984; Blackburn and Richards, 2018) giving
145 insight into their distribution but not their density distribution and wider movement patterns.
146 Sheffield's reputation as a 'green city' both within the UK and Europe (The Outdoor City,

147 2021) due to its high quantity and variety of greenspaces within its boundaries that could act
148 as habitat for the Western European Hedgehog (Gaston et al., 2005; Blackburn and Richards,
149 2018; The Outdoor City, 2021) makes the city suitable for a connectivity analysis to provide
150 predictions on species movement. Accordingly, this study is guided by the following research
151 questions: (i) How is habitat connectivity for the Western European Hedgehog spatially
152 distributed across Sheffield's urban–rural landscape? (ii) Where are the key corridors and
153 barrier areas (e.g., major roads and rail infrastructure) that most strongly constrain
154 connectivity? (iii) How can connectivity outputs be interpreted and translated into actionable
155 priorities for biodiversity-inclusive spatial planning? To answer these questions, our objectives
156 are to: (1) integrate field observation data with the most recent spatial datasets to delineate core
157 habitat patches and parameterise hedgehog-relevant land-use resistance; (2) apply circuit
158 theory to map current flow and identify corridors and barrier hotspots across Sheffield; and (3)
159 derive spatially explicit, planning-oriented insights to support targeted interventions and
160 monitoring priorities.

161 Overall, this study presents spatially explicit evidence for enhancing habitat
162 connectivity, which can be further applied in urban planning or conservation initiatives. We
163 provide these recommendations equally to contribute to the wider benefits received from
164 improving the quality and availability of urban green infrastructure, not just for the
165 conservation of one species, but to increase the overall biodiversity and ecological connectivity
166 of local ecosystems, regulate climate, and aid storm and flood water management - benefitting
167 the natural environment (Wang et al., 2019; Wang et al., 2022). The results of connectivity
168 analyses taking into account species movement and habitat fragmentation are vital for
169 biodiversity-inclusive sustainable development which can mitigate the impact habitat
170 fragmentation has had on species numbers and diversity and help to reverse the damages caused
171 by rapid land use change at the cost of habitat loss. More broadly, improving urban green
172 infrastructure to reduce fragmentation can deliver co-benefits for biodiversity and ecosystem
173 functioning, and can contribute to wider sustainability goals in cities (Breuste et al., 2015;
174 Bertram and Rehdanz, 2015; Wang et al., 2019; Wang et al., 2022).

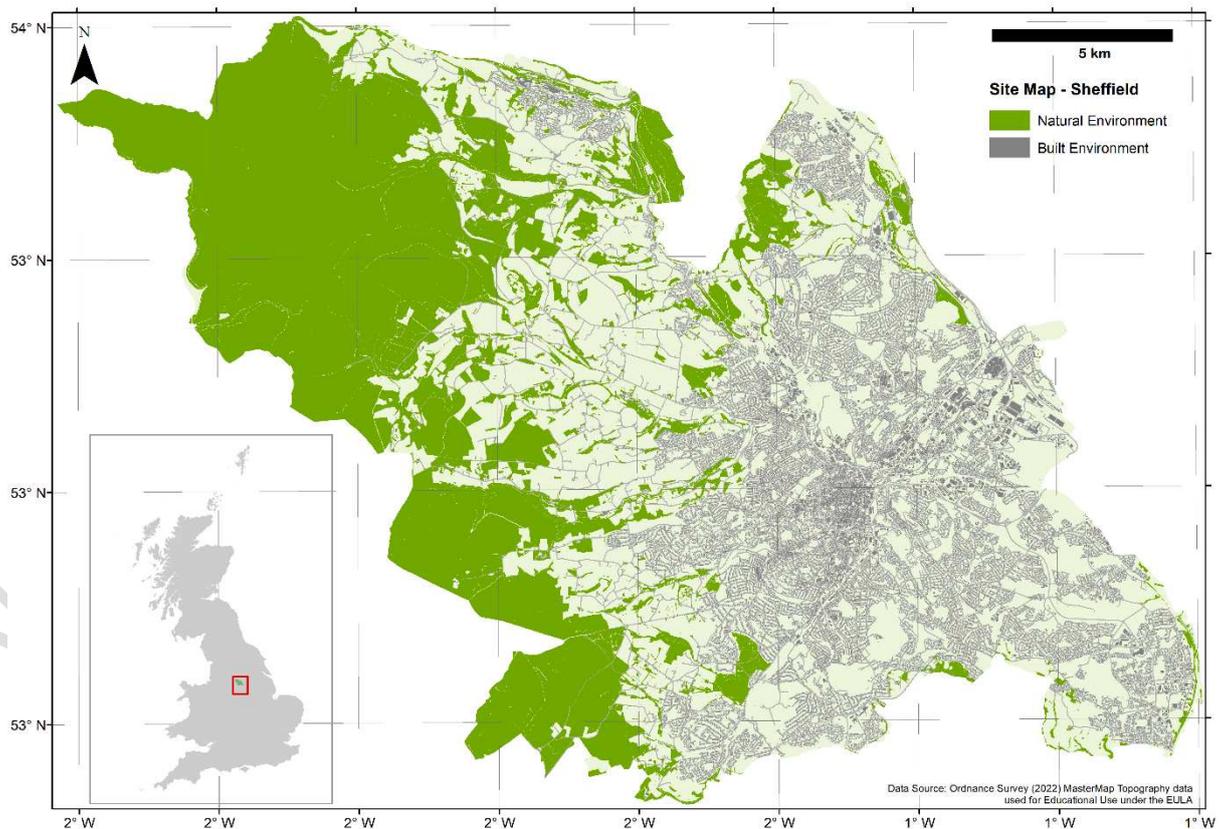
175 **2. Methods**

176 **2.1 Study Area: Sheffield, UK**

177 The city of Sheffield, UK, has a city boundary that includes both urban and rural areas,
178 stretching into the Peak District National Park in the west whilst evidence of its industrial past

179 is most notably seen towards the east (Hey, 2005). Modern Sheffield has a reputation for being
180 a particularly green city, with its proximity to the Peak District usually one of its key tourism
181 selling points, and has been described as the greenest city in the UK (The Outdoor City, 2021).
182 The Sheffield Greenground map (Ilus, 2021) highlighted how well-connected greenspaces are
183 for the public, in terms of walking, cycling and outdoor activities at 356 of the 800 plus
184 managed greenspaces covering over 4,000ha. Sheffield has gained recognition as an
185 extraordinary city due to its legacy of pioneering open and green space planning initiatives
186 (Ersoy et al., 2019), such as The Green Network, managed by Sheffield and Rotherham
187 Wildlife Trust, and The Don Catchment 2020, which aims to connect the Peak District to the
188 port (i.e. from ‘Peak to Port’). This makes the city well-connected for humans looking to access
189 greenspaces and gives a promising outlook for wildlife, particularly hedgehogs who have their
190 own need for connected greenspaces (Hof and Bright, 2009; Braaker et al., 2014).

191 Overall, Sheffield provides a suitable urban–rural setting to examine how green
192 infrastructure and transport barriers shape habitat connectivity for a widespread urban mammal.



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Figure 1: Sheffield, UK study area

2.2 Land Use Mapping and Classification for Hedgehog Habitat Analysis

Using ArcMap 10.7.1 and ArcGIS Pro, a land use map for Sheffield and its surrounding 2 km boundary box was created using three Ordnance Survey datasets; OS Open Roads (OS, 2022a), OS MasterMap Greenspace (OS, 2022b) and OS MasterMap Topography (OS, 2022c), and supplemented with the European Environment Agency's Corine Land Cover data (EEA, 2018) which provided additional distinction in land cover relevant to hedgehog habitat preference. MasterMap Topography included roads, water bodies and buildings which are major barriers to hedgehog movement whilst MasterMap Greenspace provided further detail to differentiate between types and functions of green infrastructure which vary in their suitability for hedgehog habitat (Hof and Bright, 2009; Braaker et al., 2014). For clarity, the landscape was classified into a set of hedgehog-relevant LULC classes covering (i) greenspace and semi-natural habitats, (ii) agricultural land, (iii) transport infrastructure, (iv) built-up/impervious surfaces, and (v) water bodies. These classes form the basis for subsequent habitat suitability and resistance assignment.

Open Roads data was used to reclassify roads into four categories by function; Tracks, Small Roads, Large Roads, and Motorways. Large roads included A roads and B roads and the remaining local access and minor roads were grouped as small roads. There is a notable difference in the size, and traffic flow, of a road and its impact as a barrier to species movement (Rondinini and Doncaster, 2002; Hof and Bright, 2012). Generally, large roads and motorways restrict species movement for hedgehogs, their nightly foraging is bounded by larger roads which they will avoid crossing, whereas smaller roads may be crossed frequently by populations (Rondinini and Doncaster, 2002).

The final CLC 2018 dataset was used to make a distinction between types of agricultural land; land used as meadows or pastures, and arable land ploughed or used for temporary crops. Previous studies on the behaviours of hedgehogs have shown a strong difference in preference between the different types of agricultural land, most significantly in the use of pastures versus arable land (Doncaster et al., 2008; Hof and Bright 2010b). As the OS data classified more accurate field boundary extents at a finer scale than the CLC data, the CLC data was used to reclass agricultural land from the OS Topography layer as pasture, arable or heterogeneous agricultural land with complex cultivation patterns or unspecified usage. This approach has limitations. Approximately 8% of agricultural land remained unclassified when using this method as it did not overlap with the CLC layer and their sub-category 'complex cultivation patterns' was not easily translated into hedgehog habitat suitability when referring

229 to wider literature. This category was therefore grouped with unclassified agriculture in the
230 following steps. The reclassified categories were merged into one single vector layer containing
231 all of the relevant variables as a land use map ready to be converted into a map of resistance.

232 The resulting LULC classes and their relative suitability for hedgehogs (i.e., more
233 permeable vegetated habitats versus higher-resistance built-up areas, major transport
234 infrastructure, and water bodies) are summarised in Supplementary Table S1.

