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From small footprints to BIG connections: Building-Integrated Greenery boosts ecological connectivity in the Sydney basin

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Abstract

Building-integrated greenery (BIG), implemented through green roofs and walls, can restructure urban ecological networks by enhancing habitat continuity and reducing fragmentation. However, quantifying these benefits across the city remains challenging due to complex interactions between urban morphology and landscape ecology. This study simulates incremental BIG adoption across existing buildings in Sydney, Australia, to evaluate how

progressive roof and wall greening influence spatial structure and functional connectivity for insect pollinators and woodland birds. Using open-source spatial datasets and geocomputational modelling, we quantified habitat fragmentation, cluster configuration, and ecological connectivity across scenarios from 0% to 100% BIG coverage. We identified the inflection points at which ecological benefits accelerate or decelerate using landscape metrics and network analysis. We found that BIG catalyses non-linear ecological transitions with threshold-dependent dynamics across four phases: transition, reconnection, consolidation, and saturation. A critical inflection point emerged at 20% BIG coverage, where connectivity metrics shift from negative to positive rates of change. Between 20-40% coverage, configuration metrics showed sustained acceleration as critical patches proliferate across the landscape. Betweenness centrality indicated that connectivity emerged from the collective contribution of moderately important stepping-stone patches rather than dependence on individual bottleneck nodes. There were diminishing returns in connectivity from additional greening beyond 70% coverage. Green walls outperformed green roofs in early connectivity for insect movement, retaining broader spatial distributions of important patches at equivalent early coverage levels. These findings indicate that effective strategic placement of BIG matters in lower coverage of up to 40%. Cross-jurisdictional governance frameworks aligned with landscape-scale ecological processes would be more effective at improving ecological connections in urban environments than the existing emphasis on individual buildings or administrative boundaries.

Keywords

urban ecology; green roof; green wall; biodiversity; stepping stones

Highlights

- Connectivity metrics and network analysis measure BIG's ecological benefits.
- Early ecological gains occur at 10-20% BIG across taxa and greening types.
- Corridor formation emerges consistently at intermediate BIG levels of 20-40%.

- Large-scale connectivity develops at 40-70% BIG.
- Green roofs reduce fragmentation earlier than walls.

1 Introduction

1.1 Urbanisation, habitat fragmentation, and biodiversity loss

Urbanisation is among the most pervasive drivers of biodiversity loss globally, replacing vegetated land with impervious surfaces and reducing habitat continuity for a wide range of species (Grimm et al., 2008; Butchart et al., 2010; de Barros Ruas, Costa and Bered, 2022). The global wildland-urban interface covers 4.7% of land yet houses approximately 3.5 billion people, creating a persistent structural boundary between natural and built systems (Schug, Bar-Massada, Carlson, et al., 2023). Built infrastructure, including roads, buildings, drainage channels, and impervious paving, fragments landscapes into disconnected habitat patches, restricting species movement, reducing gene flow, and intensifying edge effects in remnant vegetation (Forman and Godron, 1986; Forman and Alexander, 1998; Benítez-López et al., 2010). In Europe, 27% of land is classified as highly fragmented, with average habitat patch sizes below 2 ha, conditions are steepest near human settlements (EEA, 2022). A global meta-analysis confirmed that urbanisation decreases species richness while favours generalist and disturbance-tolerant taxa at the expense of specialist species (Szabó et al., 2023). Up to 30% of biodiversity loss is attributed directly to construction activity (WALCC, 2024). The cumulative ecological consequence of these pressures is a landscape in which remnant habitat patches are insufficient to support viable populations of many native species without functional connections between them (Laurance et al., 2015; Haddad et al., 2015).

1.2 Ecological connectivity: theory, metrics, and network approaches

Landscape ecology provides the theoretical foundation for understanding how spatial structure mediates species movement and population persistence. Patch-matrix-corridor models, formalised by Wiens (1976) and extended by Forman and Godron (1986), establish that the arrangement and quality of habitat patches, not only their total area, determine the functional

connectivity of landscapes. Ecological network analysis operationalises this theory by representing habitat patches as nodes and potential movement pathways as edges, enabling connectivity to be quantified and optimised across real urban landscapes (Opdam, Steingrover and van Rooij, 2006; De Montis et al., 2016).

Percolation theory offers a complementary framework for identifying connectivity thresholds where the critical coverage levels at which habitat transitions from a fragmented to a connected state (Boswell, Britton and Franks, 1998; With, 2022). At the percolation threshold, small additions of habitat produce disproportionate gains in structural connectivity, an inflection dynamic of direct relevance to planning interventions that are rolled out incrementally (Huth et al., 2014; Quebbeman et al., 2021). Network metrics, including betweenness centrality and effective mesh size, capture these non-linear dynamics and distinguish between area-based gains and structural reorganisation of the habitat network (Kirk et al., 2023; Zhang et al., 2025).

1.3 Building-integrated greenery (BIG) as urban habitat

BIG, encompassing green roofs, living walls, and vertical gardens, has emerged as a strategy for reintroducing vegetation into the built environment by utilising the underexploited surface area of existing buildings (Al-Kodmany, 2023; Zhong, Schroder and Bekkering, 2024). By converting building surfaces into vegetated patches, BIG has the potential to function as a stepping-stone habitat within urban ecological networks, linking larger remnant patches and enabling species movement across otherwise impervious streetscapes (Braaker et al., 2014; Wu, Zhang, Luo, et al., 2022).

Empirical evidence supports the biodiversity value of BIG, particularly for invertebrates and birds in urban ecosystems. Extensive green roofs in London hosted over 80 plant species and provided refuge for rare ground-nesting insects (Gedge and Kadas, 2005). A systematic review of 72 studies found that green roofs consistently supported higher arthropod richness and abundance compared with conventional rooftops, with substrate depth and vegetation diversity as key drivers (Wang et al., 2022). Braaker et al. (2014) demonstrated that urban green roof connectivity is a significant predictor of arthropod community composition, with species

assemblages reflecting the surrounding landscape matrix when connectivity is low. For birds, Chiquet, Dover and Mitchell (2013) documented nesting, foraging, and shelter-seeking behaviours on green walls, with species richness positively associated with vegetated façade coverage. Wooster et al. (2022) found that green roofs in Sydney increased local bird and invertebrate species richness compared with adjacent non-vegetated rooftops.

1.4 Planning policy and the governance gap

Recognition of urban biodiversity as a planning priority has grown substantially, with frameworks including the Kunming-Montreal Global Biodiversity Framework and national biodiversity strategies increasingly directing attention to urban greening as a conservation mechanism (Nilon et al., 2017; Lepczyk et al., 2017). In Australia, the NSW Government's Greener Places framework and the Sydney Green Grid strategy prioritise green infrastructure connectivity at the metropolitan scale (NSW Government, 2020, 2023). At the local level, the City of Sydney's Greening Sydney Strategy and Green Roofs and Walls Policy Implementation Plan establish targets for canopy cover and encourage BIG installation as part of broader urban greening commitments (City of Sydney, 2020, 2021). Sustainability rating tools such as LEED increasingly integrate BIG into their assessment criteria (Reyes et al., 2024), and several Sydney councils have adopted technical guidelines for green roofs and walls (Inner West Council, 2020; Woollahra Municipal Council, 2023).

Despite this policy momentum, BIG remains embedded within broader urban greening strategies rather than governed by dedicated frameworks that set ecologically informed targets for coverage, placement, or species outcomes. Current policies tend to specify area-based or percentage canopy targets without reference to the connectivity thresholds at which ecological benefits accelerate. Governance operates at the scale of individual buildings or local government areas, whereas the ecological processes that BIG is expected to support for species movement, network reconnection, and corridor formation operate at landscape scales that cross administrative boundaries (Opdam et al., 2006; De Montis et al., 2016). This mismatch between governance

scale and ecological scale represents a fundamental limitation of existing policy, and one that city-scale connectivity modelling can directly inform.

1.5 Knowledge gaps addressed by this study

The majority of BIG research has focused on the co-benefits of individual installations, such as thermal performance, stormwater retention, urban heat island mitigation, and carbon sequestration (Susca et al., 2011; Alim et al., 2022; Xi et al., 2022; Ghazalli et al., 2019), rather than on the city-scale ecological connectivity that accumulates as BIG adoption increases across an urban area. This building-by-building evidence base does not address the landscape-scale question of whether BIG, when adopted progressively across an entire city, can restructure urban ecological networks.

Three gaps motivate the present study. First, while the biodiversity value of individual BIG installations is well established, no study has modelled the cumulative connectivity gains that result from progressive BIG adoption across an entire metropolitan area. Second, the relative performance of green roofs versus green walls as stepping-stone habitats at equivalent coverage levels and for taxa with differing dispersal modes has not been systematically compared at the city scale. Third, the identification of critical coverage thresholds and inflection points in connectivity trajectories, which would provide a quantitative basis for setting ecologically grounded policy targets, has not been attempted for BIG in an Australian urban context.

This study addresses these gaps by simulating incremental adoption of BIG across all buildings in the Greater Sydney Basin and evaluating the resulting changes in habitat fragmentation, cluster configuration, and ecological connectivity for insect pollinators and woodland birds, using landscape metrics, percolation theory, and network analysis.

