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Assessing habitat connectivity in environmental impact assessment: a case-study in the UK context

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ABSTRACT
Ecological connectivity across landscapes is vital for the maintenance of biodiversity and the processes that enable life on earth. Despite this, environmental planning decisions are usually made at the scale of individual projects, failing to account for landscape-scale impacts. Incorporating habitat connectivity analysis in Environmental Impact Assessments (EIAs) could provide an opportunity to address this gap. We present a novel approach to model habitat connectivity in an EIA undertaken for the Heathrow Third Runway Expansion Project, a proposed development in south-east England. Drawing on field data, remote sensing, and species-specific literature reviews, a circuit theory approach was used to assess functional connectivity across the project landscape for grass snakes *Natrix helvetica* and soprano pipistrelles *Pipistrellus pygmaeus*. Results indicated key areas for species movement and potential 'pinch-points' vulnerable to development impacts. We discuss lessons learnt, potential applications to inform impact assessment, mitigation design, and biodiversity net gain approaches, and further work required to mainstream connectivity analyses in EIA and decision-making.

Introduction

Biodiversity loss is occurring at an unprecedented rate across the world, primarily caused by land-use change, habitat loss, and fragmentation (Butchart et al. 2010; IPBES 2019; World Economic Forum 2021). This is often driven by infrastructure development, which can open up new areas to environmental threats, or further fragment already developed zones (Bekker and luell 2003; IPBES 2019).

Ecological connectivity is the free movement and flow of species and the underlying natural processes that enable life on earth (CMS 2020; Hilty et al. 2020). This includes gene flow, metapopulation dynamics, range expansion, and seed dispersal and is determined by habitat connectivity – the degree a landscape enables or hinders movement between resource patches (McRae et al. 2008). The loss and division of habitats through fragmentation creates smaller, more isolated patches (Scolozzi and Geneletti 2012). This can result in changes to ecosystem dynamics which affect the persistence of many plant and animal populations.

The range of methods used to measure habitat connectivity has steadily increased in recent decades (Hilty et al. 2020), reflecting the importance of landscape-scale connectivity for biodiversity. But despite a growing recognition of this in conservation practice, law, and policy, environmental planning and permitting decisions generally continue to be made at the scale of individual infrastructure and development projects (Hilty et al. 2020; Harker et al. 2021). This is often in the context of environmental impact assessments (EIA), a process that emerged in the 1970s to assess potential environmental implications of proposed actions, ranging from policies to projects (Morgan 2012).

EIA is now a legal requirement for large projects in many countries across the world and is a condition of numerous international lenders. Various best practice guidelines relating to biodiversity impact assessment have been published and generally apply the mitigation hierarchy, often with the aim of achieving no net loss or net gain of biodiversity (IFC 2012; Hardner et al. 2015; CIEEM 2018; Phalan et al. 2018). This framework requires developers to first design mitigation which avoids impacts, before aiming to minimise remaining impacts, restore affected areas and, finally, offset residual impacts. However, the EIA and mitigation hierarchy processes have been criticised for failing to adequately address landscape-scale effects (Tarabon et al. 2019a; Bergès et al. 2020). A recent study found that connectivity continues to be poorly integrated in the EIA process, despite the importance attributed to it by the vast majority of practitioners (Patterson et al. 2022).

Without effectively incorporating habitat connectivity in EIA, mitigation for the avoidance and reduction of

negative biodiversity impacts fail to consider population-level implications or the extent to which remaining or compensatory habitats will be ecologically functional (Harker et al. 2021). This can contribute to unanticipated long-term effects on species in the project area, as well as cumulative effects from multiple projects within the wider landscape. This gap in EIA practice contrasts with the huge growth in quantitative connectivity metrics within academia and mounting calls to increase connectivity to improve nature conservation across degraded landscapes (Lawton et al. 2010; Bergsten and Zetterberg 2013; Hilty et al. 2020).

The need to undertake an EIA in the UK is determined by the type and scale of a project. In England, this is primarily driven by the Town and Country Planning (Environmental Impact Assessment) Regulations 2017, with specific separate legislation relevant to certain development types (MHCLG 2014). However, there is no explicit requirement for EIA to include habitat connectivity analysis, and it is not known whether planned reforms to EIA will introduce connectivity as a consideration (MHCLG 2020).

The UK government commissioned report and subsequent policy document highlighted 'bigger, better and *joined up*' sites for more resilient and effective ecological networks (Lawton et al. 2010; Defra 2018). Meanwhile, the latest National Planning Policy Framework (NPPF) refers to safeguarding 'wildlife corridors and stepping stones' and promoting 'the conservation, restoration and enhancement of … ecological networks' (MHCLG 2021). Despite this, consistent quantitative implementation has proven challenging.

Incorporating connectivity in the planning process was to be undertaken through biodiversity net gain (BNG), which has been mandated in the UK's new Environment Act (UK Parliament 2021). It should also be an important consideration in Local Nature Recovery Strategies, a system of spatial strategies for nature which are to be created in support of BNG (Defra 2021). BNG aims to leave biodiversity in a better state than before a development is undertaken and is applied using a defined metric. Natural England (the English government's adviser for the environment) published a beta version of the 'Biodiversity Metric 2.0' in 2019, which included a connectivity component. However, testing found that the connectivity tool was unreliable and overly complicated, with quantitative connectivity analyses removed from the process, not being included in the most recent 'Biodiversity Metric 3.1' (Natural England 2020, 2022).