235 **2.3 Core Habitat Identification for Hedgehogs**

236 Core habitat for hedgehogs contains shelter in the form of natural vegetation used for
237 both nesting and foraging for food. In Braaker et al. (2014) the most selected habitat was
238 ‘gardens with structures’ with structures including flower and vegetable beds, hedges, shrubs,
239 bushes, trees and branches which provided that necessary shelter. Following this evidence, we
240 defined core habitat in Sheffield as land use classes that provide comparable shelter and
241 foraging opportunities, and we operationalised this definition by selecting private gardens and
242 allotments from the reclassified LULC layers as core habitat.

243 Technically in GIS, core habitat patches were delineated by extracting the selected
244 LULC classes, dissolving contiguous polygons into patches, and removing non-habitat
245 features. To reflect functional constraints, we treated large roads and motorways as barriers
246 and used them to split otherwise contiguous core habitat into separate patches. The value of
247 green infrastructure is made visible by the high selection of these land cover types as core
248 habitats for hedgehogs - their preservation is necessary to maintain population numbers (Baker
249 and Harris, 2007).

250 Sheffield’s core habitat was structurally well-connected, no patches were isolated when
251 buffered using a maximum distance of 3.8 km seen when searching for new habitat, or when
252 using an average home range span of 0.8 km (Doncaster et al., 2008). To factor in functional
253 connectivity, large roads and motorways were used to divide core habitat into smaller patches
254 separated by these barriers which would divide local populations on the ground level (Morris,
255 1988; Rondinini and Doncaster, 2002). We thus applied a minimum patch size threshold to
256 identify core habitat patches likely to support local populations. This identified 47 patches of
257 core habitat greater than 17ha. Home-range estimates vary by study, location, methods and
258 individual behaviours (Rasmussen et al., 2019) however, the parameter for minimum patch size
259 was set at 17ha which reflected the average nightly activity range of hedgehogs in Doncaster
260 et al. (2008), a UK study.

261 2.4 Resistance Value Assignment

262 Detailed resistance values for all land-use classes are reported in Supplementary Table
263 S1. The ease of movement through the landscape and through differing land types was
264 represented as a cost, and in this case, a resistance value. Resistance values were assigned based
265 on published evidence of hedgehog habitat preference and movement behaviour, with lower
266 values indicating more suitable or permeable habitats and higher values indicating barriers or
267 low suitability. The full set of land-use classes, resistance values, and literature-based
268 justification is provided in Supplementary Table S1; Section 2.4 summarises the rationale and
269 key assumptions underpinning the assignment. A key reference for this step is Braaker et al.
270 (2014) where forty urban hedgehogs within Zurich were GPS tracked to determine their
271 preferred habitats and their dispersal patterns to inform a circuit theory connectivity analysis.
272 As this study did not collect primary movement data due to practical and timescale limitations,
273 we used the findings of Braaker et al. (2012; 2014) to guide resistance ranking and calibration
274 in the Sheffield context. In Braaker et al. (2014), five resistance schemes were tested; their
275 best-performing r-exponential model increased resistance exponentially from most- to least-
276 selected habitat, and these values formed a baseline for this study.

277 App et al. (2022) similarly used Braaker's resistance values and land classes as a base
278 but benefitted from adapting to suit their city of focus – Braunschweig by including the
279 shipping canal and an airfield as barriers, and differentiating between tree types. Following this
280 established approach, we used the Zurich-based scheme as a baseline and introduced Sheffield-
281 specific adjustments where local landscape context and UK evidence suggested different
282 suitability. The most notable change was the inclusion of an “Upland” category, representing
283 the north-western area influenced by the Peak District. In Williams et al. (2018), hedgehogs in
284 the UK were found in all land classes except upland (defined as mountainous, with moorlands,
285 afforestation, and bogs). We therefore assigned upland the highest resistance (100 Ω),
286 consistent with other strong barriers such as major roads and water bodies.

287 Pastures and arable land were given values of 1 Ω and 85 Ω respectively, to represent
288 the strong difference in selection by hedgehogs seen in the UK (Doncaster et al., 2008; Hof
289 and Bright, 2010) and in Denmark (Riber, 2006). As a small percentage of nests in Riber (2006)
290 were still found on arable land, 85 Ω was given instead of the maximum 100 Ω , and for
291 unclassified agricultural land, a mean average of 43 Ω was taken. While resistance assignment
292 necessarily involves assumptions, converting habitat suitability into a numerical surface is a

293 required step for rasterisation and subsequent circuit-based modelling. Detailed resistance
294 values and their ecological justification are provided in Supplementary Table S1.

295 **2.5 Habitat Connectivity Analysis**

296 The analysis took place in Circuitscape 5.0, a Julia programme designed using circuit
297 theory and applicable for habitat connectivity mapping (McRae et al., 2008; McRae et al.,
298 2013; Anantharaman et al., 2020). It was selected for its open-source nature, its user-friendly
299 design and its success in similar studies assessing connectivity for hedgehogs at the city scale
300 (Braaker et al., 2014; App et al., 2022). The Sheffield land use map was converted into a raster
301 using the resistance values chosen for each land type. The spatial resolution was set at 5m, the
302 highest resolution that produced successful outputs for Sheffield's city boundary with a 1 km
303 buffer zone added. The buffer zone of 1km was kept in order to limit the impact of the boundary
304 effect seen in similar studies (Koen et al., 2010). The resolution was acceptable at 5m as linear
305 features such as large roads and rivers, which were important barriers, were maintained and
306 produced meaningful results (McRae et al., 2008). To maximise memory capacity focal nodes
307 representing the centroids of the habitat patches were used instead of regions to represent core
308 habitat in Circuitscape. A pairwise analysis of current flow was calculated between each pair
309 of nodes, for this study seven nodes distributed across Sheffield were chosen, rather than the
310 full 47, giving fifteen pairs to solve and showing cumulative current flow between all seven in
311 a final output. The seven habitat nodes were selected for their geographical spread across the
312 city and to encompass a range of the city's varied land use types and characteristics. This
313 ensured nodes were placed to include representation of habitat patches nearest the denser urban
314 centre of Sheffield, within the upland and predominantly rural North-West, suburban gardens
315 associated primarily with detached and semi-detached housing in residential areas of the city
316 outskirts in both the North-East and South-West, and habitat nearest the current and former
317 industrial sectors of the city nearest the River Don.

318 **2.6 Spatial distributions of hedgehogs using kernel density analysis**

319 To understand and visualise the current spatial distribution density of hedgehogs in
320 Sheffield, we used the Kernel Density analytical tool, given it is considered to be a more
321 advanced and localised approach for a city-scale analysis. This approach is efficient for
322 evaluating how frequently hedgehogs were resided or seen in specific areas like within the City
323 of Sheffield. This hedgehog data in Sheffield contains the hedgehog sightings that have been
324 sent to Nature Counts via Sheffield Wildlife Trust, including historic hedgehog records,
325 postcard and website sightings of hedgehogs registered by citizens. They are the best available,

326 open access and live data that is managed and collected by the hedgehogs protection
327 organisations. As the citizen collected data via postcards and websites was aggregated to the
328 postcode level and required further data quality control considering metadata, and the historic
329 hedgehog data is the only data that has georeferenced recorded in Sheffield. The historic
330 hedgehog data contains a total of 1295 hedgehog registers in the adjacent area of Sheffield,
331 including areas such as the Peak District and Rotherham. For 701 hedgehog point data within
332 Sheffield city boundary, it was utilised for kernel density analysis in this study to evaluate the
333 spatial distribution density of hedgehogs in Sheffield.

334 The hedgehog's data was sourced from the Sheffield Wildlife Trust originally as KML
335 files and were firstly transferred into layer files in ArcGIS Pro using KML to Layer toolbox.
336 To calculate the spatial density of hedgehogs in Sheffield, we executed Kernel density analysis,
337 with the output cell size of 1 ha and the search radius of 0.8 km, as we specified in section 2.4,
338 to keep the methodology consistent and calculate the hedgehog's density using an average
339 home range span of 0.8 km (Doncaster et al., 2008).

