Coding a Biophilic Core

Digital Design Tools for Toronto's Avian Habitat Networks

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
I understand that my thesis may be made electronically available to the public.

ABSTRACT

This research develops a methodology for computationally sensing, illustrating, and utilizing avian-focused patch networks to locate and inform ecological interventions in dense urban settings. These interventions are designed to extend the range of regional avian ecosystems, promoting beneficial urbanite-fauna interaction, often referred to as biophilia. This research is in response to Toronto's rapid densification, where in recent years, there has been a major increase of residential and mixed-use development in the downtown and central waterfront areas. Literature shows that as populations move to urban centers, there is a need for people to have access to thriving, biodiverse green space to foster mental health and environmental responsibility. At the same time, experts in landscape architecture and urbanism critique existing approaches to providing green space in cities, which often lead to sterile, ornamental lawns that limit urban biodiversity. To move beyond this approach, experts call for more dynamic and complex strategies in urban ecology.

As a response, this work explores computational methods of modeling networks and habitats that are borrowed from landscape ecology, graph theory, and parametric architecture, in the pursuit of a design methodology that thrives amidst the complexity and dynamic nature of urban and ecological systems. The resulting body of work involves simulating two dimensional and three-dimensional agent movement within patch networks, populating these networks with bird sighting data, and using this information to locate and inform a variety of intervention typologies. The work generated in this thesis is broken into three parts, with each part exploring a progressively smaller piece of urban fabric. The first part maps patch networks and suggests interventions in Toronto's downtown and central waterfront, the second part explores how these interventions affect bird movement in the three-dimensional fabric of CityPlace and Fort York, and the final part composes an artificial habitat that attracts local bird species and acts as a biophilic amenity for urbanites in CityPlace's Canoe Landing Park.

ACKNOWLEDGMENTS

I would like to begin by thanking my supervisor Maya Przybylski. Over the years, your guidance, critical insight, and mentorship in the field of computational design has shaped my approach to architecture and imbued my relationship to design with a sense of fascination and vigour.

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

BIOPHILIA AND URBANIZATION
UNPACKING TORONTO’S GREENSPACE
PATCH NETWORKS
DESIGN APPROACH AND METHODS

BIOPHILIA AND URBANIZATION

The concept of biophilia is central to the motivation behind this work. This idea that interaction with other living beings is psychologically beneficial to humans was first dubbed biophilia by biologist and theorist E. O. Wilson in his 1984 book by the same title.[1] Here, Wilson poetically describes biophilia as, "the innate tendency [in human beings] to focus on life and lifelike process. To an extent still undervalued in philosophy and religion, our existence depends on this propensity, our spirit is woven from it, hopes rise on its currents."[2] In the same year, this theory was strengthened by Roger S. Ulrich's scientific study, where he found that patients who had a window that looked at a natural setting recovered from surgery more quickly.[3] This idea of health and psychological benefits from exposure to nature was further explored in Environmental Psychologists Kaplan and Kaplan's 1989 book, *The experience of nature : a psychological perspective*.[4] This comprehensive book provided findings on beneficial relationships between humans and nature, as well as scientific methods for further research.

These foundational works buy Ulrich and Kaplan and Kaplan have since been expanded on by many studies, which have produced compelling findings, specifying the qualities and outcomes of these beneficial human-nature relationships. Key findings for this thesis include that a quantifiable "connectedness with nature" is linked to well being[5], that biodiversity is perceived by the public and is positively linked to well-being,[6] and that people exhibit better cooperation and make more environmentally sustainable decision after visual exposure to nature.[7] Latent within these findings, is a critique of current perceptions regarding urban greenspace. In a study linking perceived biodiversity to psychological well-being, the authors noted,

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1 Edward O. Wilson, Biophilia (Cambridge, Mass.; Cambridge, Mass. : Harvard University Press, 1984; Cambridge, Massachusetts: Harvard University Press, 1984).

2 Edward O. Wilson, Biophilia

3 Roger S. Ulrich, "View through a Window may Influence Recovery from Surgery," Science 224, no. 4647 (1984), 420-421.

4 Rachel Kaplan, The Experience of Nature : A Psychological Perspective, ed. Stephen Kaplan (Cambridge; New York: Cambridge University Press, 1989).

5 Renate Cervinka, Kathrin Röderer and Elisabeth Hefler, "Are Nature Lovers Happy? on various Indicators of Well- being and Connectedness with Nature," Journal of Health Psychology 17, no. 3 (2012), 379.

6 Richard Fuller et al., "Psychological Benefits of Greenspace Increase with Biodiversity," Biology Letters 3, no. 4 (2007), 390-394.

7 John M. Zelenski, Raelyne L. Dopko and Colin A. Capaldi, "Cooperation is in our Nature: Nature Exposure may Promote Cooperative and Environmentally Sustainable Behavior," *Journal of Environmental Psychology* 42 (2015), 24-31.

> Our results indicate that simply providing greenspace overlooks the fact that greenspaces can vary dramatically in their contribution to human health and biodiversity provision. Consideration of the quality of that space can ensure that it serves the multiple purposes of enhancing biodiversity, providing ecosystem services (Arnold & Gibbons 1996), creating opportunities for contact with nature (Miller 2005) and enhancing psychological well-being. [8]

This call for a focus on biodiversity in the design of urban greenspace is also made by Ecologist James R. Miller, who states concerns about the majority of the worlds population living in urban centers becoming disconnected from nature. He goes on to say that,

> If there is to be broad-based public support for biodiversity conservation, the places where people live and work should be designed so as to provide opportunities for meaningful interactions with the natural world. Doing so has the potential not only to engender support for protecting native species, but also to enhance human well-being.[9]

A key researcher bringing these ecological perspectives to the field of planning and architecture is Timothy Beatley. In his book, *Biophilic Cities Integrating Nature into Urban Design and Planning*, Beatley elaborates on the necessity of a biophilic city, saying,

> We need wonder and awe in our lives, and nature has the potential to amaze us, stimulate us, and propel us forward to want to learn more about our world. The qualities of wonder and fascination, the ability to nurture deep personal connection and involvement, visceral engagement in something larger than and outside ourselves, offer the potential for meaning in life few other things can provide. [10]

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8 Richard Fuller et al., "Psychological Benefits of Greenspace Increase with Biodiversity," Biology Letters 3, no. 4 (2007), 390-394.

9 James R. Miller, "Biodiversity Conservation and the Extinction of Experience," Trends in Ecology & Evolution 20, no. 8 (2005), 430-434.

10 Timothy Beatley, Biophilic Cities Integrating Nature into Urban Design and Planning (Washington, DC: Island Press, 2011).

Beatley's words bring specific attention to the role of architecture and landscape architecture in accomplishing urban biophilia. Here it is evident that, while it is important to design urban habitats to support biodiversity, designers also play a key role in mediating the interaction between urbanites other species in a way that accentuates the quality of wonder and fascination.