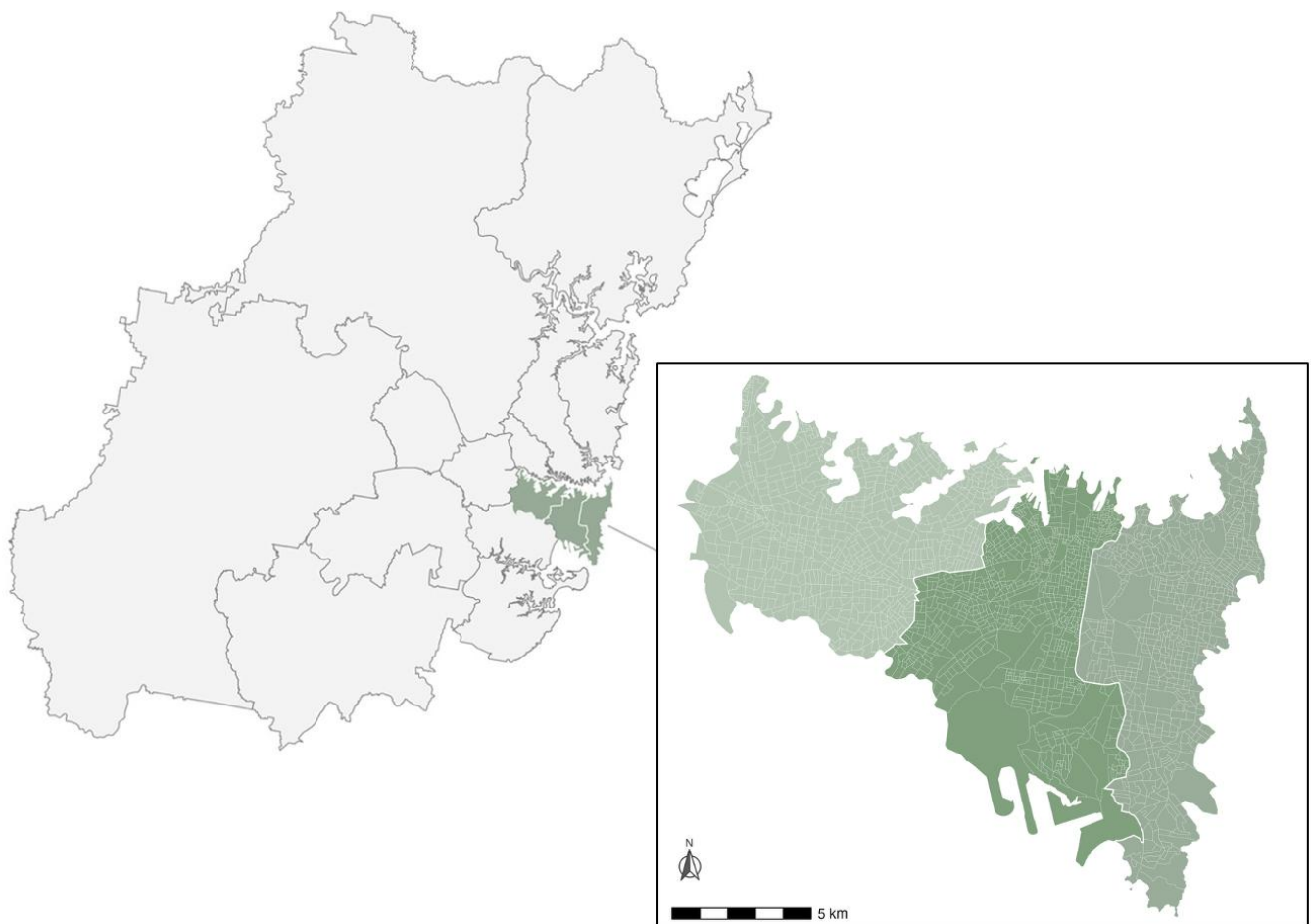
2 Methods

2.1 Study area

Greater Sydney, Australia's largest city, with a metropolitan population of approximately 5.3 million and an urban extent spanning over 12000 km², provides an ideal model system for testing how incremental BIG adoption restructures ecological connectivity at the metropolitan

scale. Its size, morphological diversity, and the gradient from a dense inner core to peri-urban bushland make it suitable for detecting the cumulative connectivity gains that emerge only when greening scales from individual buildings to city-wide coverage.

This study focuses on the three inner-city Statistical Area (SA) Level 4 regions: City and Inner South, Eastern Suburbs, and Inner West, that together cover 188 km² and constitute the most heavily urbanised part of the metropolitan area (Figure 1). The area encompasses approximately 124247 buildings occupy this zone, with building footprint covering 22% of the total surface area and vegetation limited to 37% of the landscape pixels. This low connectivity, high density baseline maximises the detectability of incremental BIG effects and it is representative of the dense urban cores of major cities globally.



165 **Figure 1.** The study area (shaded) within Greater Sydney, Australia’s largest city (population >5 million). The three
166 highly urbanised inner-city SA4 regions, City and Inner South, Eastern Suburbs, and Inner West, sit within the
167 dense core of the metropolitan area, shown in relation to the broader Greater Sydney boundary (Benson, 2024).

168

169 **2.2 Data sources and analysis**

170 We used publicly accessible datasets covering species, land cover, building footprints, and road
171 networks. These are summarised in Table 1, including their attributes and the derivative metrics
172 used in the analysis. Data analyses were performed using R (version 4.4.1) and RStudio
173 (version 2024.9.1.394), with the ‘tidyverse’ suite of packages (Wickham et al., 2019) for data
174 wrangling. Spatial data packages included ‘sf’ (Pebesma, 2018), ‘terra’ (Hijmans, 2025),
175 ‘geojsonsf’ (Cooley, 2022), and ‘lwgeom’ (Pebesma, 2025). Other stand-alone packages used
176 were ‘here’ (Müller & Bryan, 2025), ‘glue’ (Hester & Bryan, 2024), ‘rgbif’ (Chamberlain et al.,
177 2025), ‘aws.s3’ (Leeper, 2025), ‘units’ (Pebesma et al., 2016), and ‘patchwork’ (Pedersen,
178 2025).

179

180 **Table 1.** Data sources and attributes

Data	Data sources	Data collection types	Embedded metric	Attributes	Reference
Species occurrences	Global Biodiversity Information Facility (GBIF)	Observation	Species distribution	Species count and location	GBIF.org, 2024
Vegetation and land cover	DEA Land cover	Satellite imagery	GSF, ecological connectivity	Vegetation cover, land cover classification and lifeform	Tissott et al., 2025
Soil landscapes	SEED NSW	Satellite imagery	GSF	Soil groupings and locations	NSW Government and NSW Department of Climate Change, Energy, the Environment and Water, 2009
Buildings	Microsoft	Satellite imagery	GSF, ecological connectivity	Building footprints, areas, and location	Microsoft - Planetary Computer, 2025

Road Segment Data	Transport Open Data	Satellite imagery	Ecological connectivity	Road networks, road width and location, railways, railway width and location	Transport for NSW, n.d.
Sydney Region Carriageway	Transport Open Data	Satellite imagery	Ecological connectivity	Road lanes, length, roadway, and surfaces width	Transport for NSW, 2020.
Land parcel property theme	Data.NSW	Satellite imagery	GSF, Total Site Area	Total site area and Lot	Spatial Services (DCS), 2025.
Habitat (National Connectivity Index 2.0 (2001-2018))	Australian Government Department of Climate Change, Energy, the Environment and Water	Satellite imagery	GSF	Ecosystem site condition index, habitat condition subindex, ecosystem site condition classification	Australian Government Department of Climate Change, Energy, the Environment and Water, 2022.

2.3 Urban pollinators and woodland birds as focal taxa

Insect pollinators and woodland birds are ecologically important and iconic taxa in urban environments. Pollinators underpin the reproduction of approximately 87.5% of flowering plant species globally (Ollerton, Winfree and Tarrant, 2011) and provide essential ecosystem services (Langellotto et al., 2018; Baldock et al., 2019; Goddard, Dougill and Benton, 2010). Woodland birds play complementary ecological roles as predators, pollinators, seed dispersers, and indicators of habitat quality (Bael et al., 2008; Pejchar et al., 2008). Both groups are sensitive to habitat fragmentation, showing declines as patch isolation increases and urban matrix permeability decreases (Ikin et al., 2013; Threlfall et al., 2016), and are target taxa for many restoration and greening efforts in cities (Pinto et al., 2025).

Although no complete inventory exists, Sydney likely supports several thousand insect pollinator species, including hundreds of species of native bees such as blue-banded bees, resin bees, carpenter bees and stingless bees (Dollin et al., 2000), hoverflies and other flower-visiting flies (Lequerica Tamara et al., 2023), as well as abundant beetles, butterflies, and moths. It also home to a diverse community of native birds, with 365 native bird species recorded from the metropolitan area, (NSW Government, 2025a, 2025b). Fifty-one woodland bird species are in severe decline across Eastern Australia, driven in part by the progressive fragmentation of native

vegetation (BirdLife Australia, 2025). Existing remnant bushland, parks, and waterways in Sydney provide essential refuges but are insufficient on their own to maintain functional connectivity across an urbanised matrix (Davies et al., 2017; City of Sydney, 2014). The two focal taxa represent contrasting dispersal ranges and habitat sensitivities. Pollinators respond to spatial configuration and vegetation type, while woodland birds are more dependent on total habitat area (Kirk et al., 2023). This makes them complementary and ideal test cases for evaluating the connectivity benefits of BIG across different ecological scales.

2.4 Landscape metrics

We used several common landscape metrics to quantify the ecological impacts of various BIG scenarios relative to a baseline. These metrics included the Green Space Factor (GSF) and various landscape indices for habitat fragmentation, structural cluster configuration, and ecological connectivity. These are summarised in Figure 2.