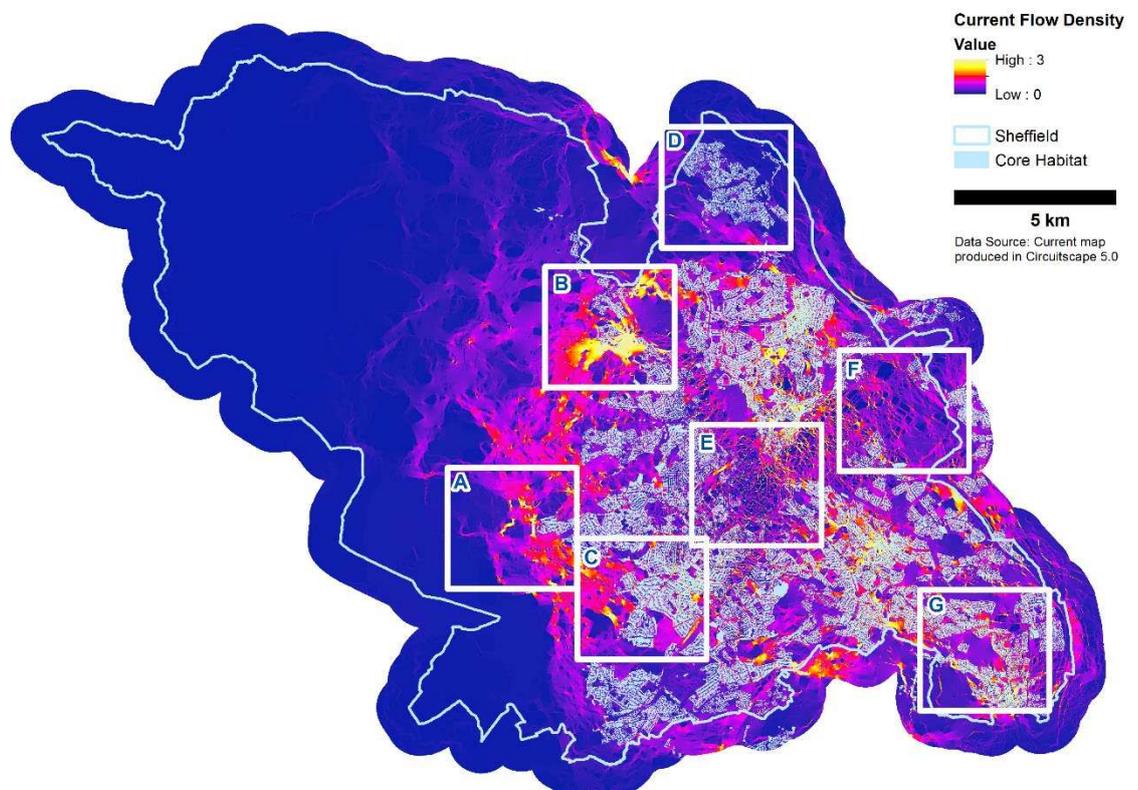
340 **3. Results**

341 **3.1 The core habitats of hedgehogs within Sheffield's boundary**

342 The resulting current maps were symbolised to create visualisations that investigate the
343 areas of the city where connectivity is highest and lowest, identifying pinch points and areas
344 most relevant to urban planning and conservation. To support interpretation, we selected five
345 focal areas for closer inspection (Figure 2; Table 2 in the Supplementary Material). These areas
346 were identified from the city-wide current flow and core habitat patterns to represent
347 contrasting connectivity contexts across Sheffield, including suburban corridors with high
348 current flow, locations where transport and built-up features constrain movement, and edge-
349 of-city transitions towards the rural and urban landscape. The extent of each focal area was
350 defined to capture the core habitat patches and surrounding land-use context that shape the
351 mapped current-flow patterns at neighbourhood scale. These areas of interest were selected for
352 detailed analysis, shown in Figure 2 and Table 2 of the Supplementary Material. The
353 cumulative current map shows a clear ring of higher current flow circling the centre of Sheffield
354 (Figure 2) whilst avoiding the West of the city boundary. There is a noticeable network of
355 pathways that do not follow the shortest Euclidean distance and instead converge and diverge
356 in their path width whilst travelling between obstacles, indicating areas of locally concentrated
357 current ("pinch points") and areas of low current where movement is inferred to be less likely.

358 The suburbs show the highest modelled current flow with wider paths seen in those
359 towards the West of the city before the transition into extremely low current low density closer
360 to the boundary. These results indicate that hedgehogs would avoid travelling through the city
361 centre in a similar manner and depend on its outskirts to travel between habitat patches, largely
362 through pasture, residential gardens and urban greenspaces. Where the Northern and Western
363 limits of the city show a low level of current flow the southeast habitats do not appear to be
364 particularly isolated, and current flow stretches into the more central suburbs without
365 significant issue. The most obvious pinch point, at a city scale, is to the east of the city centre
366 where current flow is funnelled through a narrow path connecting the two nearest areas of
367 habitat north and south of the pathway. This route is playing a necessary role in connecting the
368 habitats given the few alternative routes hedgehogs would be likely to undertake here.

369 At an overview, Sheffield's habitats are largely suburban and are well connected via
370 the outskirts of the city despite their absence in the centre. The five focal areas are highlighted
371 because they illustrate distinct connectivity situations and help explain how different landscape
372 features contribute to either maintaining or constraining connectivity for hedgehogs at a finer
373 scale. .



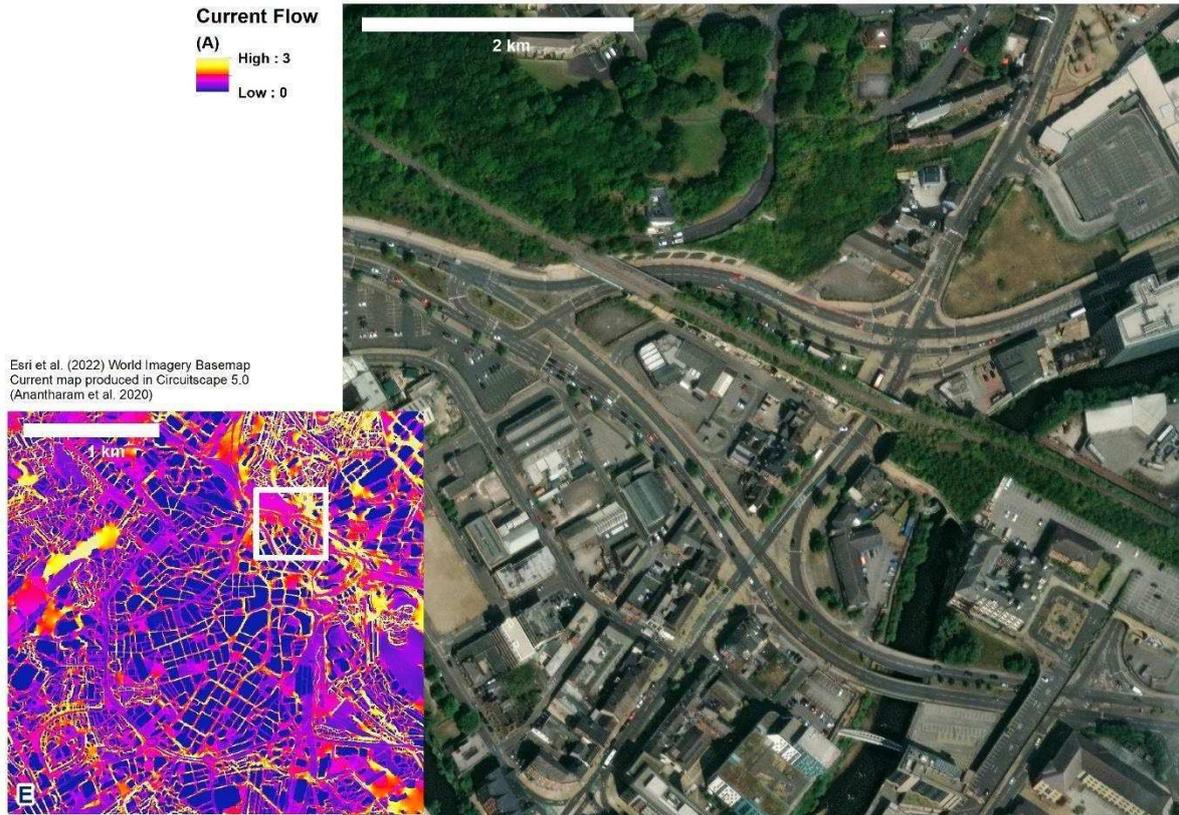
375 *Figure 2: Current flow density representing species movement across Sheffield, modelled in*
376 *Circuitscape 5.0. (Note: A is the area surrounding Lodge Moor, B is Middlewood, C is Bents*
377 *Green, D is High Green and Chapeltown, E is City Centre, F is Attercliffe, G is Owlthorpe)*

378

379 **3.2 Significant connectivity pathways in Sheffield**

380 Several locations within the City of Sheffield contained pinch points, areas where the
381 current flow was high yet funnelled through a narrow path. These form significant connectivity
382 pathways which hedgehogs' movement is heavily dependent on, given the alternatives are
383 limited. Both the City Centre and Owlthorpe contained notable pathways relevant to Hedgehog
384 movement where large areas of high-resistance land types were present. While they contrast
385 one another in their land types - urban land cover and arable farmland - they both show narrow
386 routes present around the margins or through other land types acting as habitat corridors, and
387 highlight significant pathways that are relied on to make movement possible as a result. These
388 highlight the critical role of such pathways, which hedgehogs rely on for movement across
389 otherwise fragmented landscapes.

390 In particular, Burngreave near the city centre was identified as containing a key
391 connectivity pathway for hedgehogs avoiding the centre, as highlighted in Figure 10. However,
392 it should be noted that the land use map and model used in the study presented limitations due
393 to their 2D representation of the landscape. To gain a more comprehensive understanding of
394 the pathway in this area and explore opportunities for future improvements, conducting a
395 ground-based study would be highly beneficial. A ground-based study and detailed
396 investigation in Burngreave could consider the intricate network of junctions between various
397 roads and the railway line, as well as account for the presence of overpasses and bridges. By
398 surveying the hedgerows and crossings for hedgehog activity, researchers can assess the
399 pathway's effectiveness and identify specific areas for potential enhancements and guiding
400 future conservation efforts.



401

402 *Figure 11: Connectivity pinch point located in Sheffield's city centre.*

403

404 In Owlthorpe the key pathways for hedgehogs were field margins, as depicted in Figure
405 11. These pathways primarily consisted of hedgerows and woodland strips, accompanied by
406 trees along the roadside. They served as crucial connections between the private gardens
407 surrounding the agricultural land where current flow avoided the ploughed land in the central
408 area, emphasizing the significance of field margins and the adjacent residential gardens for the
409 movement of hedgehogs as pathways and potential habitat.

409

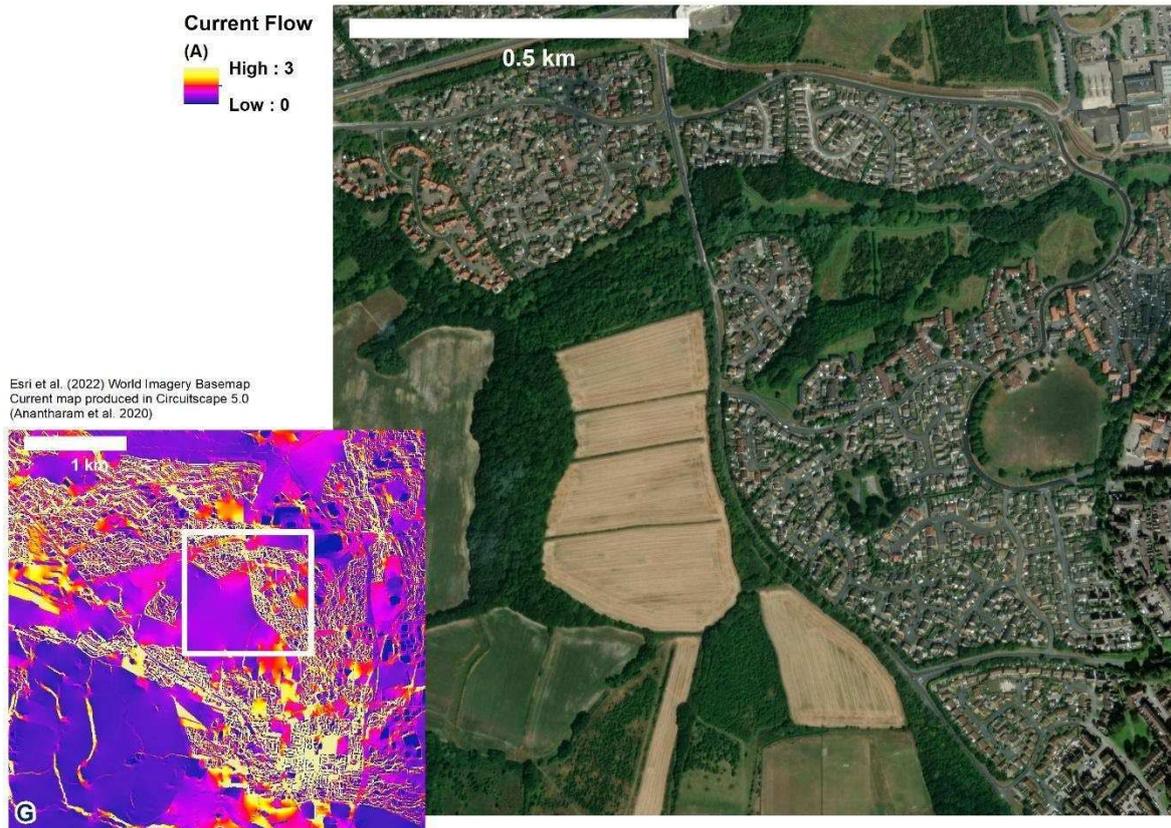
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411