Difficulties in integrating habitat connectivity in BNG and EIA in the UK reflect an acknowledged lack of practical tools for incorporating and conveying quantitative ecological analyses in the planning process (Sandström et al. 2006). This, coupled with difficulties in how to objectively measure losses and gains in connectivity, also hinders the establishment of policy and requirements for its inclusion in the planning process (Patterson et al. 2022). In the face of these challenges, there remains an urgent need to evolve from assessing biodiversity impacts of projects at a local scale, to recognising and addressing impacts at larger geographical scales, including habitat connectivity and fragmentation (Bergsten and Zetterberg 2013; Bergès et al. 2020).

This study aimed to pilot a new methodology to quantitatively assess habitat connectivity as part of the EIA for a Nationally Significant Infrastructure Project (NSIP) in the UK – the Heathrow Third Runway Expansion Project (HEP). The HEP was put on hold in 2020; however, significant steps had been taken in conducting the project's EIA, including design and initial implementation of habitat connectivity analysis in the baseline biodiversity assessment. If constructed, the proposed development, located in the heterogeneous landscape of south-east England, is anticipated to alter the area's habitats and species. This includes habitat clearance; demolition of existing infrastructure; construction of new infrastructure; and the creation of habitats through European Protected Species (EPS) mitigation areas; green infrastructure; and biodiversity offsetting areas. Species populations and their movement will be affected positively and negatively, with the need to assess ecological connectivity highlighted in the first stage of the project's development consent process (The Planning Inspectorate 2018).

This paper details the approach taken, and results gained, from what is to our knowledge the first quantitative assessment of habitat connectivity in a UK EIA (Supplementary Table S1). In particular, we present:

(1) The process undertaken to select appropriate tools and methods to assess connectivity;
(2) Methodological steps and results for the HEP; and
(3) A discussion of the benefits and limitations of our approach and lessons for mainstreaming connectivity assessment in EIA and planning.

Methodology

The HEP was a proposed infrastructure project to develop a new, full-length runway and associated facilities at Heathrow Airport, a major international airport in London, UK (LHR Airports Ltd 2019). Considered

a NSIP, an EIA was required as part of an application for a 'development consent order'. Though currently on hold, the runway was scheduled to open in 2026, with full completion in 2050. The project plans had four phases, with a complex construction phase lasting several decades, including the movement of existing large infrastructure assets within the surrounding area.

The study area for the habitat connectivity analyses consisted of a defined Connectivity Study Area (CSA) of 8,523 ha surrounding Heathrow Airport (51°28′N, 0°27′W) and encompassing the 5,923 ha ecological study area (ESA) considered for other aspects of the biodiversity impact assessment in the project EIA (Figure 1). This larger CSA was required to allow modelling of species movement in the wider landscape. The area is highly modified, consisting of a mix of anthropogenic and semi-natural habitat types fragmented by

infrastructures such as roads, industrial areas, and residential areas.

Based on legislative requirements for protected species, availability of baseline data, and consultation with Natural England, nine species and one species assemblage were selected for inclusion in connectivity analyses to inform the EIA. In this paper, we focus on two of these species: grass snake *Natrix helvetica* and soprano pipistrelle *Pipistrellus pygmaeus*. These have been chosen to represent orders with different range sizes and forms of movement across landscapes. The bat species (Order Chiroptera) is capable of aerial movement, in contrast to the terrestrial reptile species (Order Squamata) which has a more limited ability to traverse habitat barriers. However, both have an affinity to linear connecting features such as waterways to move across a landscape.
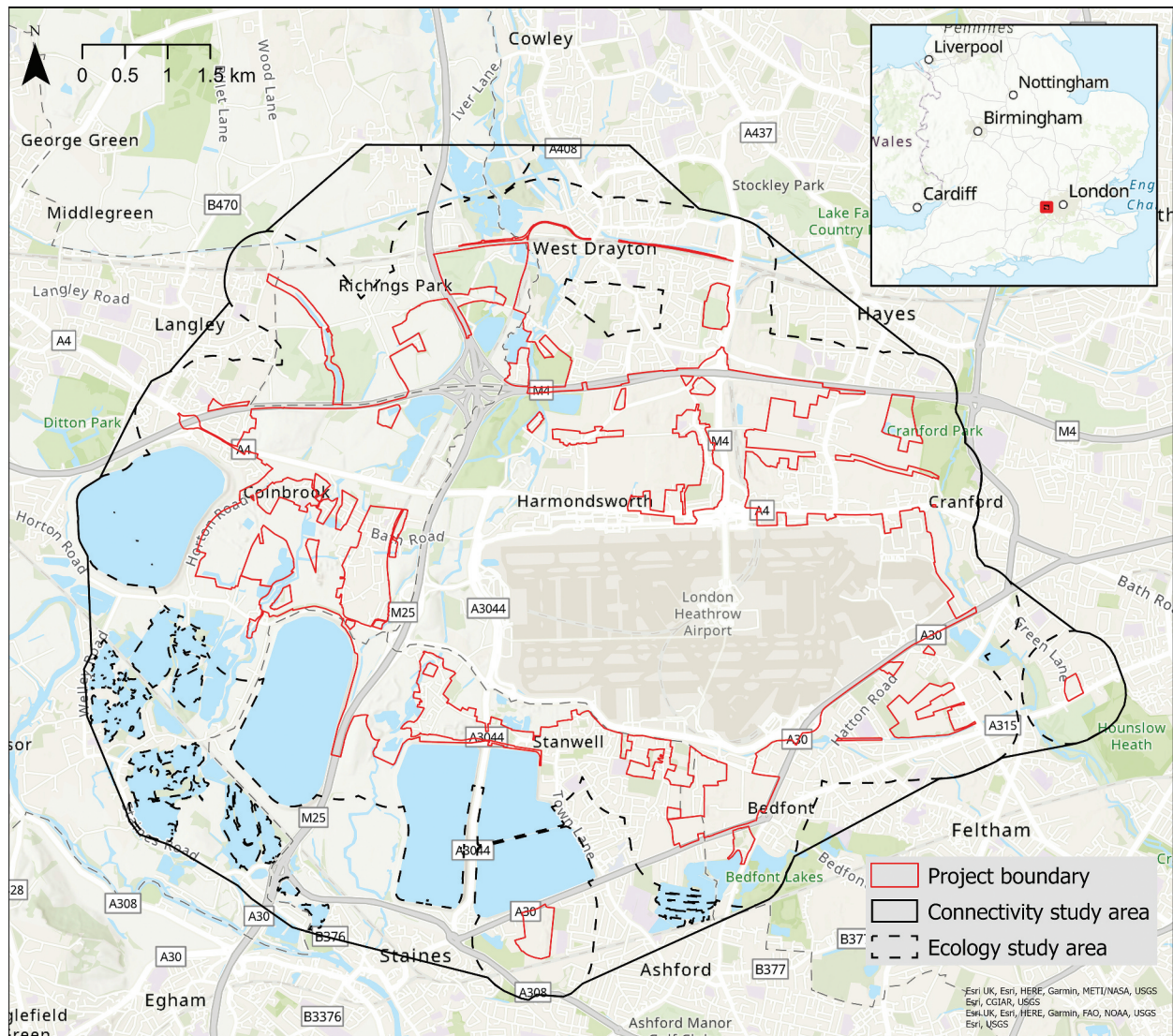