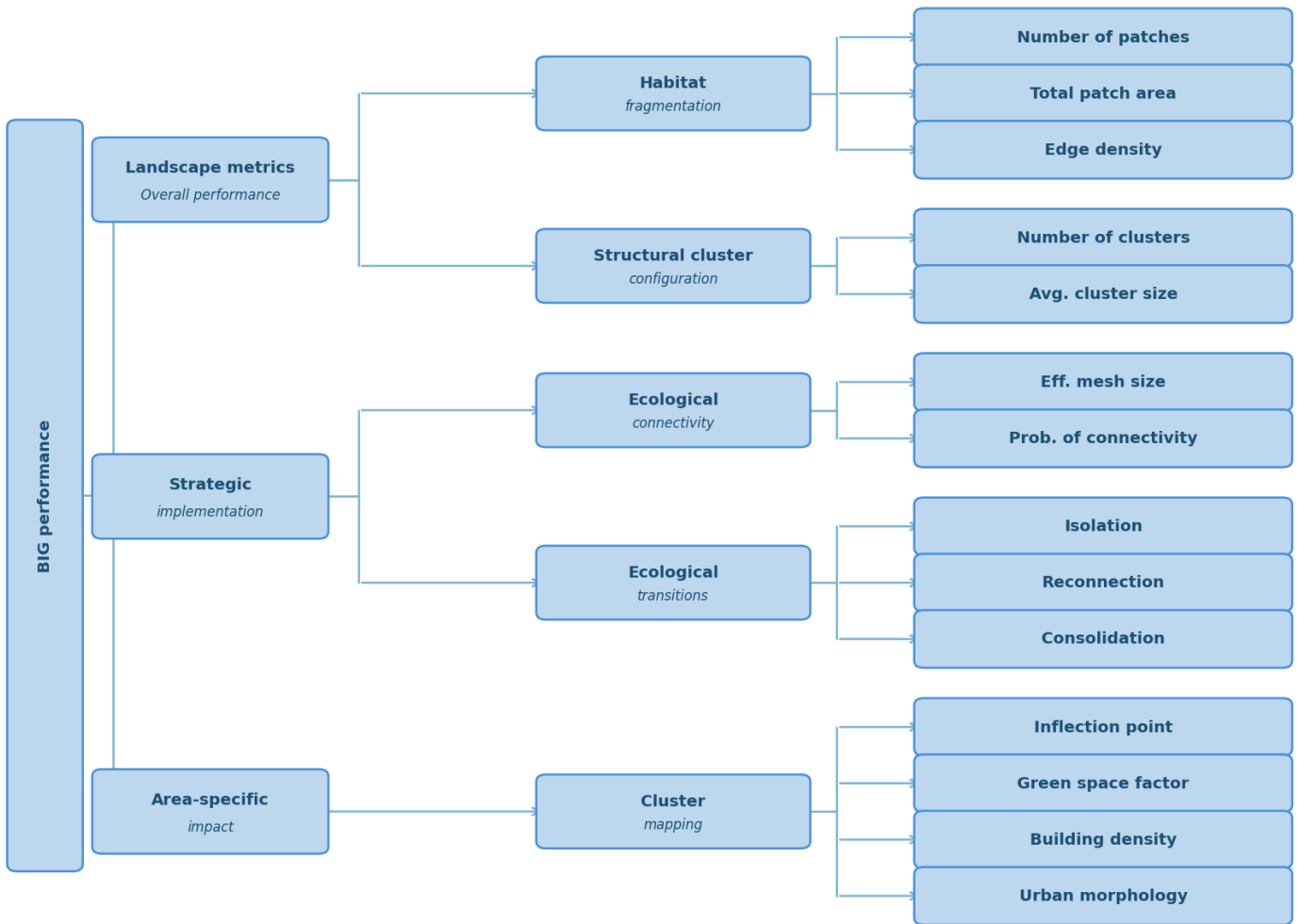


Figure 2. Performance metrics for BIG

Habitat patches are “core areas” that are of high natural value for the conservation of habitats and species (De Montis et al., 2016). Edges, also known as continuous or discontinuous (stepping stones) environmental corridors, refer to the number of connections between core areas and habitat patches (Foppen et al., 2000). Edge density is the number of edges between different land cover types relative to the unit area. Clusters describe the grouping of habitat patches into connected ecological networks (Luo et al., 2022).

We used the *GSF* metric, which measures the ratio of vegetated surface area to total site area, adjusted for ecological quality (Equation 1) (De Lotto et al., 2015; Vartholomaos et al., 2013).

$$GSF = \frac{\sum AGE \times WF}{TSA} \text{ (Equation 1)}$$

Where, *AGE* (Area of Green Element) is the surface area (m²) occupied by each distinct vegetation type (e.g., lawns, trees, green walls, green roofs)

225 *WF* (Weighting Factor) is a multiplier assigned to each green element based on its ecological contribution

226 *TSA* (Total Site Area) is the entire area of the site under evaluation (m²)

227

228 *pc* is the likelihood that a randomly selected patch is connected (Kirk et al., 2023). To calculate
229 *pc*, we first identified habitats, their connectors and barriers. We assigned habitats to areas with
230 more than 15% vegetation cover, cultivated terrestrial vegetation, or herbaceous lifeform
231 habitats. We buffered the selected habitat areas by a 25m offset, following Kirk et al. (2023). We
232 estimated landscape fragmentation by assigned barriers to roads and carriageways wider than
233 10m for insect pollinators, larger than 15m for woodland birds; and buildings taller than 12m for
234 insect pollinators , and taller than 20m for woodland birds. We identified habitat areas that were
235 still connected. These were habitat patches that were not divided by barriers with less than
236 350m distance in between for insect pollinators, and less than 1500m for woodland birds. We
237 then erased habitat buffers and calculated *pc* based on the following formula (Equation 2):

238
$$P_c = \frac{1}{A_{total}} \sum_{i=1}^n \frac{A_i^2}{A_{total}} \text{ (Equation 2)}$$

239 Where, P_c is equivalent to Jaeger's degree of coherence [a value between 0 and 1, where one would be a
240 completely connected landscape for the individuals in question]

241 A_{total} is the total area of all habitat patches

242 A_i^2 is squared area of each of the n groups ($i = 1, \dots, n$) of connected habitat patches

243 $\frac{A_i^2}{A_{total}}$ is the Effective Mesh Size (m_{eff}) that calculates the approximate area of connected habitats a species
244 dropped at random in a landscape can access

245

246 To identify the ecological thresholds and phase transitions, we calculated the discrete second
247 derivative of each landscape metric trajectory (Equation 3). Zero-crossings-coverage levels at
248 which Where $f'(x_i)$ across all species-BIG type combinations, identifying coverage thresholds at
249 which the habitat network underwent collective structural transitions rather than isolated metric-
250 by-metric shifts.

$$f''(x_i) = (f(x_{i-1}) - 2f(x_i) + f(x_{i+1})) / h^2, h = 0.1 \text{ (Equation 3)}$$

Where f is the value of the landscape metric

i is the proportion of buildings with BIG

h is the fixed step size between coverage levels (10% increments, $i=10\%, 20\%, \dots 90\%$)

Ecological networks are used for the recovery and maintenance of ecological connectivity and environmental continuity in urban and natural environments (De Montis et al., 2016; Opdam, Steingrover & van Rooij, 2006). To investigate the role of newly introduced patches created by BIG habitats within the broader ecological network, we calculated betweenness centrality (bc) to quantify how often a particular habitat patch or edge lies on the shortest path between other pairs of patches in a network. bc identifies which elements serve as critical bridges, corridors, or stepping stones within the network structure. bc is the sum over all distinct pairs of nodes (s, t) of the fraction of shortest paths between s and t that pass through the node under consideration, normalised by the total number of possible paths in the network:

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \text{ (Equation 4)}$$

Where, v is a node

σ_{st} is the total number of shortest paths from s to t

$\sigma_{st}(v)$ is the number of those paths that traverse v

In an ecological network context, criticality refers to the structural importance of a habitat patch to network-wide connectivity. A high criticality patch lies on many of the shortest movement pathways between other patches, such that its loss or degradation would most severely disrupt species dispersal across the landscape. To translate continuous bc values into a four-level criticality classification (e.g., low, moderate, important, critical), we divided the normalised bc

values into quantile-based categories. Nodes in the lowest 25% of *bc* were classified as low, those between the 25-75th percentile as moderately important, those between the 75-90th percentile as important, and the top 10% as critical.

2.5 Baseline and BIG scenarios

To calculate the impacts of BIG on urban ecology using a systematic approach, we developed BIG as scenarios for incremental improvement, assuming that the baseline conditions for buildings in the Sydney basin had no green roofs or walls. We determined baseline conditions for the green spaces using the DEA Landsat dataset, including vegetation cover type, land cover classification, and soil landscape groupings, to calculate the GSF (Green Space Factor) (Tissott et al., 2025). BIG types assigned in each scenario received a *WF* of 0.7 for green roofs and 0.5 for green walls.

We developed scenarios for green roofs and green walls separately, applying BIG to 10%–100% of buildings in 10% increments. Buildings were assigned to scenarios using a pre-computed random ordering, ensuring reproducible scenario construction. We applied green roofs across the full footprint area of each selected building, derived from the Microsoft Building Footprints dataset (Microsoft Planetary Computer, 2025). We applied green walls to the largest exposed façade of each building, estimated from the building footprint perimeter and building height sourced from the NSW Electronic Planning Instrument (EPI) dataset. *WF* of 0.7 (green roofs) and 0.5 (green walls) were applied to reflect their relative ecological quality contributions to the Green Space Factor.