412

413 Overall, recognising the importance of field margins, hedgerows, woodland strips, and
residential gardens in Owlthorpe is crucial for promoting and preserving habitat connectivity
for hedgehogs in the area. Protecting and enhancing these features can contribute significantly
to maintaining viable populations and facilitating their movement across the landscape.

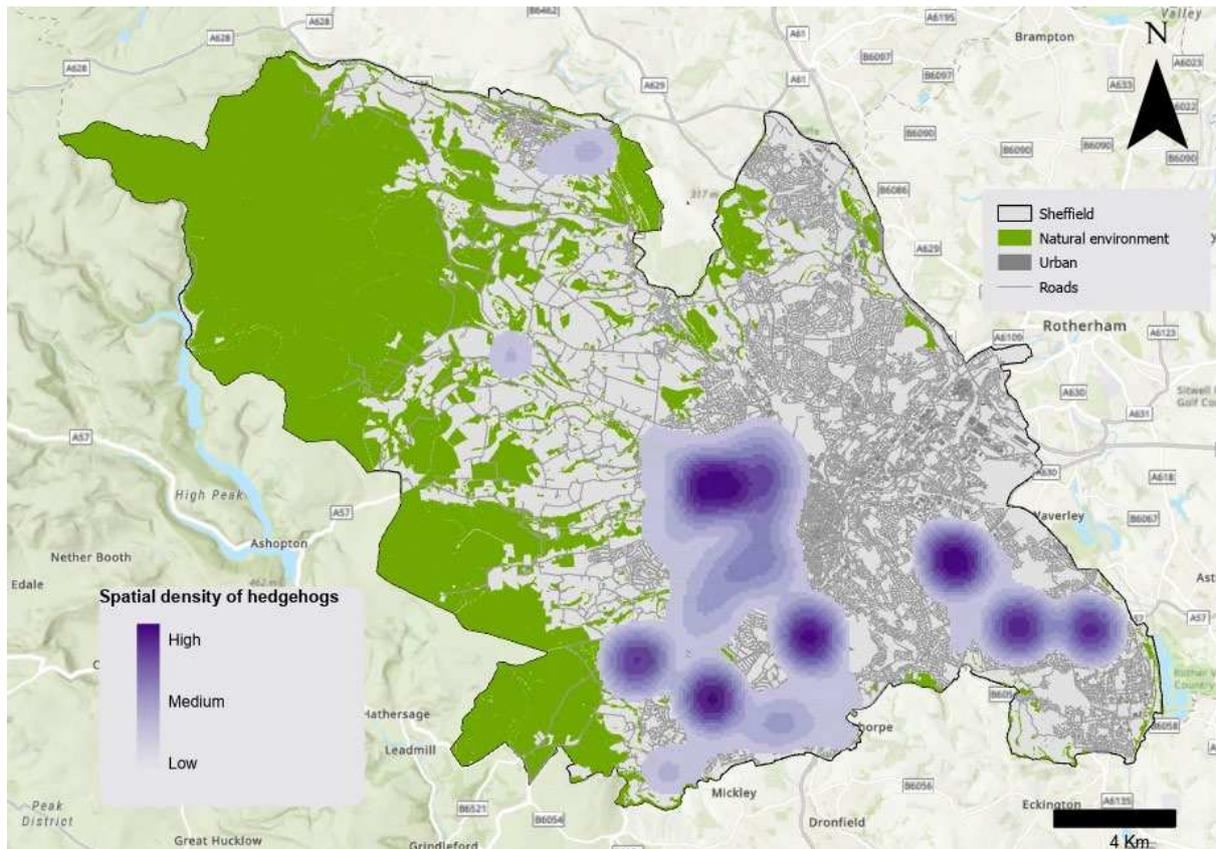
413



414

415 *Figure 12: Connectivity pathways in Owlthorpe.*416 **3.3 The spatial distribution density of hedgehogs and comparison**

417 The results of the kernel density analysis regarding the spatial density of hedgehogs are
418 illustrated in Figure 10. This analysis highlights distinct density patterns of hedgehogs
419 associated with various natural environments within the urban landscape. High-density areas
420 for hedgehog populations predominantly coincide with key green spaces: Shire Brook Valley
421 in the east, Richmond Park in the central region, and the Hang Allotment Gardens in the
422 western part of the city, as well as the Thurman Grove Allotment Gardens in the north and the
423 Torley Hall Park in the south. Both the Hang and Thurman Grove Allotment Gardens show
424 high-density hedgehog populations. These areas, featuring a mix of natural and managed land,
425 support a diverse wildlife community. Areas on the fringe of urban settings show medium to
426 low hedgehog density, possibly serving as transitional zones where hedgehogs might be
427 attempting to adapt or are being pushed out due to urban sprawl.



428

429

Figure 10: The spatial distribution density of hedgehogs in Sheffield

430

431 3.4 The core areas for connectivity improvements

432

433

434

435

436

Areas with particularly high or low current flow, as well as locations showing narrow high-flow “pinch points” or low-flow dead ends, were selected for closer analysis because they provide complementary insights into hedgehog movement constraints and opportunities for targeted interventions. We summarise the focal areas and their dominant connectivity signals, barriers, and planning implications in Table 1, followed by area-specific notes (Figures 3–9).

437

Table 1. Comparative summary of focal areas and planning implications

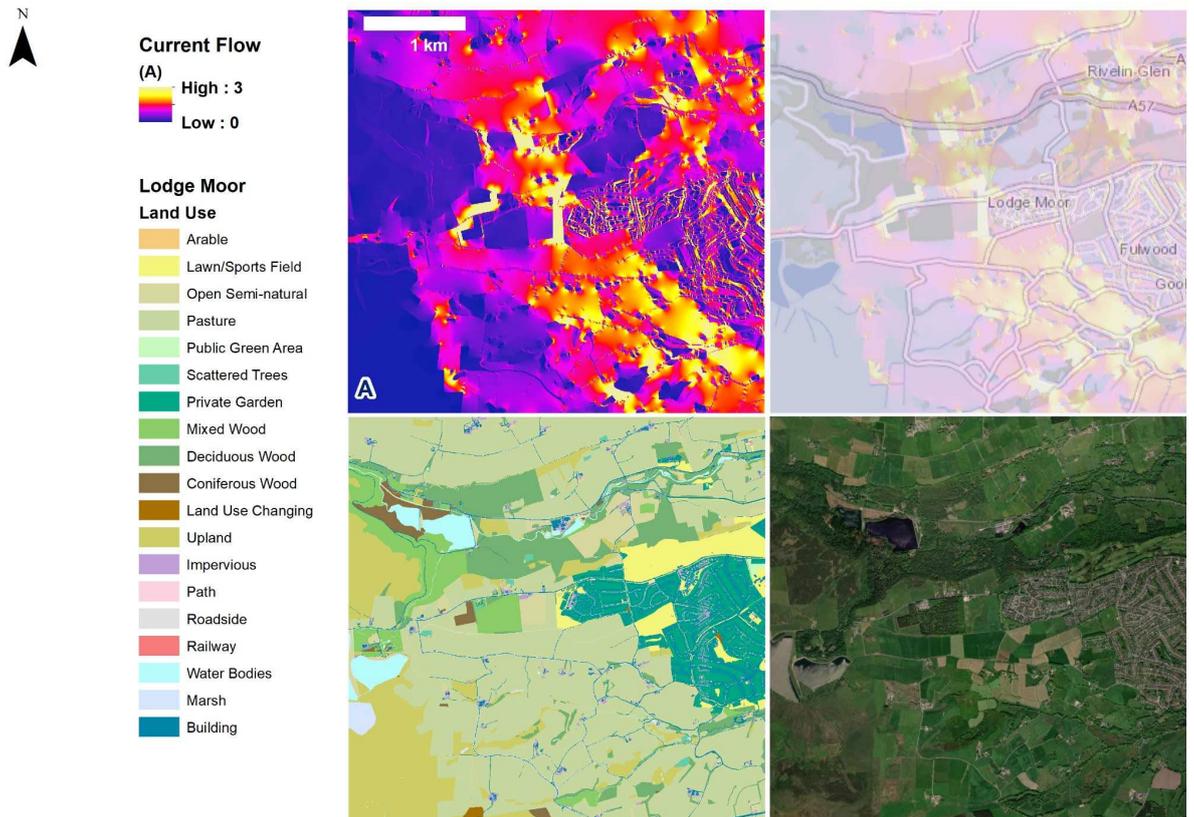
| Focal areas | Connectivity signal | Main barrier(s) | Enabling habitats | Planning implication (actionable) |
|-------------|---------------------|-----------------|-------------------|-----------------------------------|
| | | | | |