While Miller and Beatley discuss the importance of incorporating ecologies into the city, other architects, landscape architects and urbanists engage in a strong critique of existing approaches to providing urban green space. An early contributor to this discourse, Toronto Landscape Architect Michael Hough, criticizes the values of existing urban form, saying it isolates humans by ignoring natural dynamics and processes. Hough exemplifies this point by stating that abandoned urban sites offer more ecological resilience and diversity than planned parks, which are weak, resource intensive, and only serve shallow aesthetic purposes.[11]

A more recent addition to Hough's critique is Ecologists Cristina Ramalho and Richard Hobbs' 2012 call for "dynamic urban ecology". Here, they speak on the rapid, complex, and nonlinear growth of young modern cities (Toronto is a strong example of this), making a case for a methodology in urban ecology that is adaptable and dynamic, and thus, exhibits resiliency as urban context quickly and sporadically densifies.[12] This approach to urban ecology is in contrast to the standard notion of an urban-rural gradient, where "nature" is most dominant outside the city, and as you move towards the city's center, it fades and human's built environment becomes more dominant.

Another voice seeking to break the traditional narratives in urban landscape is Architect Emma Flynn. Flynn calls for "flexible, resilient, and efficient urban models" while focusing on how new technologies and socio-cultural shifts can create a scenario where urbanites and living ecologies are entwined as part of a larger system, rather than being viewed as separate entities.[13] To leverage this new social and technological paradigm, it is important to understand how views on nature are shifting in the age of the Anthropocene. In the past, the natural world has often been seen either as a "silent and passive backdrop" [14] , or as a wild, un-tameable antagonist. [15]As human's effect on the worlds geography and climate becomes clearer, it is apparent that we are much more intertwined in natural systems than previously culturally understood.

11 Michael Hough, *Cities and Natural Process* (London ; New York: Routledge, 1995).

12 Cristina E. Ramalho and Richard J. Hobbs, "Time for a Change: Dynamic Urban Ecology," *Trends in Ecology & Evolution* 27, no. 3 (2012), 179-188.

13 Emma Flynn, "(Experimenting with) Living Architecture: A Practice Perspective," *Architectural Research Quarterly* 20, no. 1 (2016), 20-28.

14 Chakrabarty, D The Climate of History: Four Theses. Critical Inquiry, 2009, (pg 197-222).

15 Margaret Atwood. Survival : A Thematic Guide to Canadian Literature, edited by House of Anansi Press, (Toronto: Anansi, 1972).

This interconnectedness could be interpreted through Bruno Latour's Actor-Network Theory, where everything is equal and irreducible, and it is the connection between things that gives meaning.[16] This philosophy puts us on the same ground as the natural systems we engage with and highlights our various interactions with the world around us as what is important. Object Oriented Ontologists, such as philosopher and Sci-Arc professor, Graham Harman take this leveling to the extreme by suggesting that humans, or plants or animals, by default are not any more important than any other object, such as a rock, or a smart-phone, or a pixel. Timothy Morton uses this philosophy to address our understanding of the natural world in this book *Ecology without Nature*, where he attempts to separate the idea of "natural" from ecology, stating that if we want to understand ourselves as equal to the world around us and thus think more environmentally, we must remove the idea of natural vs artificial, and forget the romantic aesthetics of nature.[17] By doing this we can better understand relationships between the elements in our environment, without prescribed notions of what is part of "nature" and what is not. In the scope of this thesis, Morton's theory would reject re-creation of pristine nature, and instead require a more complex and involved approach to urban greenspace, evaluating a multitude of relationships.

By removing the importance of what is perceived as natural, Morton's ideas also make room for technology and traditionally artificial constructs to help design biophilic green spaces. This thesis will aim to use this opportunity to digitally curate performative hybrid structures assembled from a variety of "natural" and "artificial" elements. These hybrid structures could be understood through the philosopher Donna Haraway's cyborg myth, which she describes as being about "transgressed boundaries, potent fusions, and dangerous possibilities...".[18] Haraway's cyborgs are products of the Anthropocene and do not respect traditional boundaries between human, animal, and machine, allowing for a novel urban ecology that intertwines all these elements.

In summary, It is important that designers acknowledge the importance of ecological agents, and provide for them as much as for humans. Rather than seeing ecology as it's own system, it must be seen it an intertwined component of our urban systems. Moving forward it is also important to recognize technology's role in synthesizing complex ecological relationships and creating potent hybrids.

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16 Harman, Graham. The Importance of Bruno Latour for Philosophy. Cultural Studies Review, [S.l.], v. 13, n. 1, p. 31–49, may 2011.

17 Timothy Morton. Ecology without Nature : Rethinking Environmental Aesthetics. (Cambridge, Mass. : Harvard University Press, 2007).

18 Donna Jeanne Haraway, Simians, Cyborgs, and Women : The Reinvention of Nature (New York: Routledge, 1991).

UNPACKING TORONTO'S GREENSPACE

While biophilic design is an important area or research for any city, the work presented in this thesis focuses on the City of Toronto. Toronto is chosen based on it's relative youth and rapid densification, which, as explained by Cristina Ramalho and Richard Hobbs, requires a new dynamic approach when it comes to designing greenspace.[19] Toronto is also an interesting case study because of it's underlying infrastructure of greenspace. While Toronto enjoys a large overall amount of greenspace, and considers itself a city within a park, preliminary research regarding the qualities of these spaces reveals that there are large differences in their ability to accommodate avian populations and provide biophilic experiences. Within Toronto's Ravines, Island/Spit, and older parks such as High Park, very robust habitats and ecologies can be found. These systems of greenspace carry a large amount of biodiversity, with Tommy Thompson park being of particular importance as a stop-over for migrating birds.

While these systems of green space are a strong resource for Toronto's human and non-human species, as greenspace in more central areas is examined, it becomes clear that many are lacking in their ability to provide habitat outside of these ecosystems. Part of this comes form the fact that many downtown parks are very focused on human occupation, consisting primarily of manicured lawns and sparse trees. It is this approach to urban green space that was addressed by Hough, as being aesthetically focused and lacking engagement in natural systems.[20] While these spaces may work for recreation, they do not provide habitat or a biophilic experience.

Toronto is in a position where its rapid development and sometimes questionable urban greenspace practices could risk isolating it's habitat ecosystems. This being said, if Toronto can allow species to penetrate its high density residential developments and create spaces where interaction with these regional ecologies can occur, it is uniquely positioned to take advantage of its periphery ecosystems to provide downtown biophilia.

19 Cristina E. Ramalho and Richard J. Hobbs, "Time for a Change: Dynamic Urban Ecology," *Trends in Ecology & Evolution* 27, no. 3 (2012), 179-188.

20 Michael Hough, *Cities and Natural Process* (London ; New York: Routledge, 1995).

Don Valley, Toronto

Tommy Thompson Park, Toronto

PERIPHERY
GREENSPACES

DOWNTOWN
GREENSPACES

Dog Park, Toronto

Trinity Bellwoods Park, Toronto

Fig 0.1. Comparison of periphery and central green spaces in Toronto

PATCH NETWORKS

> "Many things in cities take to the skies, and we should begin to understand the airspace above buildings, roads, and parks as life routes used by birds and bats and insects that spend at least some of their life in the air."[21]
> Timothy Beatley

To achieve species movement from Toronto's major habitats into it's core, this research focuses on bird movement in habitat patch networks. This exploration draws on patch principles originally developed by Landscape Ecologists, Wenche Dramstad, James Olson, and Richard Forman in their book, *Landscape Ecology Principles in Landscape Architecture and Land-use Planning*.[22] This book introduces the components and dynamics of patch networks, as described in Part I of this thesis.