Figure 1. Connectivity study area and other relevant boundaries of the Heathrow Third Runway Expansion Project (HEP), based on design plans in 2019 (LHR Airports Ltd 2019).

Landscape connectivity metrics have generally been developed to measure one of two main features: *structural* connectivity (the physical relationships between habitat patches in a landscape), or *functional* connectivity (response to the landscape by biological elements, such as species) (Mühlner et al. 2010; Hilty et al. 2020). Within these, a range of tools, and resources have been developed, with the choice of the most appropriate being context dependent (Conservation Corridor 2021). We undertook a screening process to determine the most suitable approach for this study. This included assessing the data requirements and availability of eight connectivity tools, including both structural and functional connectivity approaches. We scored them on three criteria linked to our objectives: (1) production of visuals; (2) quantifiable outputs for impact assessment and mitigation design; and (3) low-cost or freely available.

Two tools were brought forward and trialled in an initial pilot study: Circuitscape v4.0 (McRae et al. 2013) and Conefor v2.6 (Saura and Torne, 2009). For the pilot study, a demonstrative habitat connectivity assessment was undertaken on a limited number of species using habitat, scheme design, and ecological survey data available at the time. Both tools were reviewed for their appropriateness for use across the wider HEP and Circuitscape was selected, primarily due to its ability to consider specific blockers to connectivity such as major roads.

Circuitscape is an open-source package which applies the functional connectivity approach through 'circuit theory'. This treats landscape features as an electrical circuit with varying levels of 'resistance' (McRae et al. 2008), considering least-cost flow pathways to determine a species' likelihood of moving through different land cover types between habitat patches. This has been shown to effectively predict biodiversity in urban environments (Grafius et al. 2019). Outputs are relevant at the individual species level and can be applied to identify areas which are important for connectivity in a landscape, including the production of visuals to map levels of flow.

Circuitscape requires two main inputs to assess connectivity for a species. Firstly, a 'resistance map' in raster format, where each raster cell is assigned a value indicating the relative difficulty of a species' movement based on the habitat present. Secondly, the definition of patches between which species movement is modelled, referred to as 'nodes'. The steps taken to define these inputs are summarised in Figure 2 and detailed as follows.