3 Results

3.1 Habitat fragmentation

The baseline building density, habitat patch density and the *GSF* characterised the existing built and ecological conditions of the study area prior to any BIG implementation (Figure 3). Building density followed a pronounced spatial gradient and values frequently exceeded 75%, with a distinct high-density corridor running north-south through the inner-city zone corresponding to

the Central Business District and its immediately surrounding suburbs. Moving outward from this corridor, building density declined with the southern, southeastern, and coastal portions of the study area characterised by predominantly low densities below 25%, and moderate densities between 25-50% occupying the transitional middle-ring suburbs between the two. Habitat patch density showed a bimodal distribution, with the majority of SA1 areas having values well below 25%, reflecting the high degree of impervious surfaces throughout the urban fabric. A small number of discrete high-density patch clusters, corresponding to major park precincts in the northwest, centre-east, and southern portions of the study area, recorded values exceeding 75%. Intermediate patch densities were rare, showing that meaningful habitat cover was largely confined to established parkland rather than distributed through the residential street network. The GSF baseline presented a more gradational pattern. The Inner-city core remained consistently low below 25%, but substantial contiguous zones of moderate *GSF* between 25-50% were evident in the southern area. This contributed to a more spatially coherent green fabric than patch density alone would suggest, with high-*GSF* area above 75% clustering in the northwest and along parts of the northeastern edge. These three patterns confirm that the existing built context was dominated by a dense, poorly vegetated inner core with ecological value concentrated in a limited number of large park precincts, establishing both the zones of greatest surface availability for BIG and those of greatest potential ecological gain from intervention.



Figure 3: Baseline building density (left), GSF (middle), and habitat patch density (left). The legend showing 25%, 50% and 75% marks from bottom to top.

Habitat fragmentation metrics showed consistent trends as BIG adoption increased (Figure 4). Patch count decreased substantially, indicating habitat consolidation. The most pronounced reductions occurred at 20% adoption across all cases, ranging from 49% (green roofs for birds) to 36% (green walls for insects). At full adoption, the patch count decreased by 85% (from 8970 to 1378) for insects with green roofs and 79% (to 1845) with green walls, and by 79% (to 1903) for birds with green roofs and 82% (to 1577) with green walls. In parallel, the total habitat area increased progressively with the addition of BIG. For insects, patch area rose from 66 km² to 100 km² (green roofs) and 79 km² (green walls), corresponding to a 34% and 17% increase, respectively. For birds, similar trends were observed, with patch area reaching 104 km² (37% increase) for green roofs and 80 km² (18% increase) for green walls.

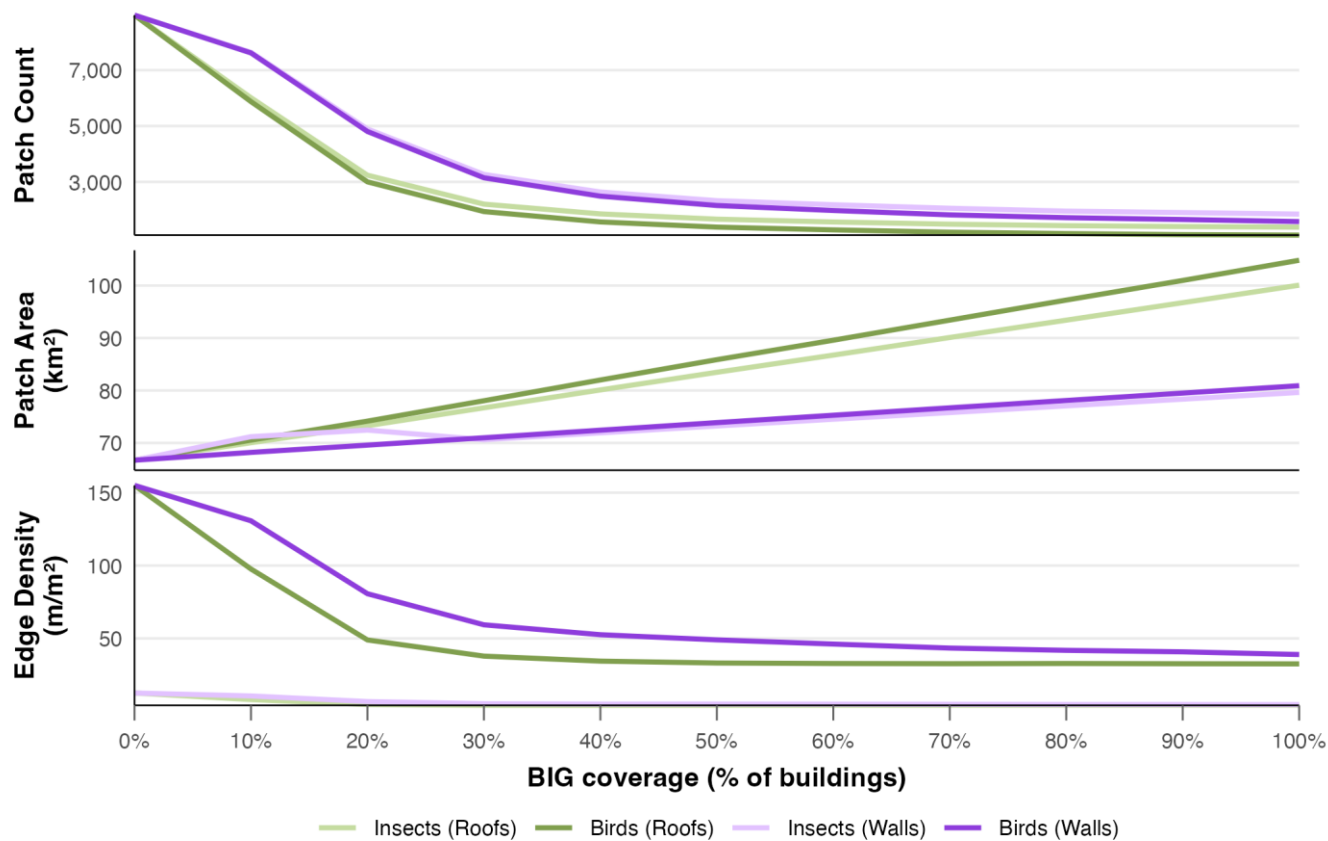


Figure 4: Relationship between fragmentation-related landscape metrics and proportion of houses with BIG

Edge density reduced as patches merge, clusters enlarge, and edges reconnect. The results stabilised for insects from 30% and for birds from 20% roof or wall greening. Both taxa experienced a wider gradient at low BIG. Edge density varied from 8 to 6 m/m² (at 10% BIG) and from 4 to 5 m/m² (at 20%) for roofs and walls, respectively, for insects, flattening to 4 m/m² in both cases. Birds occupied a structurally less fragmented landscape across all BIG levels, with an edge density of 155 m/m² (roofs or walls) at the baseline, showing a rapid decrease up to 30% greening (37 m/m² for roofs and 59 m/m² for walls).

3.2 Structural cluster configuration

We measured structural cluster configuration using the number of clusters and average cluster size metrics, which revealed strong contrasts for different taxa (Figure 5). Baseline conditions for the number of clusters ranged between 23 (green roofs) and 42 (green walls) for insects and were one for birds (both green roofs and walls). The number of clusters for insects exhibited an increase with the reducing patch count, peaking at 30% roof greening (n=279) and 40% wall greening (n=286), then declining as patches began to consolidate into larger clusters. The small number of clusters formed for birds varied slightly, while roof and wall greening showed distinct results. Clusters formed through green roofs presented an upward trend throughout, reaching 15 clusters at full roof greening. Green walls increased the number of clusters up to 60% coverage, reaching 10 clusters, then showed a slight decrease, stabilising the conditions.

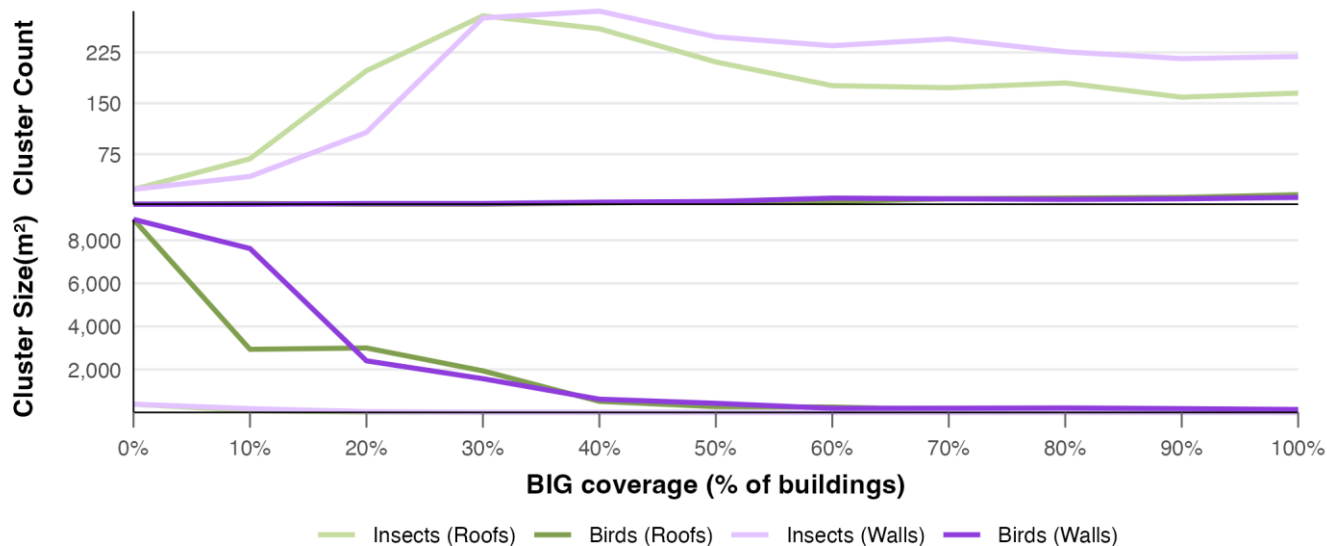


Figure 5: Relationship between habitat area and structural configuration-related landscape metrics and proportion of houses with BIG

The baseline average cluster size was 390 km² for insects and 8970 km² for birds. The lowest these values reached were 8 km² and 9 km² for insects, and 72 km² and 143 km² for birds, considering roof and wall-based greening, respectively. The cluster size stabilised at 30% BIG for insects but continued to decrease to 60% BIG for birds, with a steady decline thereafter.