While patch networks are quite complex, and require many important conditions to be effective, it has been shown that a network of small habitat patches can be effective in extending the range of large established habitats,[23] and if the small patch networks are strong enough, they can support bird populations in urban areas without connection to a larger habitat.[24] To better predict the success of a given path network, researchers in landscape ecology have developed a large body of work where multiple sophisticated methods of measuring landscape connectivity and species dispersal have been developed.[25] This field contains a great depth of technical reports, however, through a review of studies, this thesis draws several fundamental methods and principles to develop a body of work that

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21 Timothy Beatley, *Biophilic Cities Integrating Nature into Urban Design and Planning* (Washington, DC: Island Press, 2011).

22 Wenche E. Dramstad, *Landscape Ecology Principles in Landscape Architecture and Land-use Planning*, eds. James D. Olson and Richard T. T. Forman (Cambridge? Mass.] : Washington, DC : Washington, D.C.?]: Cambridge? Mass. : Harvard University Graduate School of Design ; Washington, DC : Island Press ; Washington, D.C.? : American Society of Landscape Architects, 1996).

23 Michael W. Strohbach, Susannah B. Lerman and Paige S. Warren, "Are Small Greening Areas Enhancing Bird Diversity? Insights from Community- Driven Greening Projects in Boston. (Report)," *Landscape and Urban Planning* 114 (2013), 69.

24 Erik Andersson and Örjan Bodin, "Practical Tool for Landscape Planning? an Empirical Investigation of Network Based Models of Habitat Fragmentation," *Ecography* 32, no. 1 (2009), 123-132.

25 Luc Pascual-Hortal and Santiago Saura, "Comparison and Development of New Graph- Based Landscape Connectivity Indices: Towards the Priorization of Habitat Patches and Corridors for Conservation," *Landscape Ecology* 21, no. 7 (2006), 959-967.

makes engaging Toronto's habitat networks accessible for designers.

These principles are:

- The use of graph structures to evaluate habitat connectivity [26]
- The ability to sense habitat elements from aerial imagery including ecotones, barriers, and stepping stones [27]
- The use of land cover data to measure resistance and calculate a "least cost path" between patches [28]
- The importance of threshold distances in evaluating species ability to move between patches [29]

By applying these network principles to Toronto's avian habitats, traditional urban-rural gradients can be subverted and biophilic greenspace in Toronto can be designed using more dynamic, complex, and performance-based models.

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26 Dean Urban and Timothy Keitt, "Landscape Connectivity: A Graph- Theoretic Perspective," *Ecology* 82, no. 5 (2001), 1205-1218.

27 Wei Hou, Marco Neubert and Ulrich Walz, "A Simplified Econet Model for Mapping and Evaluating Structural Connectivity with Particular Attention of Ecotones, Small Habitats, and Barriers," *Landscape and Urban Planning* 160 (2017), 28-37.

28 Deyong Yu et al., "Measuring Landscape Connectivity in a Urban Area for Biological Conservation," *CLEAN – Soil, Air, Water* 43, no. 4 (2015), 605-613.

29 Deyong Yu et al., "Measuring Landscape Connectivity in a Urban Area for Biological Conservation."

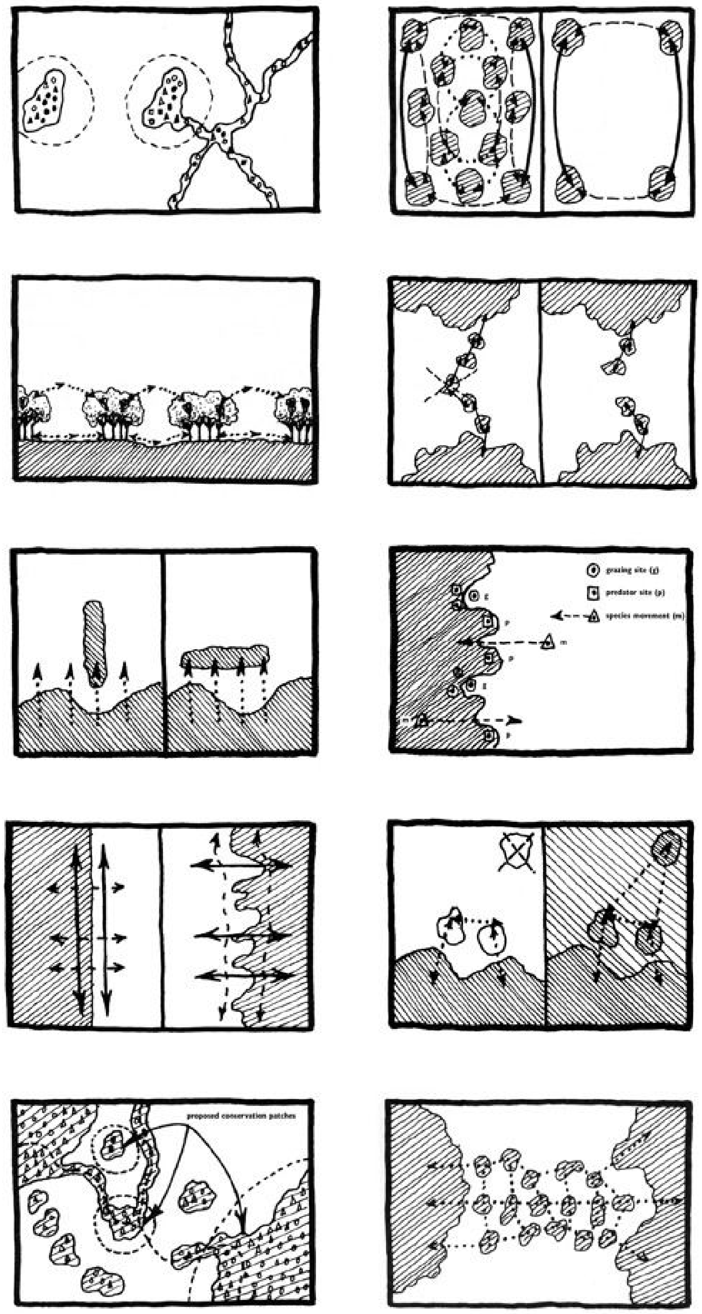


Fig 0.2. Movement diagrams: Patches, Edges, Corridors, Mosaics Landscape Ecology Principles