A land cover map at 2 m resolution was used for the analyses in this study, created using a combination of field surveys and existing mapped data. Field surveys applied the Phase 1 Habitat classification system,
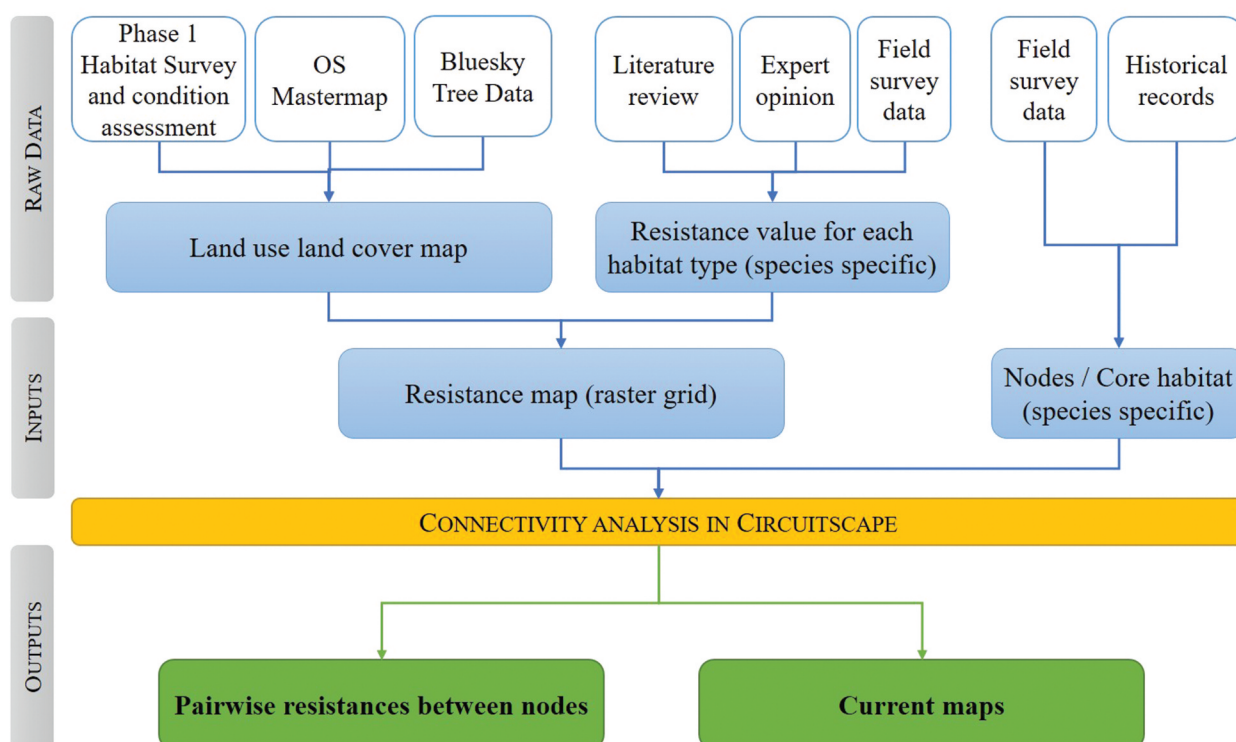

Figure 2. Sources of input data, stages of data preparation, and outputs following analysis in Circuitscape for each species assessed.

a standard technique for habitat survey across the UK (JNCC 2010). Surveys were completed in the HEP site between April 2017 and October 2019, covering 3,341 ha (40% of the CSA). To account for areas not surveyed due to access restrictions, field data were combined with computer-generated land cover values from Ordinance Survey MasterMap (Ordnance Survey 2019). It used standard MasterMap metadata including descriptive group, descriptive term, and features to predict the Phase 1 land cover type present.

Land cover maps were cleaned and converted from vector shapefiles to a 2x2m raster grid layer before analysis. This required editing certain habitat types to allow for appropriate handling by Circuitscape, including buffering tree point data to their canopy area extent based on the National Tree Map (Bluesky 2019); buffering linear data (e.g. hedgerows); and allocating areas with overlapping habitat polygons to the habitat with higher potential connectivity. All data handling and manipulation was undertaken using ArcGIS Pro 2.2.0 and earlier versions (Esri Inc 2021).

As part of the project's EIA baseline data collection, extensive surveys were undertaken across the ESA during appropriate field survey seasons between April 2017 and October 2019. These applied methodologies are recognised as best practice for each species surveyed. For bat species, surveys included activity surveys, external and internal building inspections, tree inspections and aerial surveys, emergence/re-entry surveys of built structures and trees, radiotracking surveys, and underpass surveys, as appropriate according to Collins (2016). For reptile species, the methods followed the Herpetofauna Workers' Manual (Gent and Gibson 2003), with scoping surveys undertaken, followed by presence/absence surveys applying direct observation and searches of both existing and artificial refugia.

Resistance values were assigned to the land cover map based on the Phase 1 habitat type present and the habitat's suitability for the movement of each species. These values were based on data from published literature and field surveys, alongside the expert opinion of lead field surveyors (Figure 2). Habitat types were grouped where appropriate according to similarity in their suitability as connecting habitat, with the groups then ranked in order of importance before being assigned a value ranging from 1 to 100, with 1 being the lowest relative resistance to movement and 100 being the highest.

The selection of nodes representing core habitats for each species was based on a combination of confirmed species presence from field data and predicted habitat suitability (Supplementary Material Figure S1).

Where several presence records existed within a certain habitat area, the entire area was assigned as a single node. In areas within the CSA where field surveys were not possible, core nodes were identified based on a combination of historical records from local records centres (Greenspace Information for Greater London, Thames Valley Environmental Records, and Surrey Biodiversity Information Centre) and habitat suitability, the latter based on the extrapolation of survey results and in consultation with species experts involved in the HEP EIA (Figure 2).

All data were based on pre-construction baseline conditions. They were inputted into Circuitscape to analyse the state of landscape connectivity in the study area before the construction of the HEP.

Results

The study area consisted of a wide range of habitat types. This included semi-natural habitats such as woodlands, grasslands, and wetlands, as well as extensive areas of highly modified habitats such as quarries, reservoirs, major roads, and other built infrastructure. Dominant habitats in the ESA were hardstanding (19.2%) and standing water (22.7%), primarily reservoirs. The total coverage of all grassland types was 29.1%, all woodland types was 5.6% and scrub was 2.9%.