3.3 Ecological connectivity

The results for the connectivity-oriented metrics, including m_{eff} and pc , showed green roofs exhibit an increasing trend in m_{eff} for both taxa, whereas green walls increase m_{eff} only for birds (Figure 6). Green wall implementation for insects shows a 29% initial drop from 65 km² to 46 km² in m_{eff} with 10% BIG over the baseline, followed by slight increases towards full coverage; however, it did not recover to baseline conditions. Birds benefit most from green roof adoption compared to green walls. As such, m_{eff} exhibited steady gains across the incremental BIG coverage, achieving 26% (89 km²) and 18% (80 km²) improvements over the baseline with green roofs and walls, respectively.

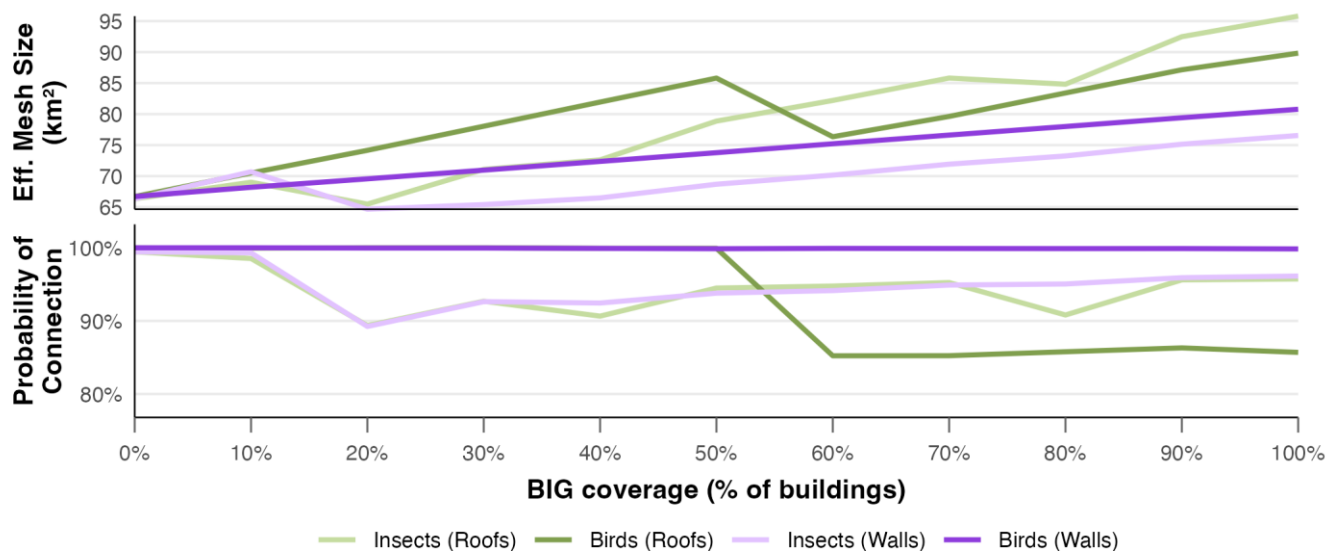


Figure 6: Relationship between connectivity-oriented landscape metrics and proportion of houses with BIG

The results for pc showed minimal variance due to the high values observed in baseline conditions, including 0.99 for insects and 1 for birds. Although the difference was small, pc for insects slightly decreased in the early phases of greenery, regardless of BIG type, before showing an upward trend at 30% and 60% BIG for green roofs and walls, respectively. This increase then plateaued, reaching values similar to the baseline.

3.4 Ecological thresholds and transitions

Landscape metrics responded non-linearly to incremental BIG adoption, producing four ecologically distinct phases including Transition (0-20% BIG), Reconnection (20-40% BIG), Consolidation (40-70%), and Saturation (70-100% BIG). We identified these phases from inflection points in the discrete second derivative of each metric trajectory and normalised each metric to a 0-1 scale for cross-metric comparison (Figure 7).

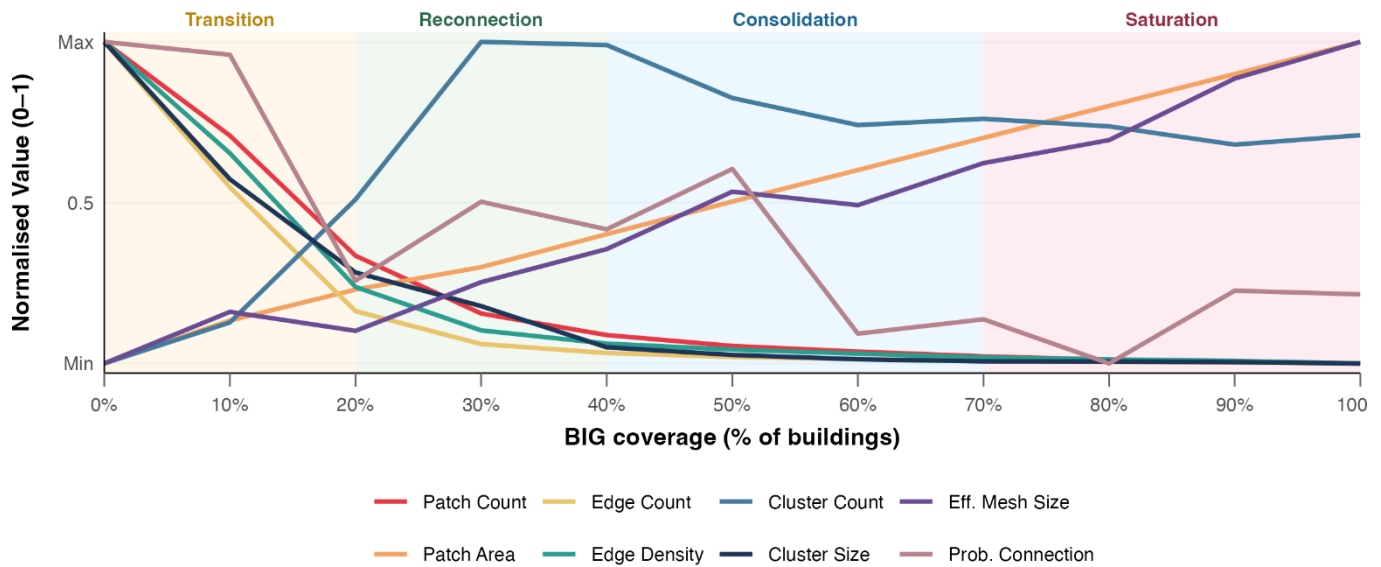


Figure 7: Normalised values for all metrics

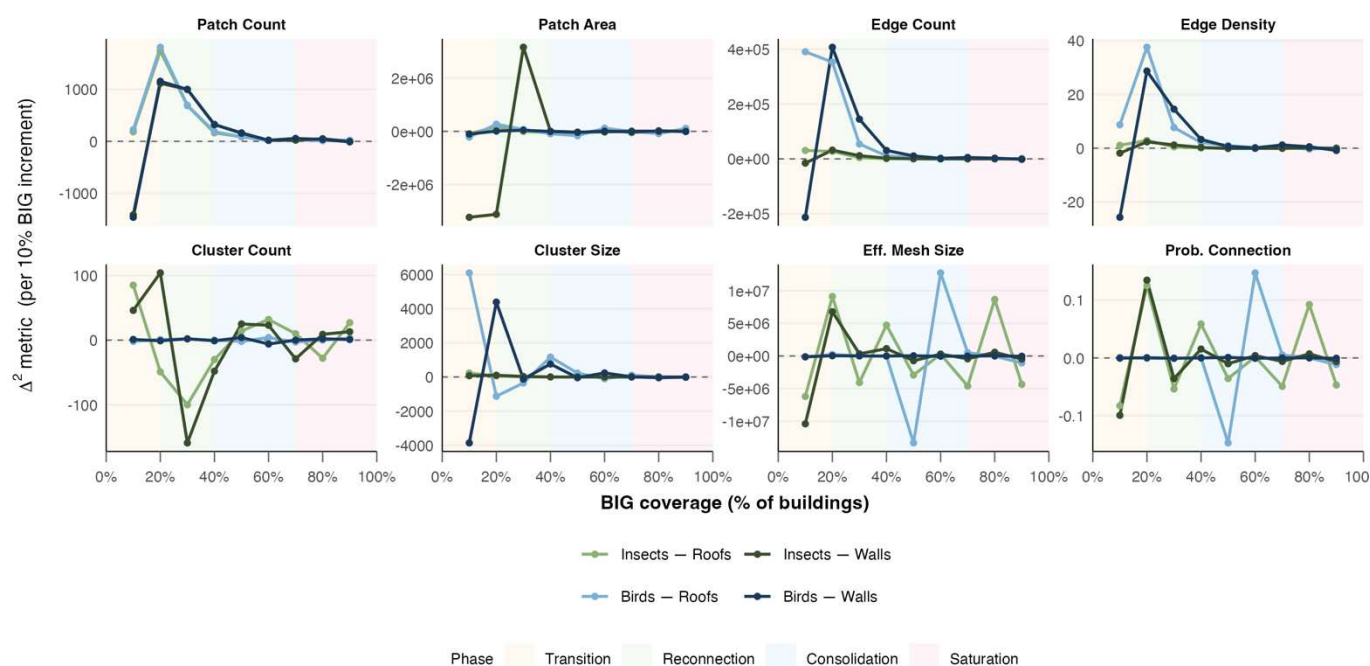
During the Transition phase, fragmentation-related metrics declined concurrently as BIG bridged gaps between existing green spaces, consolidating isolated fragments into fewer, larger habitat patches. A critical inflection point emerged at approximately 20% BIG coverage, where net fragmentation reduction gave way to ecological reconnection. Cluster count rose across the Reconnection phase as BIG established dispersal-scale connections between previously isolated patches.