Landscape Architecture and Land-Use Planning, 1996

Wenche E. Dramstad, James D. Olson, and Richard T.T. Forman

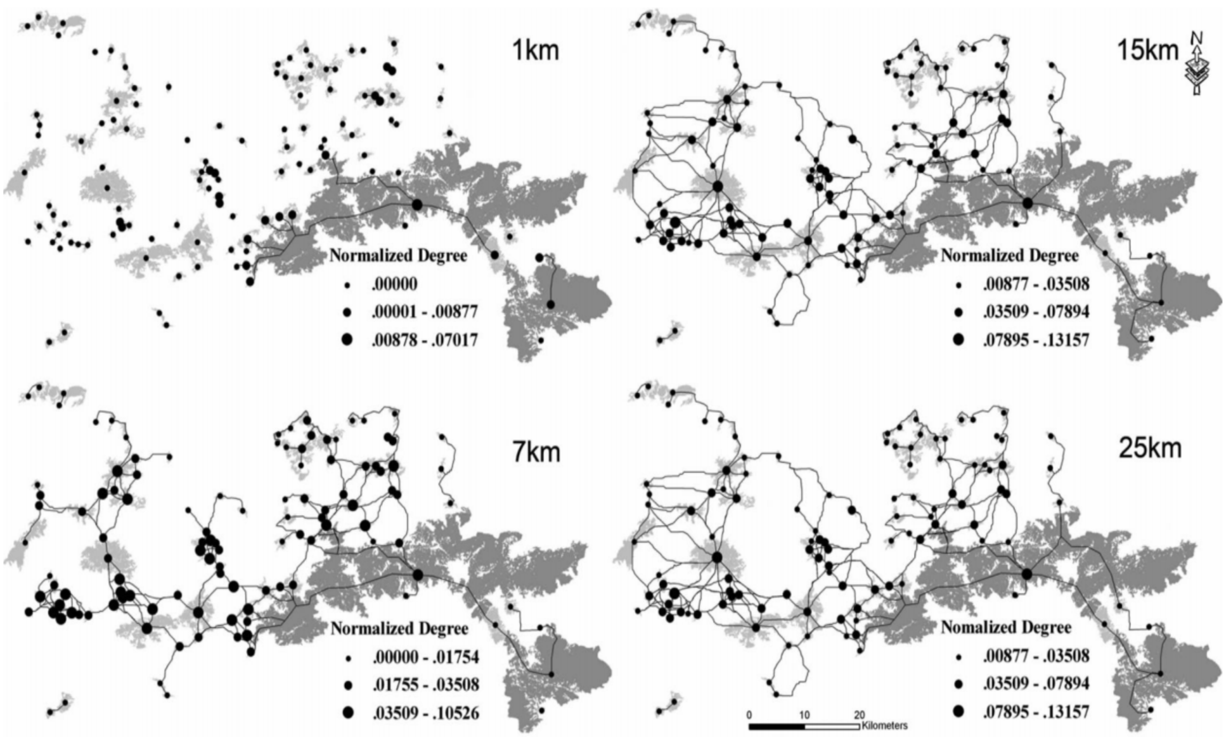


Fig 0.3. An appropriate planar graph presentation of the core habitat networks for different threshold distance scenarios (shown for 1, 7, 15, and 25 km)

Measuring Landscape Connectivity in a Urban Area for Biological Conservation, 2015

Deyong Yu, Yupeng Liu, Bin Xun, and Hongbo Shao

DESIGN APPROACH AND METHODS

From the outset, this research has been heavily invested in computational workflows, with the goal of testing several general benefits of digital tools in the field of urban ecology at multiple scales. These benefits include:

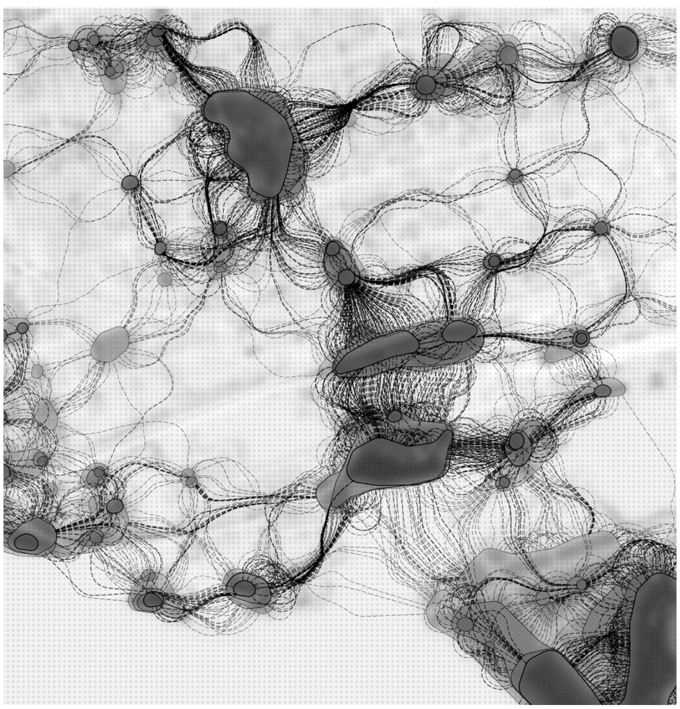
- The ability to focus on non-human design by using design parameters specific to other species
- The ability to generate and analyse complex networks and quickly update them as the city changes
- The ability to manage vast amounts of bird sighting data and utilize them in parametric habitat design
- The ability to generate and manipulate geometry that mimics the complexity, variety, and structure found in avian habitats.

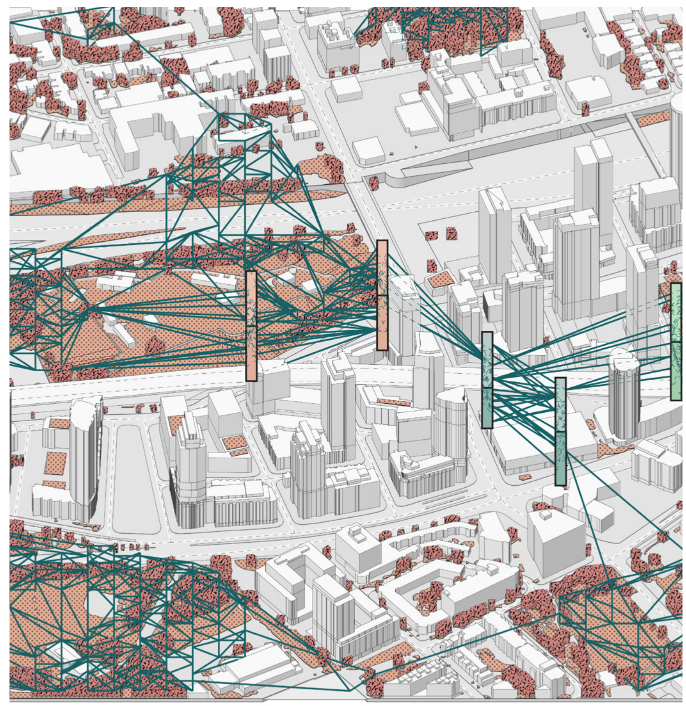
The computational tools developed in this thesis can be split into to categories. The first category includes network tools, which involve two-dimensional and three-dimensional network studies as well intervention placement tools. The second category includes habitat composition and assembly tools.

The network tools are based on computational methods from the landscape ecology studies. The use of computation is key in sensing urban fabric, building and analysing complex networks, and suggesting network improvements. This not only allows networks to intricately respond to urban fabric, but also means they can be rapidly updated as the fabric inevitably changes. The use of computation in this suite of tools also allows the network to store large amounts of species data that can inform intervention design.

The habitat composition and assembly tools seek to utilize the networks of patches, interventions, and data, to generate man-made habitats with the ability to host large amounts of bird diversity. The form and composition of these scaffolds are digitally tuned using the tools developed to simulate a variety of well established habitats, while providing the correct plants, cavities, and perching opportunities to attract numerous targeted local species.