Resistance values for *P. pygmaeus* and *N. helvetica* were assigned to each habitat type (Table 1). Results of a literature review indicated that riparian zones are important commuting and feeding habitats for soprano pipistrelles, which primarily feed in wetland areas (Nicholls and Racey 2006) and their preference for linear features and semi-open habitats compared to dense canopy has been frequently observed (Bartonička and Řehák 2004; Rachwald et al. 2016). While individuals are unlikely to successfully cross major roads and large, open industrialised areas, there is potential to do so due to their aerial movement. These findings were reflected in the low resistance values assigned to wetland habitats and higher values given to woodlands compared to hedges and grasslands. Meanwhile, highly modified areas such as major roads were allocated very high resistance values, but not made complete barriers to connectivity (Table 1).

Grass snakes are also associated with aquatic habitats and wetlands but also occur in a range of other habitats, particularly grassland, heathland, and open woodland, with the transitional zones between habitats being important (Edgar et al. 2010). While they are capable of crossing roads and are known to use man-made structures for basking, there is a mortality risk associated with this and large open areas without cover are likely to be avoided (Ciesiołkiewicz et al. 2006). This was reflected in the resistance values assigned for habitat types (Table 1).

Table 1. Resistance values* assigned to the connectivity study area land cover map for *Natrix helvetica* and *Pipistrellus pygmaeus*. Habitat types are based on the Phase 1 Habitat survey methodology, with some modifications and grouped classifications.

Habitat Type	*N. helvetica* [a]	*P. pygmaeus* [b]
Broadleaved or mixed woodland and parkland	45	60
Coniferous woodland	55	80
Scrub – dense/continuous	10	10
Semi-improved grassland	10	30
Improved grassland	15	50
Marsh, marshy grassland and swamp	1	1
Continuous bracken	65	85
Ruderal	20	50
Marginal and inundation vegetation	25	1
Standing water	1	1
Running water	25	1
Quarry	75	90
Spoil	85	90
Arable land	75	90
Amenity grassland	75	85
Ephemeral/short perennial cultivated land	45	50
Introduced shrub	85	80
Intact hedge or defunct hedge with trees	15	10
Defunct hedge	25	50
Buildings	99	99
Bare ground	75	95
Hardstanding	85	95
Major roads, runway and refuse tip	99	95

* Values based on combination of field data, expert-knowledge, and species-specific literature reviews, including: [a] (Ciesiołkiewicz et al. 2006; Edgar et al. 2010); [b] (Bartonička and Řehák 2004; Nicholls and Racey 2006; Bartonička and Řehák 2004; Rachwald et al. 2016)

Selection of core nodes resulted in 21 nodes for soprano pipistrelle and nine nodes for grass snake across the CSA (Figure 3). Soprano pipistrelle nodes were primarily based on locations of roosts in trees and buildings as well as key foraging sites recorded during baseline field surveys for the HEP EIA. Grass snake nodes were primarily based on areas where high population numbers were recorded (Supplementary Material Figure S1). Habitat suitability and historic records were also taken into consideration for node allocation in areas where field surveys were not possible.

Connectivity modelling using Circuitscape resulted in maps of 'cumulative current' across the CSA of the HEP (Figure 3). Current intensity is a proxy for potential species movement between each pair of core habitats. These maps therefore illustrate which elements and locations in the study area landscape are the most important for connectivity for each species, denoted by higher current value (shown in darker red).

Predicted movement patterns were clearly affected by the location of nodes. Current values for both species were highest in the area directly west of Heathrow Airport, where many nodes for both species were located. Current values for grass snakes were extremely low across the east of the CSA, where no core nodes were allocated based on baseline field data (Figure 3a). Conversely, pockets of high current value are shown for soprano pipistrelles due to the presence of some nodes in this area (Figure 3b). However, certain soprano pipistrelle nodes located in the east and south of the CSA appear to be isolated, with very low connectivity modelled between these and other core populations. This indicates that the habitats present in this part of the study area are generally less suitable for the species' movement.

For both species, the importance of aquatic habitats and linear features are clearly visible. Areas of both standing and running water and adjacent habitats such as scrub, woodland, and grassland display the highest predicted connectivity.

Across the landscape assessed, current values between core nodes were greater for soprano pipistrelle (maximum 67.9; mean 21.1) than for grass snake (24.2; 17.0). This indicates that overall, the habitats present around the proposed HEP provide better connectivity for the bat species than the snake. However, the degree of variation in connectivity between nodes was also far greater for soprano pipistrelle (SD 16.1) than for grass snake (SD 4.5). Additionally, current values are strongly influenced by the number of assigned nodes, with these results therefore reflecting the higher number of nodes identified for soprano pipistrelle.