Cluster count peaked early in the Consolidation phase and then fell as smaller clusters merged into larger connected structures. m_{eff} rose steadily from 0.25 to 0.7 of its normalised maximums. Beyond 70% BIG coverage, m_{eff} and patch area approached their maximum value. The pc showed apparent variability across the mid-range phases, attributed to the normalisation artefact rather than ecological instability.

We derived phase boundaries from the zero-crossings of the discrete second derivative of each metric trajectory. This revealed the coverage levels at which the sign of d^2y changed, and where a metric switched from accelerating to decelerating, or vice versa. The boundaries at 20%, 40%,

and 70% BIG coverage correspond to the three coverage levels at which the largest number of metrics simultaneously changed the direction of their rate of change across all four species-BIG type combinations (Figure 8).

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Figure 8: Results for second derivatives and inflection points across metrics

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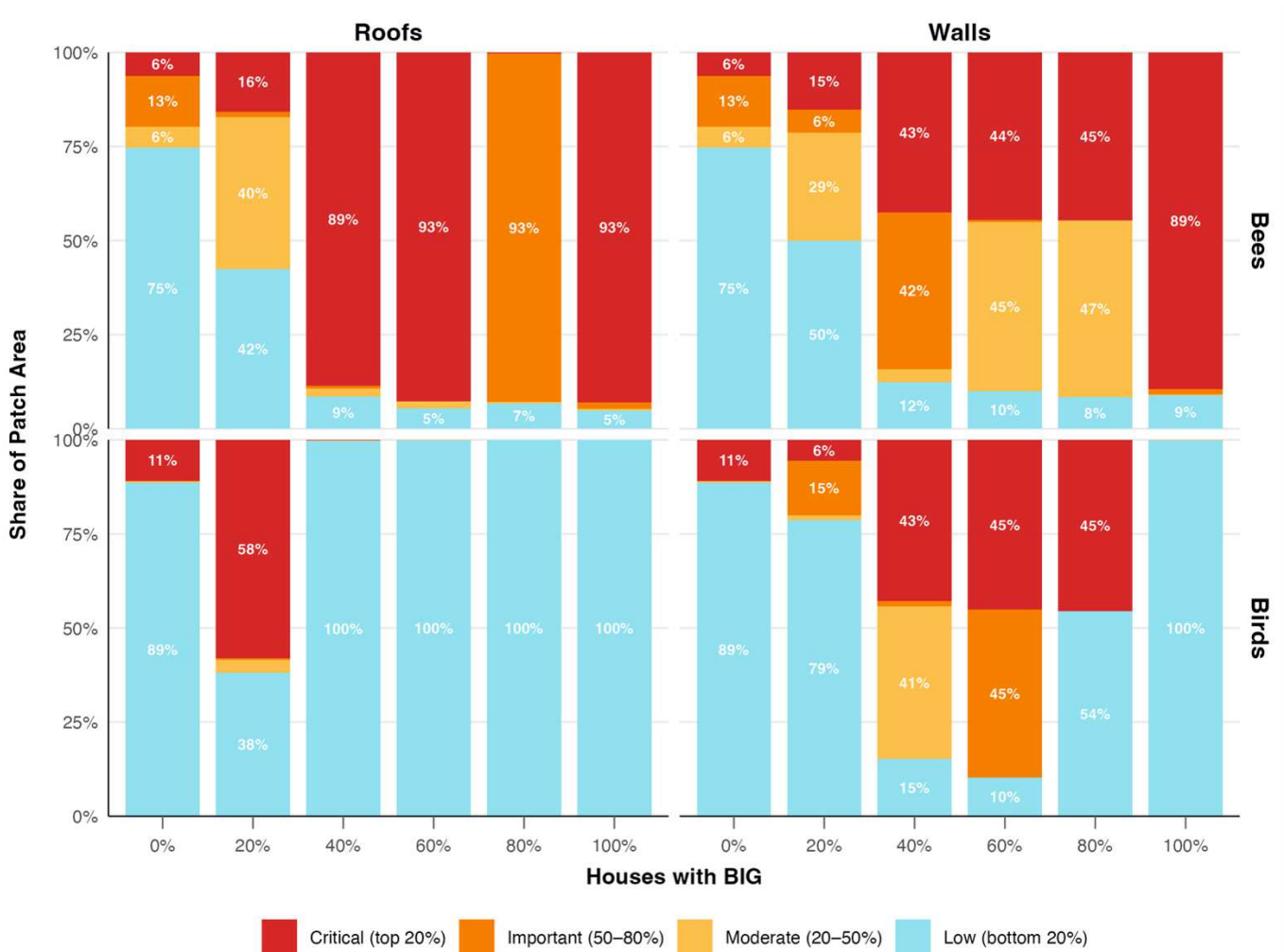
The second derivative approach captured threshold dynamics to determine whether a given curvature is accelerating or decelerating and identify ecologically productive investment or a point of diminishing returns. The negative second derivatives for patch count, edge count, and edge density at 10-20% BIG coverage confirmed that fragmentation reduction was most rapid during early adoption. The positive second derivative of the cluster count at 20-30% BIG coverage identified the percolation threshold as a genuine acceleration event, in which the network was gaining connections at an increasing rate. Beyond 70%, the second derivatives of all metrics converge to zero, confirming saturation as a structural property of the network rather than an artefact of the normalisation scale.

423

3.5 Geographical and network-driven impact

Using normalised *bc*, we classified nodes into four criticality categories: Critical (top 20%, above 80th percentile), Important (50th-80th percentile), Moderate (20th-50th percentile), and Low significance (bottom 20%, below 20th percentile) (Figure 9). At the baseline conditions, low-significance patches dominated the network for both insects and birds across roofs and walls, accounting for 75-89% of patch area. As BIG adoption increased, critical patches expanded, particularly for insects on roofs and walls, reaching 89-93% of total patch area at 40-100% adoption. For birds, roof-based BIG drove a rapid transition to entirely low-significance patches (100%) beyond 40% adoption, whereas wall-based BIG produced a more mixed criticality profile, with critical patches stabilising at around 43-45% from 40% adoption onward.

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Figure 9: The number of habitat patches per criticality category based on BC (betweenness centrality) for BIG types for both taxa

Network consolidation restructured the connectivity architecture by concentrating importance on fewer and more critical nodes. For insects, both roofs and walls produced predominantly important-to-critical patch classifications across the study area, with critical hotspots concentrated in the eastern and central zones. The 90th percentile *bc* threshold for insect networks increased 113% under roofs and 196% under walls, while mean normalised *bc* rose 93% (5.12×10^{-3} to 9.92×10^{-3}) for roofs and more steeply for walls. Ecological networks supporting birds showed a markedly different spatial pattern. Green roofs generated large contiguous low-significance areas in the western portions of the study area, while green walls produced a more graduated distribution with moderate patches dominating centrally and important-to-critical patches concentrated in the east. The 90th percentile threshold for bird-roof scenarios rose 300% (7.60×10^{-3} to 3.04×10^{-2}) and mean BC increased 294% (4.17×10^{-3} to 1.65×10^{-2}). Bird networks consolidated into configurations dominated by a small number of highly critical bottleneck nodes rather than broadly distributed importance (Figure 10).