| | | | | |
|--|--|--|--|--|
| Lodge Moor (Fig. 3) | Pinch points (narrow high-current crossings) | Road crossings at Redmires Rd and Manchester Rd (A57) | Pasture, mixed woodland and semi-natural vegetation | Prioritise safe crossing measures and protect pinch- point corridors; avoid further traffic-related fragmentation |
| Middlewood & Worrall (Fig. 4) | High current, diffuse (multiple routes) | Limited obvious barrier within focal extent | Pastures and private gardens | Maintain habitat quality and permeability; safeguard garden and pasture connectivity |
| Bents Green (Fig. 5) | High current across suburban gardens | Potential vulnerability to garden impermeability | Suburban gardens (Ecclesall, Millhouses, Carter Knowle) | Maintain garden connectivity (permeable boundaries) and greenspace management to retain multiple pathways |
| High Green & Chapelton (Fig. 6) | Cul-de-sac / dead-end (low- through flow) | A61, A616, M1 form three-sided enclosure | Limited permeable corridors | Identify feasible linkage opportunities at the single access route; targeted mitigation at the most constraining road segments |

| | | | | |
|-----------------------------------|---|--|--|---|
| City Centre / Burngreave (Fig. 7) | Low current in core; bypass via outskirts; pinch around ring road | Dense built-up area; ring road barrier | Central parks (Ponderosa, Crookes Valley, Weston Park) | Strengthen GI stepping-stones and safe movement around ring-road edge; prioritise park-to-park linkages |
| Attercliffe (Fig. 8) | Low current; fragmented | A6109, A6178, River Don, rail lines | Limited gardens corridor Handsworth–Brightside | Target linear barriers (road/rail/river interfaces) and enhance the few existing green links; prioritise crossings/retrofits where feasible |
| Owlthorpe (Fig. 9) | Multiple pathways around low-current arable core | Arable land (central low current) | Gardens and field margins | Improve field-margin management; protect garden corridors to sustain connectivity near boundary |

438

439 Lodge Moor (Figure 3) was singled out as it contained three noticeable pinch points,
440 where a narrow path of high current crossed a road. These occurred across two roads and took
441 place at boundaries where land cover changed to pasture on either side of an area of mixed
442 woodland and open semi-natural vegetation. These locations on Redmires Road and on
443 Manchester Road (A57) are where the model suggests crossing by hedgehogs is more likely to
444 take place as these are the lowest resistance connecting pathways between habitats with few
445 feasible alternative routes. Given their modelled best option involves crossing a road barrier,
446 this is a key area for improvement as increases in traffic flow could further decrease
447 connectivity at Lodge Moor and fragment the landscape here if these narrow pathways are lost.



448

449 *Figure 3: Lodge Moor current flow density representing species movement, with land use type, aerial*
 450 *imagery and contextual basemap for reference.*

451 *The species movement density paths in Lodge Moor 2022, with land use type, aerial imagery and*
 452 *contextual basemap for reference (paths are represented by current flow density).*

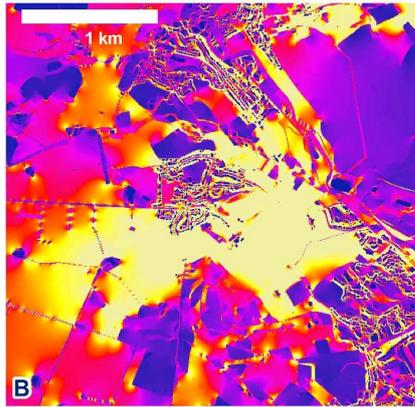
453 In contrast, Middlewood (Figure 4) and the surrounding area of Worrall had very high
 454 current flow spread over a wide area of majority pastures and private gardens. This area stands
 455 out as core habitat and is likely highly used by hedgehogs due to how well-connected the habitat
 456 is there, allowing for many possible routes to food and nesting sites. Bents Green (Figure 5)
 457 showed a similar pattern of high current flow across the suburban gardens in Ecclesall,
 458 Millhouses, and Carter Knowle, identifying these gardens as important habitats.



Current Flow
Value
 High : 2.74311
 Low : 0

Middlewood
Land Use

- Arable
- Unclassified Agricultural
- Lawn/Sports Field
- Open Semi-natural
- Pasture
- Public Green Area
- Allotment
- Scattered Trees
- Private Garden
- Mixed Wood
- Deciduous Wood
- Coniferous Wood
- Upland
- Impervious
- Path
- Roadside
- Railway
- Water Bodies
- Marsh
- Building



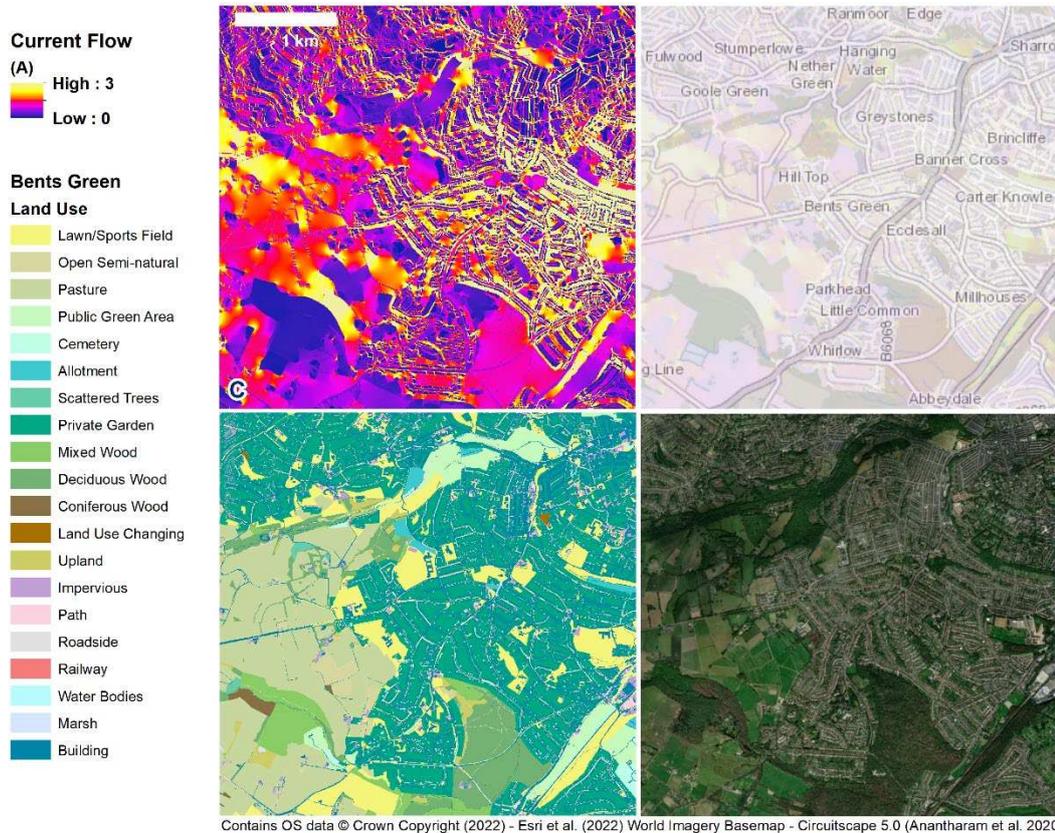
Contains OS data © Crown Copyright (2022) - ESRI (2022) World Imagery Basemap - Current flow mapped in Circuitscape 5.0

459

460

Author Accepted

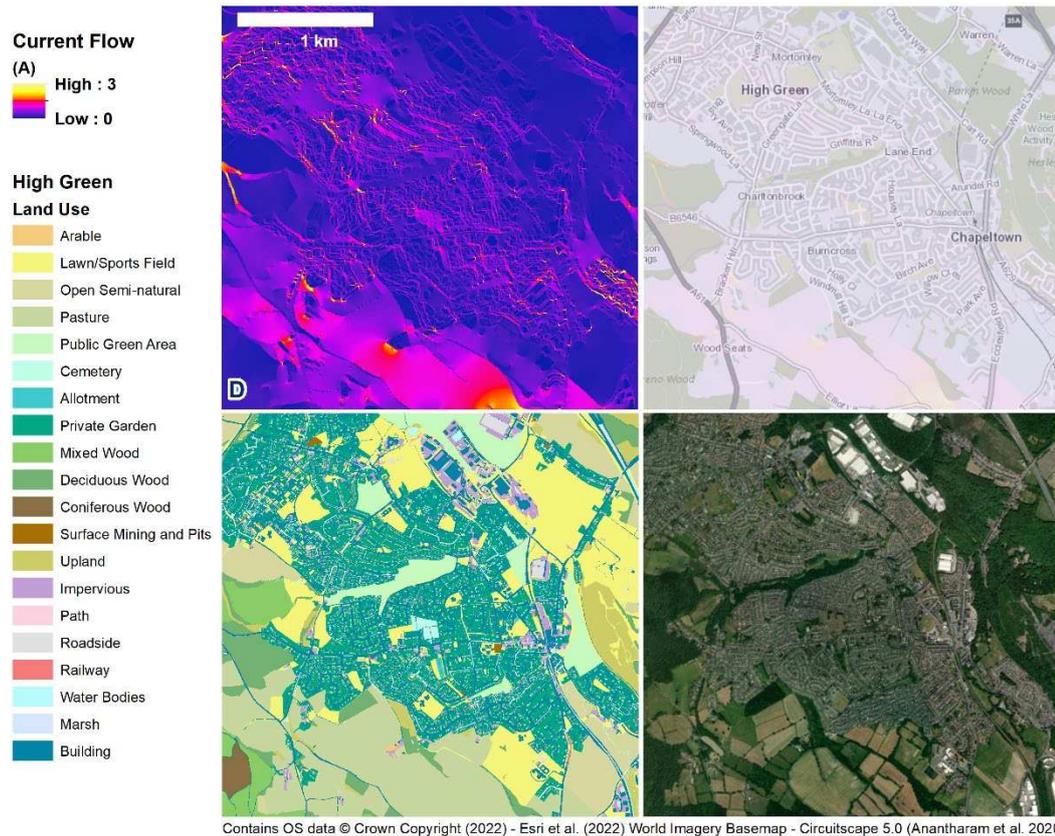
461 *Figure 4: The species movement density paths in Middlewood 2022, with land use type, aerial*
 462 *imagery and contextual basemap for reference (paths are represented by current flow density).*



463

464 *Figure 5: The species movement density paths in Bents Green 2022, with land use type, aerial*
 465 *imagery and contextual basemap for reference (paths are represented by current flow density).*

466 High Green and Chapeltown (Figure 6) showed a habitat cul-de-sac in the connectivity
 467 map. McRae et al. (2008) describe a cul-de-sac as an area of low current flow that does not
 468 play a large role in creating pathways for species movement, something of a dead end or cul-
 469 de-sac when it comes to habitat connectivity. High Green and Chapeltown are bounded on
 470 three sides by the A61, the A616, and the M1 and therefore fit this definition as modelled
 471 current flow is restricted to only one route in and out and the areas provide no through pathway
 472 beyond their boundaries.