To allow more standardised comparisons between the species, current values from Circuitscape were therefore rescaled to a minimum of zero and a maximum of one, as per Grafius et al. (2017). The mean connectivity was found to be greater for grass snake (mean 0.58; SD 0.26) than for soprano pipistrelle (0.32; 0.23) after rescaling.
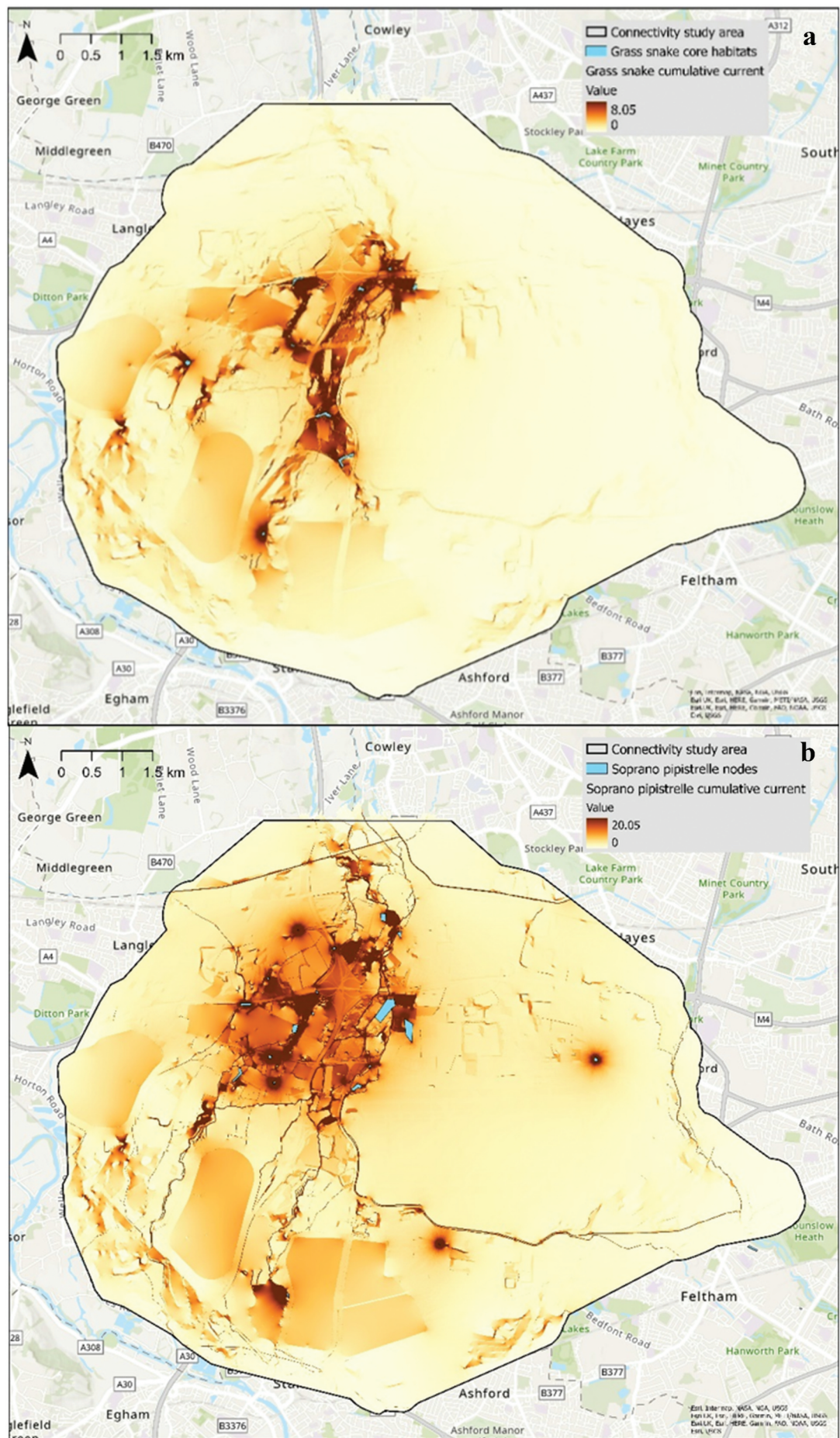
Figure 3. Core habitat nodes and modelled cumulative current indicating connectivity patterns across the baseline study area of the Heathrow expansion project, London for (a) grass snake *Natrix helvetica* and (b) soprano pipistrelle *Pipistrellus pygmaeus*. Currents are displayed by histogram equalisation.

Discussion

This study demonstrates how a circuit theory approach can be used to quantitatively assess habitat connectivity in Environmental Impact Assessments (EIAs). Our results from the Heathrow Third Runway Expansion Project EIA demonstrate that data collected for baseline biodiversity assessments can inform quantitative models of species movement across a fragmented landscape.

The work presented in this study focused on just two of the nine species included in connectivity analyses for the EIA – soprano pipistrelle and grass snake. Additionally, as the HEP was put on hold in 2020, connectivity analysis across the study area was only undertaken for the EIA baseline, with project plans not sufficiently developed to assess impacts or inform the design of mitigation, enhancement, and offsetting. In this section, we discuss the results of our analysis, benefits and limitations of the approach taken, its potential wider application in EIA, and future research and steps required to mainstream connectivity considerations in planning decisions and UK EIA policy.

Grass snake and soprano pipistrelle provided case study species with overlapping habitat preferences, but different means of movement and occurrence within the study area (Table 1; Supplementary Figure 1), allowing for inter-species comparisons to be made. The 'cumulative current maps' show that especially for soprano pipistrelle, linear features are particularly important, with waterways and their adjacent habitats acting as corridors to more isolated nodes in the CSA (Figure 3). These corridors represent potential 'pinch-points' where connectivity may be most vulnerable (Grafius et al. 2017). Identifying these locations therefore provides vital information to inform mitigation measures for the avoidance and minimisation of project impacts on these species, particularly in relation to landscape connectivity.