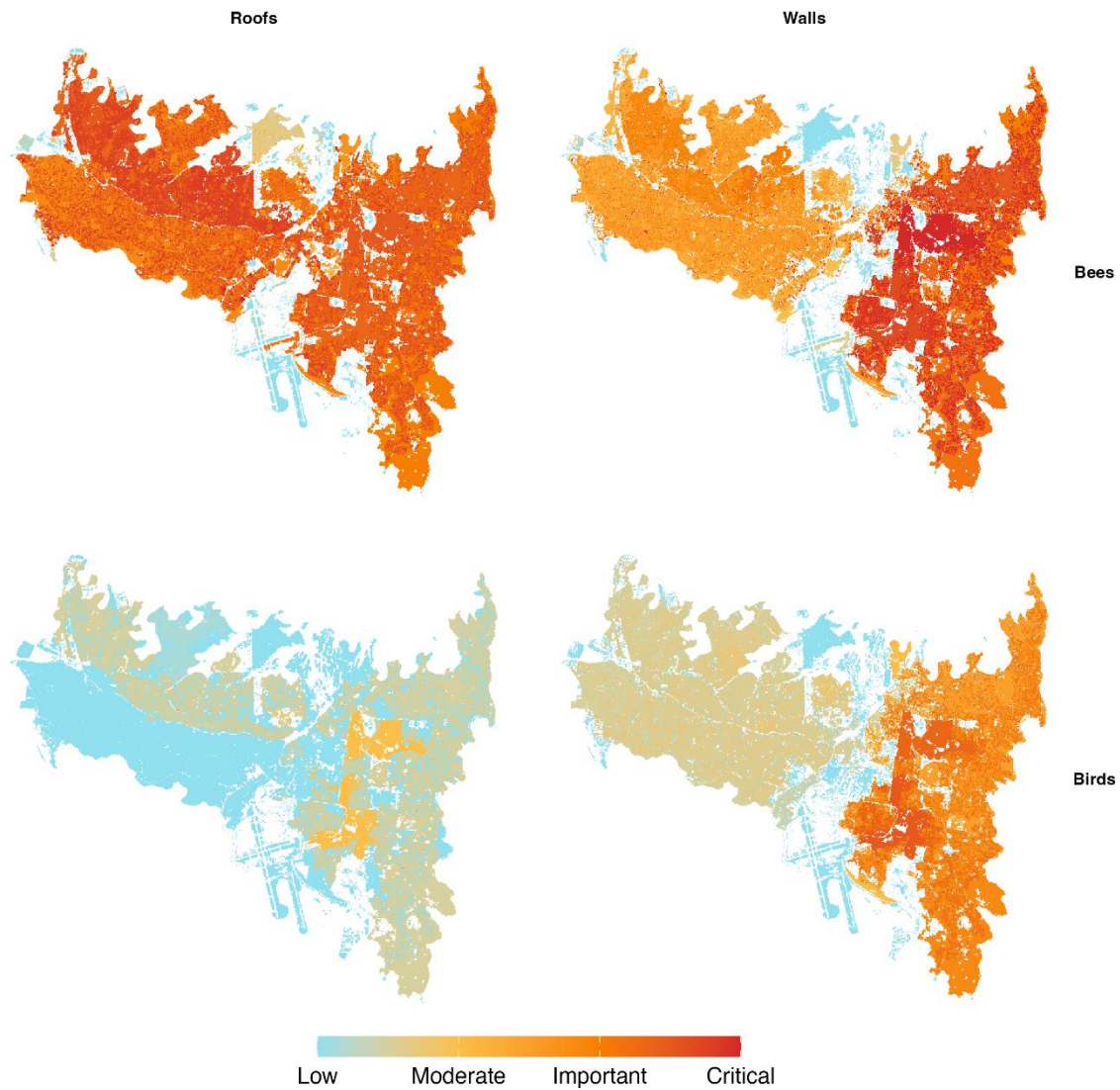


Figure 10: The geographical distribution of habitat patches based on their criticality

The spatial distribution of *bc* values across the study area presented a clear reorganisation of habitat patch criticality for insects and birds under the roof and wall scenarios. For insects, both roof and wall configurations produced broadly high-importance landscapes, with important-to-critical patches dominating across the study area and concentrated critical hotspots emerging in the eastern and central zones, particularly under the wall greening scenarios, where a distinct critical cluster was visible in the east. Ecological networks supporting birds showed a contrasting story. Under green roofs, large contiguous zones of low-significance patches dominated the western portions of the study area, with critical patches confined to isolated eastern clusters, indicating a spatially fragmented network heavily dependent on a small

number of bottleneck nodes. Green walls for birds produced a more intermediate pattern, with moderate-importance patches covering much of the central landscape and important-to-critical patches concentrated in the east, suggesting greater spatial redundancy in connectivity pathways compared to roofs. Across both taxa, walls consistently supported a more spatially distributed, higher-importance patch configuration than roofs.

4 Discussion

4.1 BIG's gains are phase-based and structural

BIG does not produce linear ecological improvements but instead induces phase-based transitions characterised by fragmentation collapse, reconnection, consolidation, and saturation. The most significant structural reorganisation in our Sydney case study occurred around 20% BIG coverage, where fragmentation indicators decline, and connectivity metrics accelerate. This was a response consistent with the percolation threshold described in landscape ecology theory, at which small increments of added habitat generate disproportionate gains in structural connectivity (Mohseni-Kabir et al., 2021). This suggests that modest but strategically distributed BIG can trigger disproportionate ecological restructuring (Boswell, Britton and Franks, 1998; Huth et al., 2014; With, 2022). The observed reduction in patch numbers and high-betweenness nodes (Kirk et al., 2023; Zhang et al., 2025) should not be interpreted as habitat loss but as network consolidation, reflecting a shift from a brittle, fragmentation-dependent network to a more resilient configuration supported by area-based connectivity.

The greatest return on ecological investment occurs within the 20-40% adoption range, where fragmentation reduction, cluster formation, and connectivity acceleration intersect (Boswell, Britton and Franks, 1998; Huth et al., 2014; With, 2022). This saturation dynamic reinforces the recommendation that strategic placement at ecologically critical locations yields greater benefits than uniform expansion of coverage. Diminishing marginal returns beyond 40-70% coverage

indicate that ecological gains plateau once structural consolidation is achieved, and unlimited BIG expansion does not proportionally increase ecological performance (see Figure 7).

The ecological benefits of BIG may not be adequately captured through area-based metrics alone. While total patch area increased steadily with coverage, transformative changes were evident only in fragmentation, configuration, and connectivity metrics (see Figure 4). Effective mesh size, edge density, cluster number, and betweenness centrality (Kirk et al., 2023; Zhang et al., 2025) had non-linear responses that surface coverage targets would not detect (see Figures 5 and 6). This demonstrates that BIG performance assessments must incorporate structural network metrics alongside area-based indicators. For insect pollinators, BIG progressively distributed network importance across many moderately critical stepping-stone nodes, reducing dependence on a few bottleneck patches (Braaker et al., 2014). Ecological networks appropriate for birds showed a contrasting pattern, particularly under roof-based BIG, where connectivity consolidated around a small number of highly critical eastern nodes, a configuration that is more vulnerable to patch loss than the insect network (Wu, Zhang, Luo, et al., 2022), which is largely comprised of underutilised building footprints converted to BIG infrastructure (see Figure 10). This spatial democratisation of network criticality explained the stabilisation of the configuration metric observed during the consolidation phase, where reduced volatility marks the transition from threshold-dependent to area-dependent dynamics. The identification of inflection points through second derivative analysis provided an interpretive lens for BIG assessment, distinguishing incremental improvements from ecological change and enabling planners to target investment where marginal ecological gains are maximised (see Figure 8).

4.2 Eco-legislative prescription of BIG

Rapid urbanisation, persistent urban sprawl and the increasing trend towards densification necessitate robust planning policies for urban greenery and BIG to mitigate environmental degradation and protect human health. Despite these well-documented benefits, urban

greenery is declining in many urban regions worldwide, especially in Asia and Oceania, highlighting an urgent need for targeted greening policies and increased investment (Falchetta & Hammad, 2025). Sustainability rating schemes, such as LEED (Leadership in Energy and Environmental Design), increasingly integrate BIG into their criteria (Reyes et al., 2024). Planning frameworks at the state and local levels have started to acknowledge the value of green infrastructure. The NSW Government's *Greener Places* policy framework guides green infrastructure planning and delivery by prioritising connectivity through integrating multifunctional spaces that encourage community involvement (NSW Government, 2020). The policy treats green infrastructure components such as parks, rivers, bushland, and private gardens to enable recreational access for the community, support an active lifestyle, and strengthen ecological resilience and biodiversity throughout the landscape. The *Sydney Green Grid* serves as a key component of the metropolitan strategy by developing an extensive network of open spaces that support recreation and waterway health, provide essential pathways for biodiversity corridors and species movement across the urban landscape (NSW Government, 2023).

The City of Sydney measured the city's canopy cover to be 19.2% in 2020 and developed a target to increase the overall canopy cover to 27% by 2050 following an interim goal of reaching 22% by 2030 (City of Sydney, 2021). The *Greening Sydney Strategy* recognises the role of an increased green cover in supporting urban wildlife, improving habitat connectivity, and creating new ecological niches for native species within the urban matrix (City of Sydney, 2021). The Strategy also reinforced actions to develop "greener buildings", including the development of a green factor score and the expansion of green roofs and walls. City of Sydney encourages the quality installation and maintenance of green roofs and walls through its *Green Roofs and Walls Policy Implementation Plan* (City of Sydney, 2020).

Other councils in the Greater Sydney region have already incorporated green roofs and walls into their strategies. For example, the Woollahra Municipal Council aimed to define green roofs and walls as part of its *Urban Forest Strategy 2024-2050* (Woollahra Municipal Council, 2023). The Inner West Council (2020) developed technical guidelines on green roofs, walls, and

541 facades, covering definitions, benefits, planning and design, construction, and maintenance.
542 Sydney's planning policies for urban greenery are comprehensive, but BIG primarily exists as a
543 component within these broader strategies. There is not yet a dedicated and standalone policy
544 specifically for BIG. The implementation of BIG is not yet driven by a distinct framework that
545 specifically promotes its uptake and evaluates its potential benefits. It is not clear how the extent
546 of BIG is considered in urban greening efforts.

547 The identification of a 20-40% transition window provided a quantitative foundation for policy
548 development. Rather than prescribing uniform greening mandates, legislative frameworks could
549 prioritise achieving a minimum BIG threshold that triggers reconnection dynamics, as coverage
550 below this threshold yields limited structural benefits. As green roofs consistently demonstrated
551 earlier acceleration in fragmentation reduction and connectivity gains than green walls (Wang et
552 al., 2022; Braaker et al., 2014), suggesting differentiated regulatory treatment by incentivising
553 roof-based greening in high-density precincts, while encouraging walls where vertical
554 connectivity enhances local microhabitat complexity (Chiquet, Dover and Mitchell, 2013) might
555 be beneficial.

556 The spatial pattern of persistent critical zones operated at landscape scales that transgress
557 administrative boundaries (Opdam, Steingrover and van Rooij, 2006; De Montis et al., 2016),
558 rendering council-by-council approaches inherently suboptimal. Since BIG benefits accelerated
559 based on cumulative coverage across the entire network rather than within individual
560 jurisdictions, urban areas must be considered collectively to achieve optimal ecological
561 outcomes. Strategic cross-jurisdictional coordination frameworks are therefore necessary to
562 target BIG deployment in persistent critical zones regardless of municipal boundaries, ensuring
563 that governance structures align with the ecological processes they seek to support. For
564 instance, the persistence of critical patches in the eastern part of the study area suggests
565 underlying landscape constraints that make certain locations disproportionately valuable
566 regardless of the overall extent of BIG.