The work presented in this thesis takes the form of several individual studies, each associated with a different computation tool. Each study is described using its inputs, process, and evaluation. The input section includes what data and portions of previous studies are used to inform the tool. The process section explains the logic and steps used by the computational tool. Lastly the evaluation section explains the results of the process and identifies how the outputs of the tool can inform further studies. While these studies occur at different scales and use different tools, the complete set of studies are informed by each other and work together to address the goals this thesis.





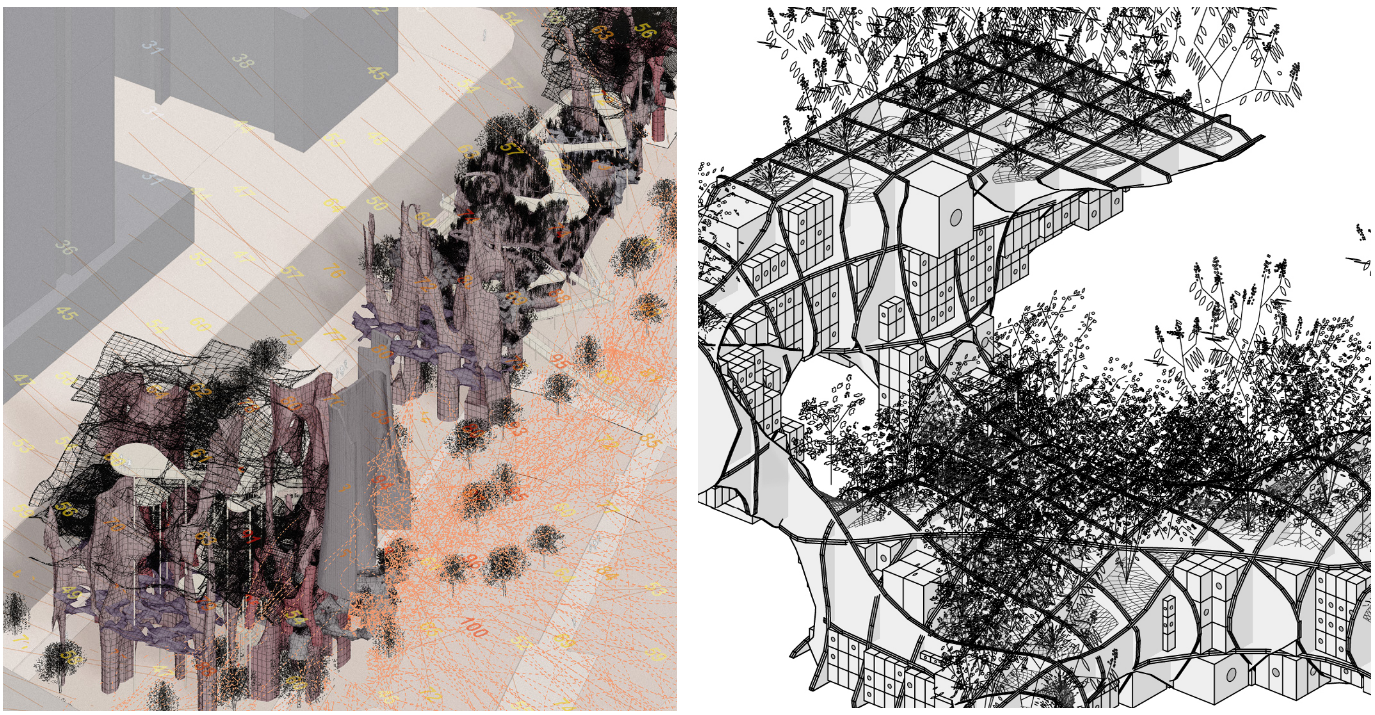


Fig 0.4. Multi-scalar computational design approach

PART I

REGIONAL PATCH NETWORK ANALYSIS
DATA INTEGRATION

Part I focuses on learning from landscape ecology to develop a language of patch networks. Here a series of network drawing studies are used to illuminate the networks of bird movement in the City of Toronto. Based on preliminary studies, West Downtown was chosen as a focus region, due to its potential connection to major ecosystems, existing park infrastructure, and heavy residential development. To improve the networks illustrated, a strategy of four synergistic interventions types are proposed along with a digital tool to locate them. Data collected from Online bird sighting records is then located within the network to further inform the design of these interventions, as explored in Part III.

PATCH COMPOSITION + QUALITIES

To begin understanding patch networks, it is important to identify the components of a patch network.

A *patch* is a significant area of fabric that can support species populations. Based on a review of literature in landscape ecology, several qualities of patches have be identified as important factors in their success as part of an avian habitat network. The two most important qualities are the size and proximity of the patches. Beyond this, a constantly varying edge condition and large ecotone,[30] as well as a high number of cavities and overall height of patch all contribute to its success. [31]

The *matrix* is the fabric between patches that is not conducive to ecological habitation. Therefore, birds must move through the matrix to utilize a network of patches. Matrices can have varying levels of *resistance* caused by physical and environmental barriers which distort bird's paths of travel and affect the distance they can travel from one patch to another.

An *ecotone* is the transition space between two habitat types, or in the case of this study, between a patch habitat and the matrix around it. Ecotones offer many benefits to a patch including increased biodiversity due to more variation in habitat and protection by acting as a buffer to the patch. An additional attribute, which greatly impacts this study, is the ability for an ecotone to promote bird movement from patch to patch through the matrix by softening what could be a harsh threshold.

30 Wenche E. Dramstad, James D. Olson and Richard T. T. Forman, *Landscape Ecology Principles in Landscape Architecture and Land-use Planning*, eds. James D. Olson and Richard T. T. Forman (Cambridge Mass.; Washington, DC: Harvard University Graduate School of Design ;Island Press; American Society of Landscape Architects, 1996).

31 Michael W. Strohbach, Susannah B. Lerman and Paige S. Warren, "Are Small Greening Areas Enhancing Bird Diversity? Insights from Community- Driven Greening Projects in Boston. (Report)," *Landscape and Urban Planning* 114 (2013), 69.