The number and location of nodes defined noticeably affected results, reflecting findings by Grafius et al. (2017). Mean current values indicated that overall connectivity in the CSA was higher for grass snake than for soprano pipistrelle, despite a smaller distribution of known records for grass snake across the landscape. This may be due to the outlying nodes for the pipistrelle species being poorly connected to other nodes (Figure 3), decreasing the overall mean and increasing the variability of current values across the CSA. This highlights a potential challenge of connectivity modelling – as modelled resistance values focus on pairwise connections between nodes, the choice of their location strongly determines outcomes, therefore requiring sound data and evidence (McRae et al. 2008). However, the connectivity gaps which this study highlighted between nodes can also be of importance to inform mitigation measures. This includes design of restoration and enhancement, where the identification of areas with poor connectivity between known populations of soprano pipistrelle provides a visual tool to inform where new habitat creation can be most effectively located.

The visual representation of connectivity provided by the cumulative current maps has numerous potential applications for impact assessments across the entire mitigation hierarchy and to help achieve the goal of BNG (Figure 3). Identifying important but vulnerable areas for connectivity between core nodes can inform spatially explicit assessments of fragmentation impacts and the design of avoidance and minimisation measures. In the evaluation of alternative construction and mitigation designs, undertaking quantitative analyses of connectivity allows for more objective, landscape-level decision-making compared to current biodiversity assessments which are primarily based on habitat maps and species records alone (Bergès et al. 2020).

A better understanding of landscape connectivity is also important for habitat restoration, enhancement, and offsetting. These are necessary for BNG, with studies indicating that considering connectivity in offsetting design leads to better outcomes for biodiversity (Tarabon et al. 2019b). Connections between habitats can therefore be restored or created in order to meet net gain requirements (IFC 2012), which was a key objective of the HEP. While differences in species traits require that modelling is undertaken per species, combining cumulative current maps could allow commonly occurring areas of low connectivity and fragmented habitat patches to be identified. These could be targeted for the siting of habitat creation, with their design considering the habitat types to be connected. Such approaches would strengthen habitat connectivity both within a project's boundary and as part of the wider landscape.

The visual outputs from Circuitscape can also create useful content for stakeholder engagement. This includes incorporating local knowledge in parameterisation during the modelling process itself (Tarabon et al. 2019a) and using mapped visuals during public consultation to demonstrate the assessment process and potential impacts of alternative designs (Pietsch 2018).

Through addressing impacts of policies, plans, and programmes, incorporating habitat connectivity assessments in Strategic Environmental Assessment (SEA) could have a role in supporting biodiversity outcomes at a scale beyond EIAs. The importance of landscape-scale processes in habitat connectivity means that SEA for network and corridor plans could allow

more meaningful identification of cumulative impacts or opportunities (Fischer 2006; Mallarach and Marull 2006). With SEA increasingly integrating wider sustainability issues, such an approach would enable more strategic planning for biodiversity, supporting emerging UK Government approaches to set long-term targets and preventative action to avert environmental damage (Faith-Ell and Fischer 2021; UK Parliament 2021).

BNG goes beyond the traditional mitigation hierarchy aims of avoiding and minimising loss to nature, aiming to leave the natural environment in a better state than before a development is undertaken. It is increasingly adopted as a requirement of international finance institutions and national governments (IFC 2012; UK Parliament 2021). Truly achieving a net gain is complex, with an urgent need for planning decisions to account for landscape-scale processes (Bergès et al. 2020; Harker et al. 2021). However, attempts to incorporate connectivity in the UK's Biodiversity Metric for BNG have proven challenging (Natural England 2020). In this study, we have shown that modelling based on circuit theory can be incorporated within the EIA process to quantify habitat connectivity across a project landscape. While further research and understanding is required to successfully mainstream these analyses, we highlight two ways in which they could also contribute to better achieving net gain and nature-positive outcomes.

Firstly, the method used based on circuit theory allows for the calculation of a mean current value across the study landscape (Grafius et al. 2017). This provides a quantitative proxy of connectivity which could be estimated for both baseline and post-construction scenarios for each study species. The existing BNG process in England has so far struggled to incorporate objective measures of connectivity and fragmentation into the Biodiversity Metric (Natural England 2022), with quantitative outputs such as these thereby providing a potential means by which this could be achieved.

Secondly, the cumulative current maps provide a visual representation which could inform the location and design of habitat creation as part of net gain requirements. Current guidelines on locating net gain measures do not go much beyond suggesting a preference for on-site or local delivery versus off-site delivery of habitat creation. However, respondents to a UK government consultation on BNG highlighted the importance of including mapping and connectivity data in directing the location of new habitats (Defra 2019). Connectivity maps could support this by highlighting areas of fragmentation, helping to locate offset measures in areas where they are objectively likely to have the greatest

impact (Figure 3). This could also bridge existing metric approaches, which focus on habitat area calculations, with landscape-scale processes, which include animal populations and their movement (Harker et al. 2021).