4.3 Limitations and opportunities

The simulation relied on available datasets of building footprints, green infrastructure attributes, and species-relevant habitat proxies, which, while comprehensive, may not fully capture fine-scale ecological conditions. Variability in data resolution, such as inconsistencies among building records, land-use maps, and habitat surveys, introduces uncertainties into the simulations. Enhancing the accuracy and precision of data sources and collection techniques is central to promoting more robust assessments of the potential of BIG. Future research can focus on advancing both data quality and methodological precision. Long-term ecological monitoring through field surveys and aerial or satellite imagery will be important to verify how BIG adoption translates into habitat persistence and species movement over time. Tracking changes across multiple years would provide stronger evidence of whether early BIG-driven gains consolidate into permanent ecological corridors.

The scale of the simulations represents another constraint. We conducted the analyses at the suburb level, with building units and BIG coverage aggregated into discrete increments. While this approach is appropriate for testing thresholds and identifying broad-scale patterns, it simplifies fine-grained ecological processes. Within-precinct heterogeneity, such as microhabitat variation or differences in vegetation quality, was not fully incorporated, meaning that results might not reflect the ecological realities experienced by species at smaller spatial scales.

The modelling approaches and assumptions also come with limitations. For example, the use of percolation-based models assumes that coverage is uniformly distributed and that each new patch of greenery contributes equally to connectivity, when in practice, spatial configuration and edge effects influence network outcomes. The models also did not explicitly account for habitat quality, seasonal variation, or species interactions. While the results validated the universal percolation threshold, the simplifications mean that the exact location of the tipping point may shift under different ecological or urban conditions.

The simplified treatment of ecological connectivity when evaluating the benefits of BIG limits the capacity to quantify structural and functional relationships across the urban landscape. Future

594 efforts could include parameters to model resistance to movement in relation to urban
595 morphology. One option would be to assign a gradient of increasing resistance to building
596 height, as nuances in building height may act as more substantial barriers for certain species.
597 This would overcome the potential to overestimate connectivity by treating all potential links as
598 equally traversable and underrepresenting the structural constraints imposed by vertical urban
599 form.

600 Data were captured at a single point in time, observed gradients and inferred patterns are
601 necessarily extrapolated rather than empirically tracked. This means that temporal dynamics
602 such as seasonal shifts, maturation of biodiverse greenery, or evolving ecological interactions
603 cannot be detected, and the relationships presented here may differ if measured longitudinally.
604 Repeated monitoring over time could reveal trends, fluctuations, or nonlinear transitions that are
605 not visible in a static snapshot, potentially altering the apparent strength or direction of the
606 gradients reported in this analysis.

607 The adoption targets derived from this study assume even implementation of green roofs and
608 walls across precincts, but real-world uptake is often uneven, with clustering in some districts
609 and absence in others. This unevenness could produce connectivity outcomes that diverge from
610 the modelled thresholds. While the study provides evidence that BIG aligns with universal laws
611 of percolation, the reliance on aggregated data, assumptions of uniform coverage, and
612 simplified representation of ecological processes means that results should be interpreted as
613 indicative rather than predictive.

614 Further species-specific studies are essential to capture the differentiated responses to BIG
615 adoption. Targeted research into individual species' dispersal ranges, nesting or foraging
616 behaviours, and sensitivity to vertical versus horizontal habitats would refine the general trends
617 highlighted in this study and support more nuanced evidence-based design guidelines.

618 It is important to integrate a cost analysis alongside the ecological assessment of green roofs
619 and green walls. While this study demonstrates how BIG can enhance urban ecological

connectivity, further research should evaluate the economic feasibility of implementation at different scales. Incorporating installation, maintenance, and opportunity costs would enable a more robust understanding of the practicality of achieving the identified connectivity thresholds and allow for direct comparisons of the cost-effectiveness of roofs versus walls.

Buildings can be more systematically characterised for ecological design potential. Variations in height, roof slope, façade exposure, and adjacency to green space all influence a building's capacity to contribute to connectivity, which relates to buildings' resistance to species movement. Developing a classification framework that links building typologies with likely ecological "handprints" would provide planners and policymakers with a practical tool for prioritising investments.

5 Conclusions

This study demonstrates that building-integrated greenery (BIG) functions as a structural ecological intervention that systematically reorganises urban ecological networks across four distinct phases. Early adoption at 10-20% coverage rapidly reduces fragmentation; intermediate coverage of 20-40% initiates corridor formation and network reconnection; and higher coverage levels of 50-70%, particularly through green roofs, maximise functional connectivity for species requiring larger and more continuous habitat networks. The observed decline in patch numbers and high-criticality nodes reflects network consolidation rather than habitat loss, as small, isolated patches merge into larger, more coherent clusters that support longer-distance movement and reduce reliance on fragile stepping-stone habitats. This progression, from a dispersed mosaic of fragmented patches toward extensive, contiguous ecological structures, signals increased systemic robustness in which connectivity is supported by habitat matrices rather than a limited number of critical bottleneck nodes.

The ecological benefits of BIG operate at spatial scales that exceed individual parcels and local government boundaries, with habitat clusters and movement corridors expanding laterally

645 across administrative jurisdictions. The identification of critical coverage thresholds provides a
646 quantitative basis for embedding performance-based greening standards into planning systems,
647 supporting a shift from percentage-based targets to ecologically informed governance
648 frameworks. When deployed strategically and aligned with ecological thresholds, BIG moves
649 beyond building-level enhancement to function as distributed green infrastructure capable of
650 restructuring urban ecological systems at the metropolitan scale, offering a practical and
651 quantifiable mechanism to enhance biodiversity in dense urban environments.

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Supplementary data

Appendix A: Data sources

Table A.1: Data sources, types, and details

Type	Name	Date	Source	Institution	Scale/Extent	Content	Data type	Data resolution	Attributes needed	Original data sources
Species occurrence	Species occurrences included in download	Date of Publication: 2024-5-17	GBIF (Global Biodiversity Information Facility)		Global	Species occurrence record (14 GB)	Simple format (.csv)	unknown	• Species • Individual count • Year (for an annual analysis) • Locality - lon - lat (for choosing an area)	GBIF.org (17 May 2024) GBIF Occurrence Download https://doi.org/10.15468/dl.t65u9z

Land cover	DEA Land Cover (Landsat)	Digital Earth Australia	Australian Government Geoscience Australia	National	Coverage: 1988 to Present 1. Cultivated Terrestrial Vegetation *Percentage of cover *Life form (woody or herbaceous only) 2. Natural Terrestrial Vegetation *Percentage of cover *Life form (woody or herbaceous) 3. Natural Aquatic Vegetation *Percentage of cover *Life form (woody or herbaceous) *Water seasonality 4. Artificial Surfaces 5. Natural Bare *Percentage of bare cover 6. Water *Water persistence *Intertidal area	Data from AWS or NCI Thredds and can be used as GEOTIFF files	Resolution: 30 m	*Land cover classification *Lifeform *Vegetation cover *Permeable surfaces	Tissot, B., Mueller, N., Jorand, C., Ebadi, T., Ai, E., Kooymans, C., Harrison, M., Miller, J., Lucas, R., Metternicht, G., Owers, C.J., Clewley, D., Planque, C., Punalekar, S., Chua, S.M.T., Bunting, P., Lewis, B., Lymburner, L., Siggins, A, 2025. DEA Land Cover 30m. Geoscience Australia, Canberra. https://doi.org/10.26186/149976 [Accessed 5 October 2025]
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Soil landscape	Soil Landscapes of the Sydney 1:100,000 Sheet	Date of Asset Publication: 2009-01-01	SEED (The Central Resource for Sharing and Enabling Environmental Data in NSW)	NSW Department of Environment, Climate Change and Water	State	This map is one of a series of soil landscape maps that are intended for all of central and eastern NSW, based on standard 1:100,000 and 1:250,000 topographic sheets.	-GIS data -JPG map -Reports	unknown	permeable surfaces	State Government of NSW and NSW Department of Climate Change, Energy, the Environment and Water 2009, Soil Landscapes of the Sydney 1:100,000 Sheet, accessed from The Sharing and Enabling Environmental Data Portal [https://datasets.seed.nsw.gov.au/dataset/8e844673-be3b-4f38-923e-40c439354f8e], date accessed 2025-10-05.
Building footprints	Microsoft Building Footprints	From 2022 - 2023	Microsoft		Global, can zoom in to region	building footprints around the world.	Interactive map	unknown	building footprints	Microsoft - Planetary Computer ©2025
Road network	Road Segment Data from Data.NSW		Transport Open Data	NSW Government	State					Transport for NSW, n.d.
Road network	Sydney Region Carriageway	Created: 2020 Last updated: 2023	Transport Open Data	NSW Government	Sydney	State Roads, Sydney, carriageway, dual lines, lanes, length, region, road, roadway, single lines,				Transport for NSW, 2020.

						spatial, state, surfaces width, through lanes, vehicles, width				
Land parcel property theme	NSW Land Parcel Property Theme - Lot	Date Publishe d: 2025- 01-28 Date Updated : 2025- 01-28	Data.NSW		State	It consists of the digital cadastral database and associated parcel and property information. NSW Land Parcel and Property Theme Lot is made up of the following features within the NSW Land Parcel and Property Theme.Cada stral Fabric - LotLot - Depicts a parcel of land created on a survey plan. Each lot may be represented by standard lots, standard part lots,	JSON, ISO19115?ISO 19139 XML, RDF	unknow n	*Total site area *Lot	Spatial Services (DCS), 2025.

						strata or stratum.				
Habitat	National Connectivity Index 2.0 (2001-2018)	Date of Asset Publication: 2022-07-30 Date of Asset update:: 2023-08-31		Australian Government Department of Climate Change, Energy, the Environment and Water	National	This indicator (NCI version 2.0) measures the amount of connected habitat within a biological neighbourhood. It accounts for how habitat condition influences the perceived connectivity of habitat, thereby promoting or impeding biological movements such as foraging, dispersal	Image collection	unknown	Long term national connectivity index	Australian Government Department of Climate Change, Energy, the Environment and Water, 2022.

						and migration.				
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