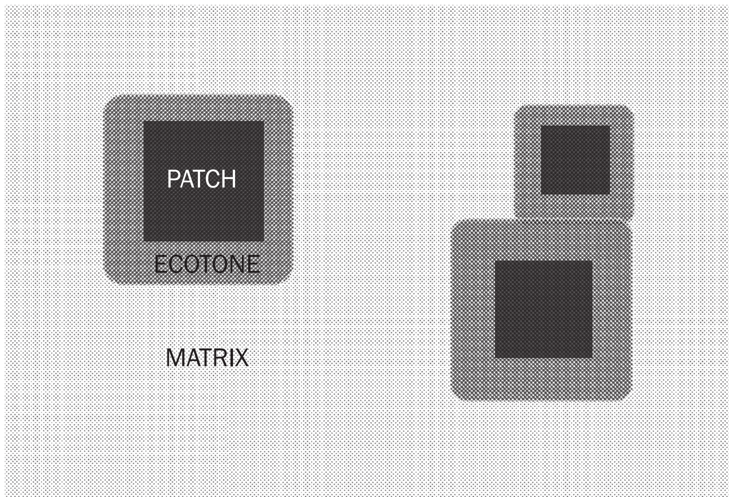


Fig 1.1. Patch network elements

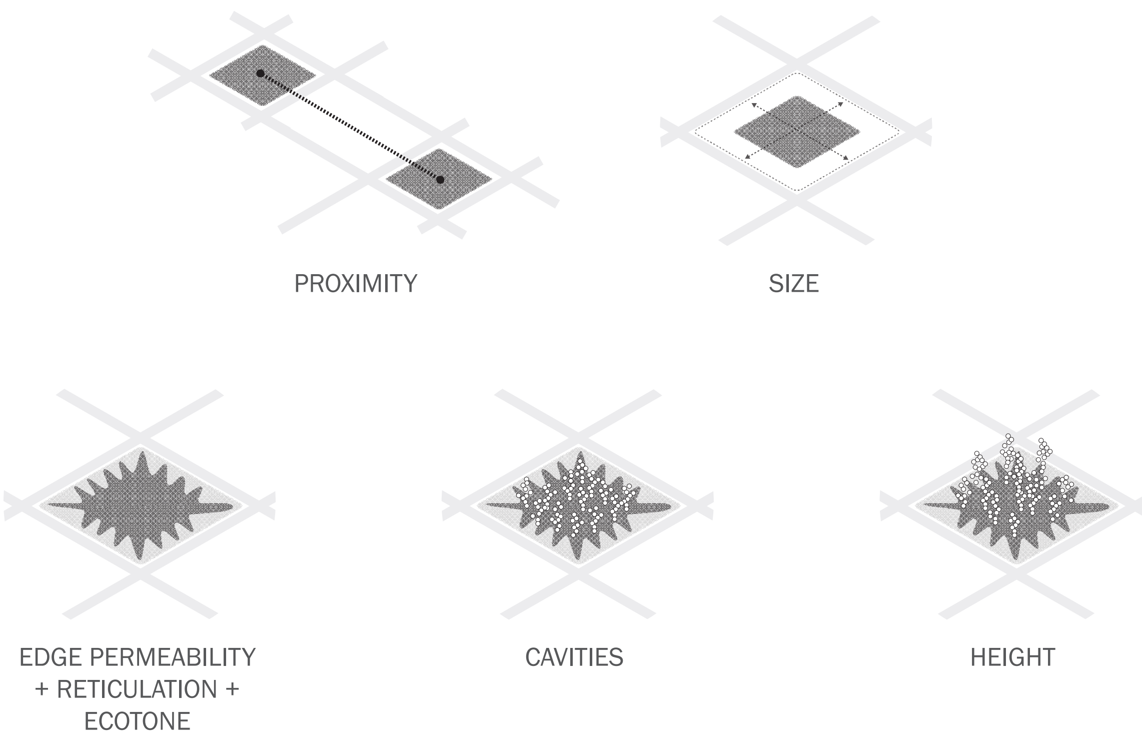


Fig 1.2. Indicators of patch success

NETWORK STUDY 01

[input]

To build the urban fabric in this study, information was collected from various geographic information system (GIS) databases. The purpose of this information is to identify and differentiate ecological territory in the target city. To do this, polygons delineating general “green space”, as well as significant vegetation cover were extracted from the city’s GIS database. In addition to this, boundaries of “natural cover” and “vegetation types” were gathered. All these boundaries were imported into Rhinoceros 3D, where the shapes containing vegetation and other natural cover were combined and defined as ecologically viable patches. Green space that did not contain significant vegetal cover was deemed a “potential patch”, assuming it could support species populations if altered.

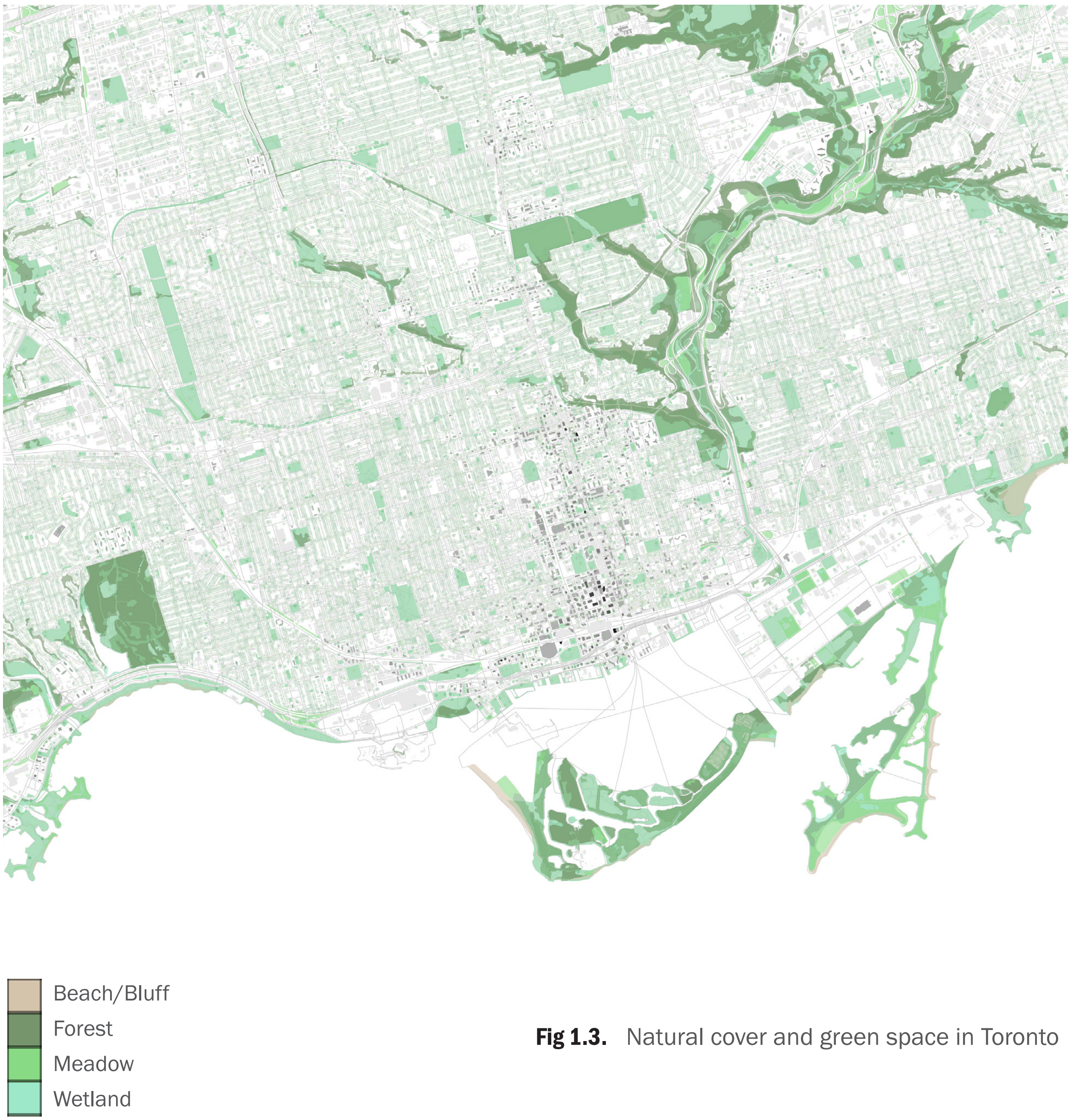


Fig 1.3. Natural cover and green space in Toronto

[process]

To begin building a preliminary ecological network, all patch polygons are populated with a grid of points. The network is built by connecting every point to every other point, before removing any connection above a specified threshold. The thresholds were selected by referencing "Behavioral barriers to non-migratory movements of birds" by Rebecca J. Harris & J. Michael Reed.[32] Based on the attributes of the species documented in this article, the network visualization procedure was completed at 100 m, 300 m, and 500 m thresholds. The paths generated at these thresholds are overlaid, with darker lines showing closer connections that are viable for more species. To illustrate potential connections, 1000m threshold lines are shown in the lightest layer.