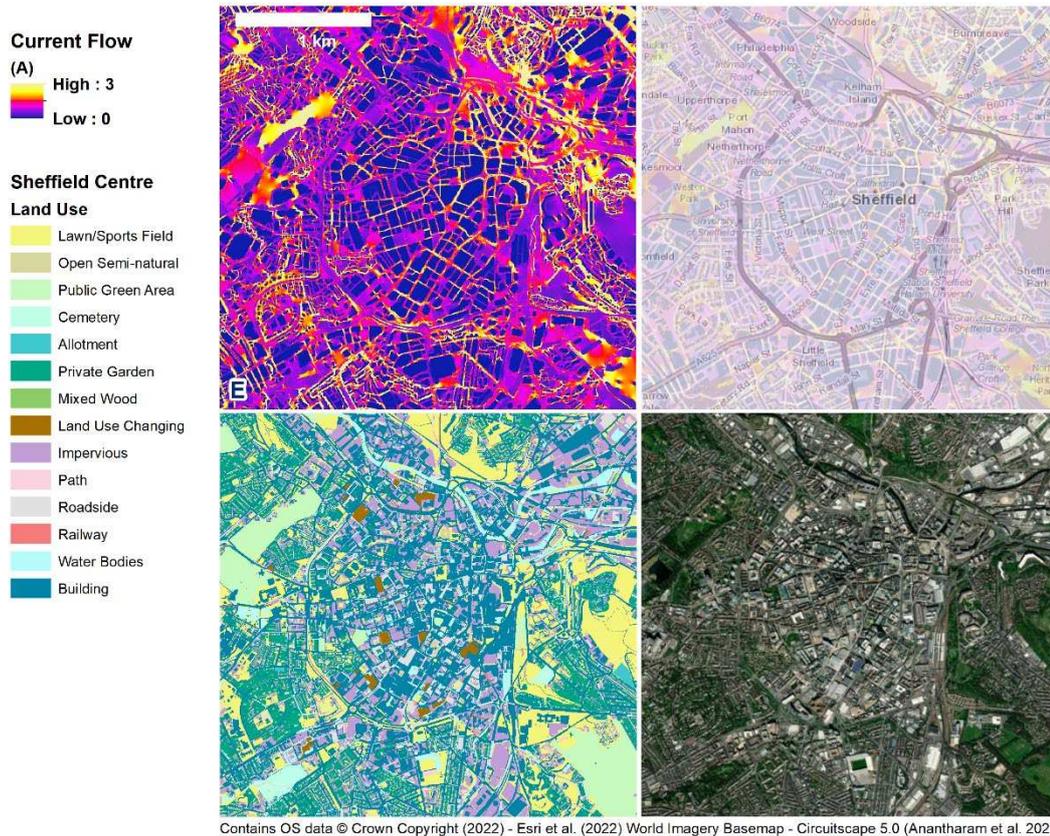


473

474 *Figure 6: The species movement density paths in High Green and Chapeltown 2022, with land use*
 475 *type, aerial imagery and contextual basemap for reference (paths are represented by current flow*
 476 *density)..*

477

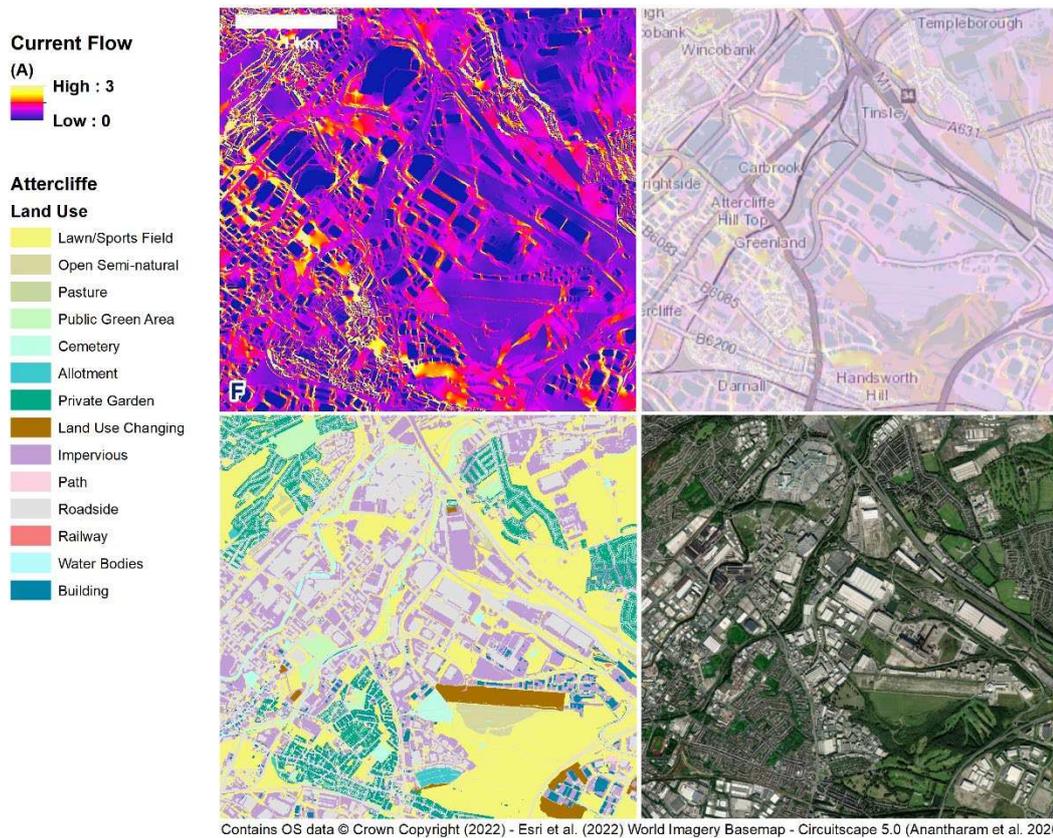
478 The City Centre (Figure 7) is densely built, lacking residential properties with gardens
 479 in place of flats and multistorey buildings, and as expected was low in resulting current flow.
 480 The ring road surrounding Sheffield's city centre also acts as an additional barrier to current
 481 flow here. As a result, Burngreave on its outskirts is a pinch point that the species may flow
 482 through to avoid the very centre of Sheffield. The Ponderosa and other central parks (Crookes
 483 Valley, Weston Park) are also important green infrastructure for connectivity in this denser
 484 urban area and play a key role as pathways around the city. Here improvements to reduce the
 485 effect of this barrier and allow movement around the outskirts of the centre would benefit
 486 hedgehog populations.



487

488 *Figure 7: The species movement density paths in Sheffield City Centre 2022, with land use type,*
 489 *aerial imagery and contextual basemap for reference (paths are represented by current flow density).*

490 Attercliffe (Figure 8) is historically an industrial area of Sheffield (Hey, 2005), and
 491 similarly shows low current flow in the connectivity map. There are few green spaces or
 492 habitats suitable for hedgehogs in the densest parts where buildings are largest and are
 493 commonly adjacent to car parks rather than gardens. The gardens in the southeast do form a
 494 pathway from the greenspaces and gardens of Handsworth to Brightside. However, at
 495 Brightside, there are several linear barriers preventing or limiting connectivity, Brightside Lane
 496 (the A6109), Attercliffe Common (the A6178), the River Don, and the railway lines.

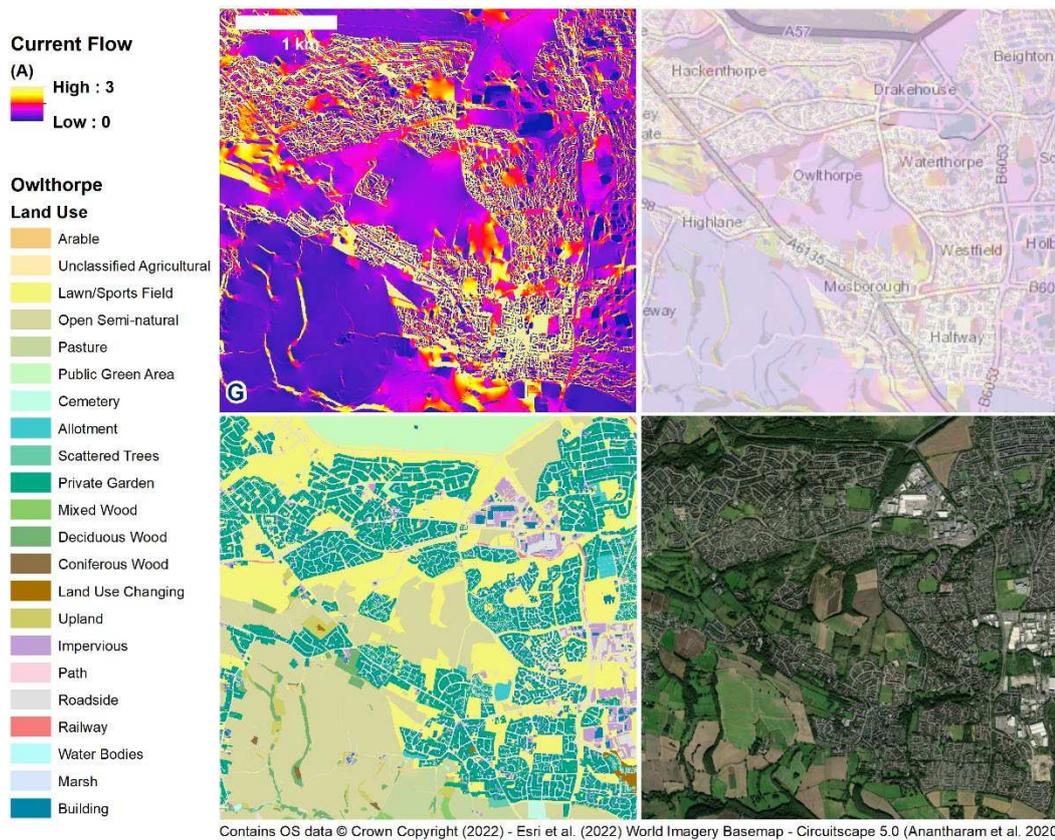


497

498 *Figure 8: The species movement density paths in Attercliffe 2022, with land use type, aerial imagery*
 499 *and contextual basemap for reference (paths are represented by current flow density)..*

500 Finally, Owlthorpe (Figure 9) has multiple pathways from the gardens in Halfway up
 501 through to Hackenthorpe via the field margins surrounding the central area of low current flow
 502 - arable land. It is not a habitat cul-de-sac despite its location closer to the boundary of Sheffield

503 in the southeast due to the gardens maintaining connectivity here.