The new legal requirement for planning permissions in England to deliver BNG represents a clear potential route for connectivity analyses to be mainstreamed in the planning process, leading to better outcomes for biodiversity at the landscape-scale. However, current BNG requirements are primarily based on the area and condition of habitats (Natural England 2022). Unlike habitats where gains and losses can be clearly quantified by area, there is currently no consensus on a metric which could meaningfully encapsulate connectivity in the planning process. Whether the definition of such a metric is realistic and how the net gain of connectivity could be implemented are key questions for those involved in connectivity research.

We used the freely available software Circuitscape to apply modelling based on circuit theory. While a range of alternative connectivity modelling and analysis methods have been assessed in the context of their application to research and conservation (Conservation Corridor 2021; Keeley et al. 2021), comparisons of their feasibility in EIA are lacking and urgently required. Following our discussion of species-specific results and promising wider applications to impact assessment and planning, in this section, we highlight five key challenges encountered: 1. resource requirements; 2. study area definition; 3. data limitations; 4. knowledge gaps; and 5. limited biological applicability.

The landscape-scale modelling approach provided by Circuitscape benefits from utilising baseline data that is already commonly collected during the EIA process (Grafius et al. 2017). However, to account for landscape-scale processes, a larger connectivity study area was required compared to the ecology study area applied for the HEP EIA. This requires the collection of additional baseline data which represents additional time, labour, and skills, which in turn can increase costs, lead to programme delays, and may face barriers in gaining access to survey land beyond a project's red line boundary. Additional data requirements could therefore act as a barrier to more general inclusion of connectivity analyses in impact assessments.

It also raises the question of how large a CSA is large enough. Bergès et al. (2020) recommend that the study area incorporate the development project plus a buffer that is at least equal to the maximum dispersal distance of the focal taxa. However, the difficulty of objectively defining study boundaries has been highlighted for EIAs more generally. Variation occurs between sites,

industries, and jurisdictions, with the process inevitably including a degree of subjectivity (Harker et al. 2021). Calls for a generic framework for strategic environmental assessment (SEA) could provide more consistency at a higher level (Fischer 2006).

Data limitations are a major challenge in accurate connectivity modelling. In this study, numerous stages of data manipulation were required to create appropriate inputs for Circuitscape (Figure 2), and the purchase of additional data was required to ensure accurate modelling for certain species. Despite this, some relevant features in the landscape are likely to have been missed. This may be due to their absence in the Phase 1 Habitat Classification system (JNCC 2010), or being too small to be identified remotely where field surveys were not possible. This includes vertical barriers such as walls and kerbs, connecting features such as small ponds and wildlife crossings, and specific habitat combinations and transitional zones. Tarabon et al. (2019a) suggested the establishment of a collaborative database that identifies some of these habitat elements – something which could form part of Local Nature Recovery Strategies in England (Defra 2021). However, the practicality of including such features in connectivity modelling for EIA, compared to their impact on outcomes is uncertain.

The habitat preferences for most UK protected species, including those in this study, are generally well documented. However, large knowledge gaps remain for many other species globally. This is a key consideration in the application of circuit theory and other connectivity assessments where outputs are strongly dependent on model parameterisation (McRae et al. 2008). Even with a sound evidence-base, parameterisation inevitably involves an element of subjectivity (Tarabon et al. 2019a). This reduces replicability and poses questions on how best to mainstream connectivity modelling within policy and legislation in a standardised way.

The applicability of this method to species with different life strategies is also questionable. Grass snakes and soprano pipistrelles both have known habitat preferences, which resulted in connectivity maps with varying current values across the landscape (Figure 3). However, for more generalist species such as badgers *Meles meles* and common pipistrelles *Pipistrelle pipistrelle*, values across the landscape were more uniform, making the results less informative for the design of mitigation measures. Specialist species also posed specific challenges. For instance, brown long eared bats *Plecotus auratus* are strongly associated with woodland and individual trees (Entwistle et al. 1996), requiring additional data on the distribution and canopy extent of all trees. Meanwhile, our attempts to model connectivity for the fish assemblage present found insufficient differentiation between aquatic habitats in the UK Phase 1 habitat classifications. Additionally, model parameterisation did not allow factors such as water flow and quality to be incorporated. These findings indicate that quantitative connectivity analyses in EIA may only be useful for certain species, and that different methodologies may be required for terrestrial and aquatic species. While raster-based approaches have been applied to assess habitat connectivity for fish, specialist software which considers movement directionality and different fish life stages has also been developed (Roy and Le Pichon 2017).

Biodiversity loss is occurring at an unprecedented rate, with its impact on ecosystems and people being experienced globally (IPBES 2019). It is therefore imperative to turn the tide for biodiversity and enable net gain to become a reality. With the interconnectedness of species and ecosystems, conservation must focus not just on habitat areas, but also on the connectivity and integrity of natural ecosystems – elements which are recognised at the highest levels of conservation planning (CBD 2021). Permitting decisions must evolve from focusing on project-level impacts to effectively incorporating the wider landscape. With the outcomes of EIAs influencing millions of hectares of land globally, they provide a vital opportunity through which this can be achieved. However, for connectivity analyses to be mainstreamed in EIA, political and legislative drivers are required, underpinned by sound research, evidence, and guidance on connectivity modelling approaches.

Disclosure statement

In accordance with Taylor & Francis policy and our ethical obligation as researchers, we are reporting that Mott MacDonald was acting as environmental consultant to Heathrow Airports Limited.

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