[evaluation]

This map is useful in revealing the density of ecological connections in different regions. Here overall conditions can be seen, making this map helpful in choosing areas of closer study. Based on the strength of connections in the island and waterfront parks, and how those connection quickly taper off towards the core, the west downtown and waterfront of Toronto are selected for closer examination.

In this study, the agents are only understood with respect to their travel distance thresholds for moving from one patch to another. To perform more detailed studies, it is important to consider how qualities of patches, presence of ecotones, and resistance in the matrix effect these connections.

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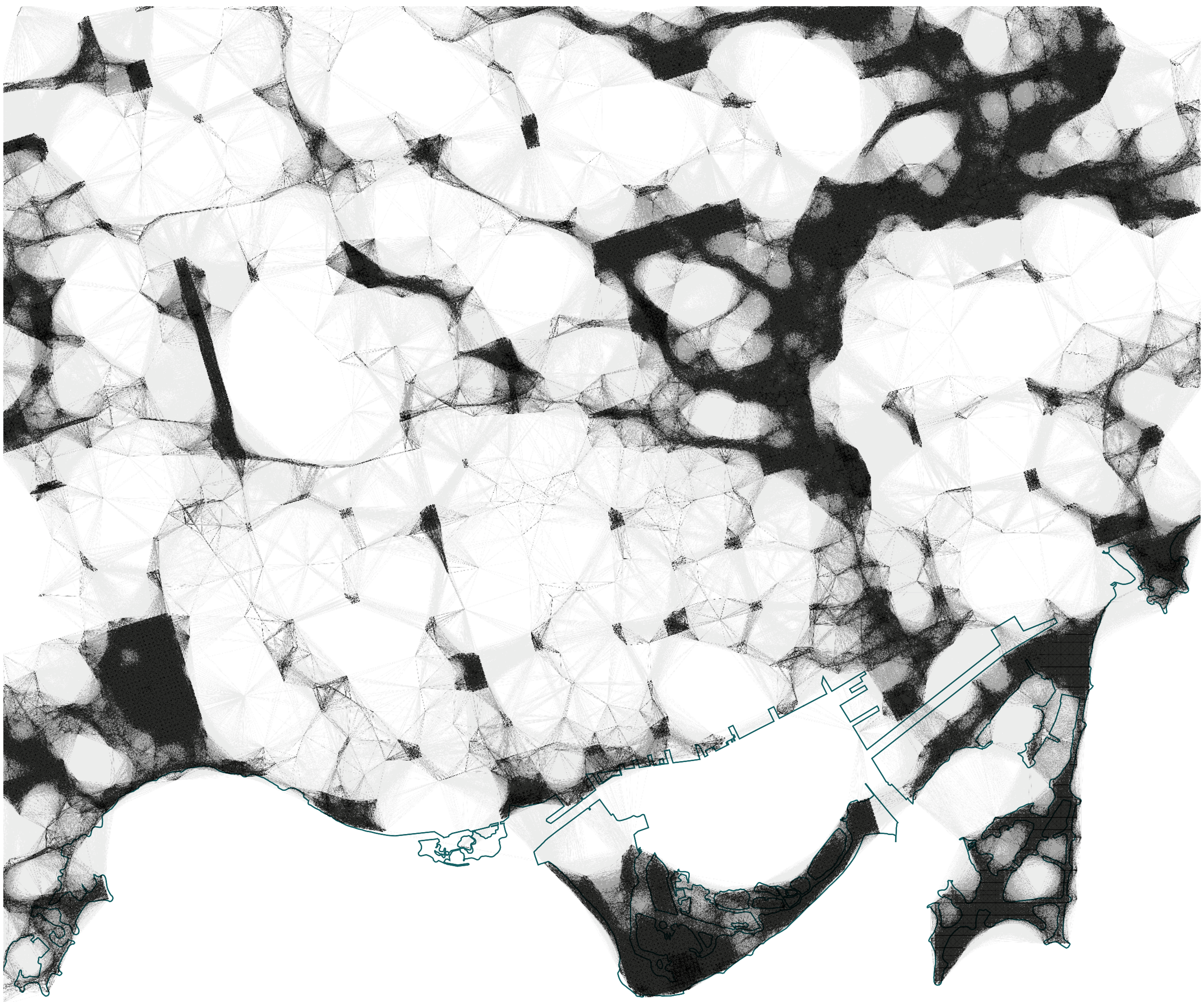
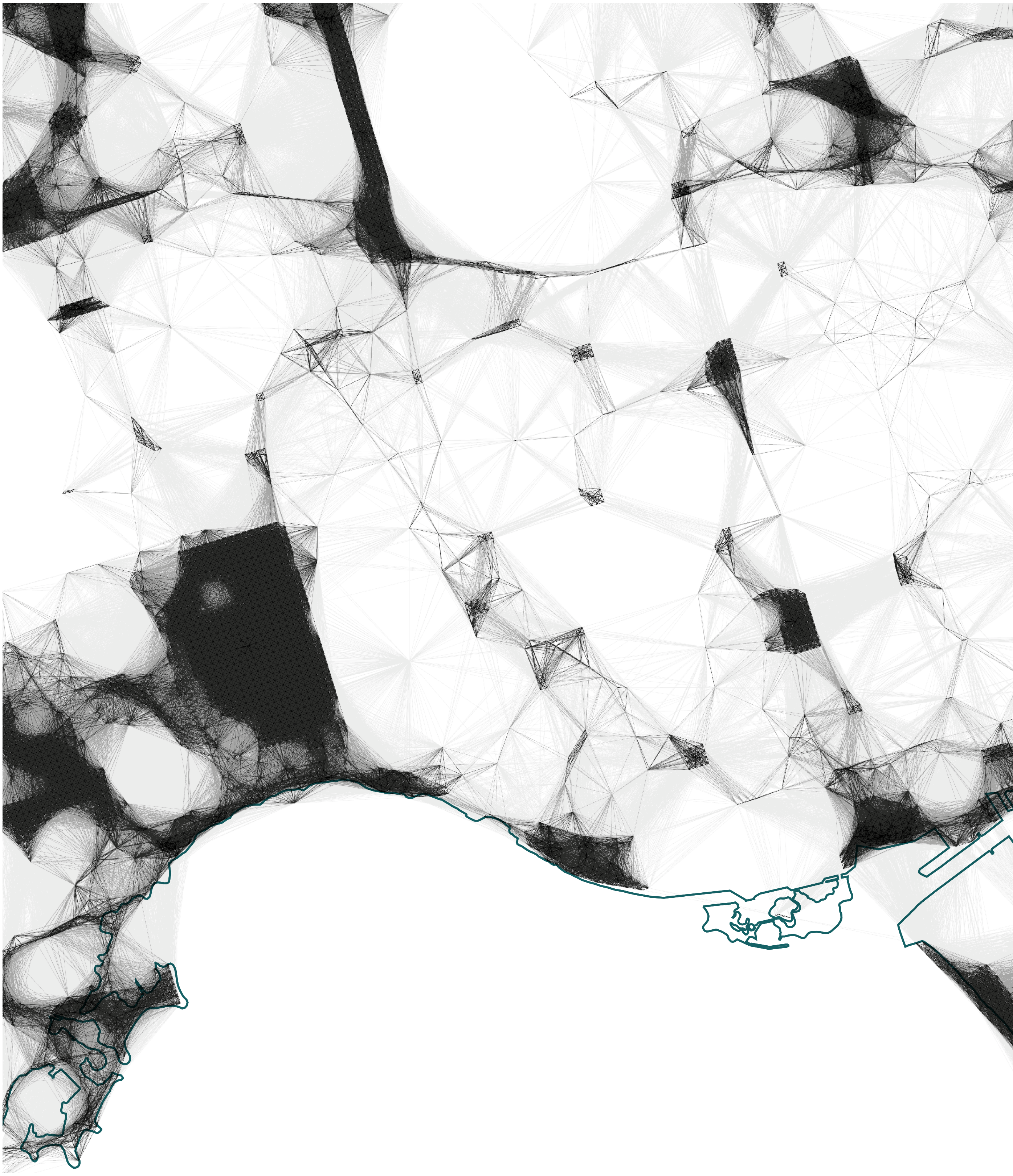
32 Rebecca J. Harris and J. M. Reed, "Behavioral Barriers to Non-Migratory Movements of Birds," *Annales Zoologici Fennici* 39, no. 4 (2002), 275-290.