504

505 *Figure 9: The species movement density paths in Owlthorpe 2022, with land use type, aerial imagery*
 506 *and contextual basemap for reference (paths are represented by current flow*
 507 *density).*

508 4. Discussion

509 4.1 Spatial Strategies for Small and Large Roads

510 The identified pinch points, especially those crossing roads, present potential locations
 511 for improving habitat connectivity. However, determining the most effective methods for
 512 improvement is a complex task, as the effectiveness of wildlife passages and other mitigation
 513 measures requires further long-term research (Mata et al., 2008; Moore et al., 2020).
 514 Nevertheless, strategies for improving connectivity have been tested and implemented both in
 515 the UK and internationally (Jarvis et al., 2019; Velázquez et al., 2019; 2022; Wang et al. 2022).

516 For Redmires Road, the smaller of the two roads crossed by narrow paths of high current in
 517 Lodge Moor (A), hedgehogs are more likely to attempt crossing (Rondinini and Doncaster,
 518 2002; Dowding et al., 2010a). Implementing traffic calming measures in this area would
 519 enhance their chances of successfully crossing the road. These measures could include speed

520 bumps, speed restrictions, or signage specifically designed to raise awareness of hedgehog
521 presence, especially during night-time (Moore et al., 2020). By implementing traffic calming
522 measures on roads like Redmires Road, the risk posed to hedgehogs during their movement
523 can be reduced, enabling safer crossings. Such measures have demonstrated positive outcomes
524 in mitigating the impact of roads on hedgehog populations and promoting their connectivity.

525 Attercliffe (F) also exhibited pinch points where the addition of crossings in those locations
526 would be beneficial to hedgehog movement both north- and southwards. Addressing these
527 pinch points would better connect these two parts of the city, allowing local hedgehog
528 populations in the habitats around Handsworth to access larger patches of core habitat located
529 northwest of Brightside.

530 Major roads, most notably in Attercliffe and the east of Sheffield but also found across the city,
531 are providing additional barriers to connectivity which may require different solutions to target
532 more complex restrictions to species movement. In the city centre and Burngreave, there also
533 exist complex arrays of junctions between several of these large roads and railway lines where
534 locations for hedgehogs to safely cross are few. For larger roads in less dense suburban areas
535 with clearer routes for hedgehog crossings such as the A57, Manchester Road, in Lodge Moor
536 (A) an alternative option to facilitate hedgehog crossings would be the provision of an
537 underpass or culvert. The usage of these passages by hedgehogs has shown varied results in
538 studies. In some studies, hedgehogs were recorded to effectively utilise culverts and
539 underpasses (Ascensão and Mira, 2007; Eldridge and Wynn, 2011; Jarvis et al., 2019), while
540 others have found them to be absent compared to other small mammals (Mata et al., 2008; Puig
541 and Sanz, 2012). The difference in these findings may be down to factors in design and location
542 (Moore et al., 2020).

543 Considering the findings of this study, which provide a reasonable basis for determining
544 suitable locations, the design of the underpasses or culverts becomes crucial. Creating a series
545 of tunnels or passages could be a viable option if the design factors are taken into account.
546 Design considerations such as the size, shape, and accessibility of the passages can significantly
547 influence hedgehog utilization. For instance, hedgehogs have shown a preference for tunnels
548 closer to urban environments, and for wider, more open tunnels short in length (Ascensão and
549 Mira, 2007). Taking these preferences into consideration when attempting to mitigate the
550 barrier effect of the road and connect the pastures and core habitats north and south of the A57

551 would be beneficial. On the other hand, the location of the passages, including their proximity
552 to hedgehog habitats and natural movement corridors, also affects their usage.

553 The solutions to the High Green cul-de-sac are indeed limited, but these major roads
554 are currently restricting movement for hedgehogs in several directions, leaving one main route
555 of movement in and out of the area. To improve connectivity dead-ends such as in this location
556 the area needs to be reconnected to other habitats by providing paths through the landscape and
557 onwards to encourage species and gene flow. The M1 motorway is understandably the biggest
558 barrier here due to its width and traffic volume (Rondinini and Doncaster, 2002; Dowding et
559 al., 2010a) and whilst fencing lowers the amount of roadkill, reducing mortality rates, it does
560 not effectively address the issue of preventing fragmentation and leaves species still at risk of
561 local extinction through isolation and population density falling below a viable level (Ascensão
562 et al., 2019). Underpasses may be an option but their usage by hedgehogs in this location to
563 cross is not certain (Mata et al., 2008), particularly for hedgehogs attempting to across such a
564 wide road. However, if sufficient funding is available, it may be worth experimenting and
565 monitoring for not just hedgehogs but other mammals and amphibians, as tunnels have been
566 particularly observed to benefit these species (Eldridge and Wynn, 2011; Jarvis et al., 2019).
567 Another solution to consider is the construction of an overpass. In Spain, overpasses were
568 exclusively used by hedgehogs to cross the motorways at the studied sites, instead of culverts
569 and underpasses (Mata et al., 2008). Therefore, a green bridge with suitable grass, shrubbery
570 and macro-invertebrate supply as a food source would potentially allow the crossing from east
571 of Chapeltown to other habitat outside of Sheffield. We acknowledge that the feasibility,
572 design, and ecological effectiveness of such infrastructure would require detailed site-level
573 assessments and field-based investigations, including behavioural data and long-term
574 monitoring, although the latter falls beyond the scope of this study. While certain interventions
575 may require longer-term planning and investment, the value of the present analysis lies in
576 identifying priority barrier locations where measures, scaled to local resources and constraints,
577 could deliver meaningful connectivity benefits. In this context, targeted actions could help
578 mitigate one of the most prominent movement constraints in the area.

579 **4.2 Sustaining Habitat Connectivity for Hedgehogs**

580 Areas identified as high in connectivity are important to maintain, given they provide
581 key pathways between Sheffield's habitat patches. In Owlthorpe (G) and its surrounding area
582 there are multiple patches of high current within locations of densely packed gardens connected

583 by agricultural land where despite the east of Sheffield being bounded by the M1 Motorway,
584 they were still able to provide connectivity for urban and rural habitat. Sustaining the current
585 levels of connectivity in these areas may take the form of maintaining field margins in rural
586 areas, such as those in Owlthorpe (G), even during possible changes in the type of agricultural
587 use of the land as they can provide both shelter and higher quantities of food for hedgehogs
588 (Hof and Bright, 2010a; 2010b). Furthermore, maintaining or even adding to the hedgerows
589 would provide increased cover for hedgehogs – particularly males who require them to travel
590 the furthest distances in search of food or mates – provided they are dense enough (Hof and
591 Bright, 2012). Farmland management could play an important role in connecting the gardens
592 of Worrall and Middlewood (B) and landowners may already be aware of or involved in UK
593 agri-environment schemes which encourage the preservation of areas of natural habitats in
594 agricultural landscapes (Natural England, 2018). This type of schemes would greatly benefit
595 the area if they are not already in place. By prioritizing the preservation of field margins,
596 hedgerows, and implementing appropriate farmland management practices, the connectivity of
597 these areas can be maintained, ensuring the continued movement and survival of hedgehog
598 populations in Sheffield.

599 The connectivity of residential gardens in Bents Green is also important, and potential
600 campaigns promoting the creation of hedgehog highways to allow access between garden
601 boundaries or for participants to survey hedgehog sightings as part of wider studies may benefit
602 from being focused here (Gazzard et al., 2021). In this case, improvements would need to be
603 made at an individual landowner scale which may require the efforts of organisations like the
604 PTES Hedgehog Street and Hedgehog Heroes projects appealing to the public to adjust their
605 gardens to make them hedgehog friendly which have seen previous successes already
606 (Wembridge et al., 2022). This may include maintaining natural vegetation type, garden
607 borders which would provide shelter and nesting sites and hedgehog-friendly gardening
608 techniques that would avoid disturbing hibernation in winter months by checking before
609 strimming and before bonfires (Wembridge et al., 2022).

610 In denser urban areas the Ponderosa and other central parks (Crookes Valley, Weston
611 Park) were noted as important green infrastructure for connectivity and play a key role as
612 pathways around the city centre, the value of these spaces in Sheffield should be considered
613 and protected when future land use change is considered. Finally, High Green's position as a
614 habitat cul-de-sac means that south of Chapeltown habitat patches and corridors need to remain

615 connected to avoid isolating a population and any land use changes in this area should be
616 carefully thought through with habitat suitability in mind, so as not to create new barriers.

617 **4.3 Connectivity for hedgehogs across various levels**

618 The areas identified with high levels of connectivity, Middlewood (Figure 4) and Bents
619 Green (Figure 5), are characterised by areas of urban greenspace and rural-non moorland which
620 allow flow density to be spread across a wider area rather than funnelled through unique
621 pathways. The absence of a major barrier keeps routes open and allows for the high
622 connectivity seen where there are multiple residential front and back gardens connecting in
623 multiple directions. With lower-risk access roads not presenting a major barrier, the gardens
624 can be accessed from multiple routes. This is similarly seen where the pasture in Middlewood
625 connects the residential gardens in two locations, expanding the habitat where alternative land
626 uses could have separated these two groupings of gardens.

627 In contrast, areas of low connectivity, such as the city centre and Attercliffe had low
628 current flow as a result of their largely unsuitable land use and land cover with regard to
629 hedgehogs. The density and area of greenspaces here were lower resulting in less potential
630 habitat and reduced species movement in the areas. The landscape characteristics created
631 higher resistance for hedgehog populations attempting to traverse these areas, making them
632 more inclined to avoid such regions. The combination of inadequate greenspace availability
633 and less favourable land use contributes to the reduced connectivity observed in these areas.

634 Land use and cover of the area itself was not the only factor resulting in habitat
635 connectivity, at a glance High Green and Chapeltown have the run of residential gardens,
636 public greenspaces, and pasture yet they showed drastically lower levels of current flow than
637 comparable areas of land use in Sheffield seen in Middlewood and Bents Green. This
638 discrepancy highlights that the suitability of potential habitat for hedgehogs is not solely
639 determined by its presence but also by its accessibility.

640 A notable factor affecting connectivity is the presence of barriers. In the case of
641 Sheffield, areas outside the city's boundaries and in close proximity, while suitable in terms of
642 habitat, are disconnected due to the presence of the M1 motorway. This restriction results in
643 limited species flow, allowing movement in only one pathway in and out, effectively creating
644 a cul-de-sac for connectivity. The potential habitat being suitable for hedgehog populations is

645 limited by how reachable it is, habitat outside of Sheffield's boundary yet near in Euclidean
646 distance is disconnected due to the presence of the M1 motorway.

647 **4.4 The implications and challenges of urban green infrastructure planning for** 648 **connectivity and biodiversity**

649 The findings revealed from 3.1 to 3.4 have primarily shown the need for built
650 environment improvement in urban areas, including for small roads, large roads, and bridges.
651 However, we also identified the pressing demand for urban GI development and enhancement,
652 including but not limited to, private gardens, allotments, community gardens and public parks
653 which all act as either suitable habitat for hedgehogs or as land able to connect core habitat
654 areas by acting as corridors across otherwise dangerous urban infrastructure. To improve their
655 habitat quality in addition to their quantity and interconnectedness, land use management
656 practises such as the introduction of new plants to promote insects vital to the food chain of
657 hedgehogs and which drive their movement paths (PTES and BHPS, 2015) and the placing of
658 shelters (Wembridge et al., 2022) for hedgehogs in places where corridor pathways are broken,
659 can improve not only connectivity but the overall biodiversity of GI. Vegetation management
660 to address biodiversity conservation is beneficial for multiple species and the enhancement and
661 protection of corridors would improve connectivity for not just hedgehogs but also the wider
662 ecosystem they are part of (Cork et al., 2024). There are further wider implications of
663 improving GI in addition to benefitting species that utilise it as core habitat and corridors for
664 movement, as these planning initiatives can be combined with addressing existing challenges
665 in urban planning such as the social equity of access to urban GI (Kimpton, 2017; Wang et al.,
666 2019), its effect on health and wellbeing (Bertram and Rehdanz, 2015), and its wider
667 environmental impacts (Wang et al., 2019; Wang et al., 2022; Pauleit et al., 2020) associated
668 with improved and increased availability of urban GI.

669 Currently, national conservation practices for hedgehogs are focused on adapting
670 existing greenspaces and encouraging the public to make their private gardens more hedgehog-
671 friendly (Wembridge et al., 2022), such as by adding hedgehog highways to allow for small
672 holes in fences and other barriers that will allow hedgehogs to move freely across blue and
673 green networks. Hedgehogs are part of the UK Biodiversity Action Plan (BAP) and are
674 recognised as a priority species in need of conservation efforts. However, they are only listed
675 under Schedule 6 of the Wildlife and Countryside Act, which means that whilst they are
676 protected from intentional harm, there is no legal requirement for developers to search for

677 hedgehogs on their sites during development (PTES and BHPS, 2020). While the European
678 Hedgehog is classed as near-threatened on the IUCN red list, and at risk in Great Britain, there
679 seems to be insufficient comprehensive land management policy to directly address the causes
680 of their decline. More could still be done to protect and restore core habitats, as their
681 populations continue to decline alongside the extent and quality of their habitat (Gazzard and
682 Rasmussen, 2024). Urban GI planning as a significant solution to addressing the connectivity
683 for biodiversity conservation should respond more actively to this pressing need. More widely,
684 other international policies in Europe offer similar protection to hedgehogs from harm directly
685 by humans. For example, in Poland and Denmark, hedgehogs are protected and receive some
686 protection under the Berne Convention. However, there are few explicit policies to repair
687 habitat lost to fragmentation and address decreasing hedgehog populations. To meet goals such
688 as those set by the Global Biodiversity Framework to reverse biodiversity loss by 2050,
689 improvements to habitat and its connectivity in growing urban environments need to be
690 implemented. The connectivity suggestions made by this study for Sheffield could potentially
691 feed into wider practical biodiversity conservation efforts needed to integrate the outputs of
692 theoretical connectivity models with real-world biodiversity improvements (Correa Ayram et
693 al., 2016).

694 To achieve these strategies on a larger scale and to address fast-paced development in urban
695 areas adding to habitat fragmentation, developers, conservation workers and policy makers will
696 need to implement biodiversity-inclusive spatial planning (IPBES, 2024) where the effect on
697 connectivity pathways and habitat quality are considered.

698 Overall, the contribution of this study should be understood in terms of how established
699 connectivity methods are operationalised and translated into planning-relevant evidence, rather
700 than as the introduction of a new modelling technique. First, we demonstrate how high-
701 resolution, up-to-date spatial data, combined with local observational records, can be used to
702 produce fine-scale connectivity outputs that are directly interpretable for urban decision-
703 making. Second, Sheffield is used as a representative urban setting that exhibits an urban–rural
704 gradient and transport-related fragmentation patterns that are common in many cities
705 internationally, rather than as a uniquely UK-specific case. Third, we provide a planning-
706 oriented integration by linking circuit-based outputs (e.g., corridors and barrier locations) to a
707 prioritisation logic that can inform biodiversity-inclusive spatial planning across different
708 governance and budget contexts.

709 Importantly, the key takeaways are transferable beyond the UK, namely the workflow for
710 identifying connectivity constraints, locating transport-related barriers, and prioritising
711 intervention locations can be applied in other cities (including non-UK contexts), while the
712 specific policy instruments and land-use classifications should be adapted to local planning
713 systems and datasets. In this sense, the study supports nature-positive urban design and
714 sustainable infrastructure planning by strengthening the evidence base for spatially targeted
715 actions that are most likely to deliver connectivity gains.

716 **4.5 Limitations**

717 This study highlights Sheffield as a city with significant potential for recovering urban
718 populations of Western European hedgehogs. While certain assumptions were made in the
719 analysis process, which may affect the modelled connectivity, the study has picked up on areas
720 where further research or conservation efforts may be worthwhile. This study underscored
721 several areas of interest regarding connectivity, but these were not exhaustive, other areas
722 showing similar patterns to those observed could benefit from their own similar
723 recommendations at a local scale using the current flow map (Figure 2).

724 One potential limitation of the land use map and model were the 2D nature of the
725 landscape representation, exact points where hedgehogs may cross are difficult to pinpoint
726 from the modelled current flow results and the site would be a good location for a ground-
727 based study to take into account the overpasses and bridges and determine real world hedgehog
728 usage. Additionally, the assumption of patch homogeneity, where a uniform value was assigned
729 per patch based on land use attribute, may overlook potential edge effects and variations in
730 movement costs (Wang et al., 2019) based on direction travelled through the patch. Future
731 research may need to move towards the use of more detailed and more frequent geospatial data
732 which can capture smaller components of greenspaces such as bushes, roadside flower beds,
733 scrubs, hedgerow and front courtyards relevant to hedgehogs as shelter potentially through
734 drones to provide this higher resolution to capture and model more complex aspects of the
735 landscape.

736 It is important to acknowledge that circuit theory assumes omniscience (Almenar et al.,
737 2019; Hashemi, et al., 2024) in that an individual has complete knowledge of the landscape
738 and will always make ideal choices or know their destination—a scenario that may not align
739 with the actual behaviour of the species. As such, it is crucial to note that connectivity as

740 analysed in this study is subject to the limitations of circuit theory and the methodological
741 decisions made.

742 **5. Conclusions**

743 The aim of this study was to assess habitat connectivity for hedgehogs in Sheffield by
744 utilising the most recent, high-quality data and methodologies available. The findings indicate
745 that suburban areas of Sheffield, particularly in the west, exhibit well-connectedness due to the
746 presence of Sheffield's private gardens and public greenspaces. Whilst the upland moorlands
747 are largely unsuitable for hedgehog habitat requirements, the rural outskirts of Sheffield,
748 specifically pastureland, natural vegetation areas, hedgerows, and deciduous woodland, serve
749 as key pathways between the gardens that urban populations of hedgehogs are likely to use and
750 important habitats for declining rural populations.

751 To further advance our understanding, future monitoring efforts focusing on both rural
752 and urban hedgehog population density, particularly in the northwest of Sheffield, would
753 provide valuable insights. Additionally, monitoring of badger tracks would add to the accuracy
754 of the actual ease of movement in this region. The study results reveal movement patterns of
755 hedgehogs and highlight the broader areas where connectivity is either too high or low,
756 emphasizing the importance of ground-level and place-based monitoring to validate the model
757 outcomes and observe local hedgehog populations.

758 These findings provide valuable and evidence-based guidance for directing future initiatives
759 aimed at enhancing hedgehog populations and promoting their habitat connectivity not only in
760 Sheffield but also in other areas. By considering the connectivity needs of hedgehogs,
761 conservation efforts can be targeted effectively, contributing to the preservation of this species
762 and the wider biodiversity of the ecosystems they inhabit – addressing connectivity issues faced
763 by multiple species and helping to guide spatial planning with biodiversity and habitat
764 connectivity in mind.

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768

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