100m Connection — 1000m Connection

Fig 1.4. Regional mapping of connection densities



100m Connection 1000m Connection

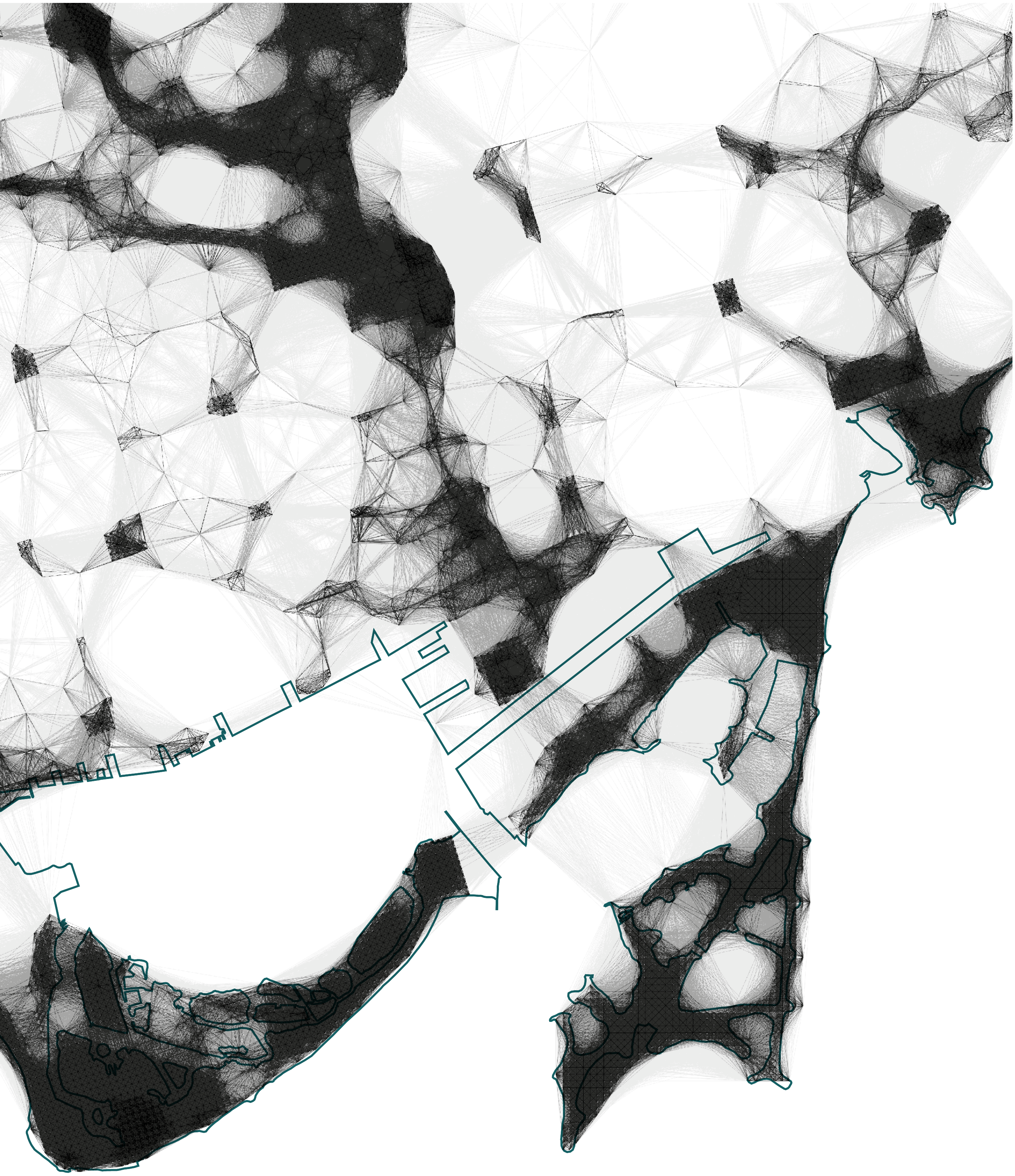


Fig 1.5. Connection densities - Detail

INTRODUCING RESISTANCE

To generate more accurate habitat networks, a resistance map is created to inform the following studies. This maps illustrates the ability for birds to move through or occupy urban fabric.

[input]
The resistance map is made up of multiple GIS and aerial imagery layers that are assigned a gray value based on the resistance level of their contents. Features with high levels of resistance such as highways and tall buildings are lighter, and features that accommodate birds such as tree canopies and other natural ground covers are darker.

[process]
The layers are overlaid to create a bitmap that is the sum of all the resistance layers. The grey value of the layer, and its weight when it is overlaid are chosen by the designer, based on an understanding of how different urban elements effect accommodation or resistance of birds. The map is then blurred to reduce the effect of insignificant elements and allow for more consistent digital sampling of the image.

[evaluation]
While any representation of patches and resistance is an estimation, this multi-layered approach is much more accurate than the previous use of greenspace polygons. In this method, the more layers compiled, the more sophisticated the representation of the fabric becomes. This resistance image can now inform what portions of fabric are considered a habitat patch, and how species moment will be affected by the matrix.

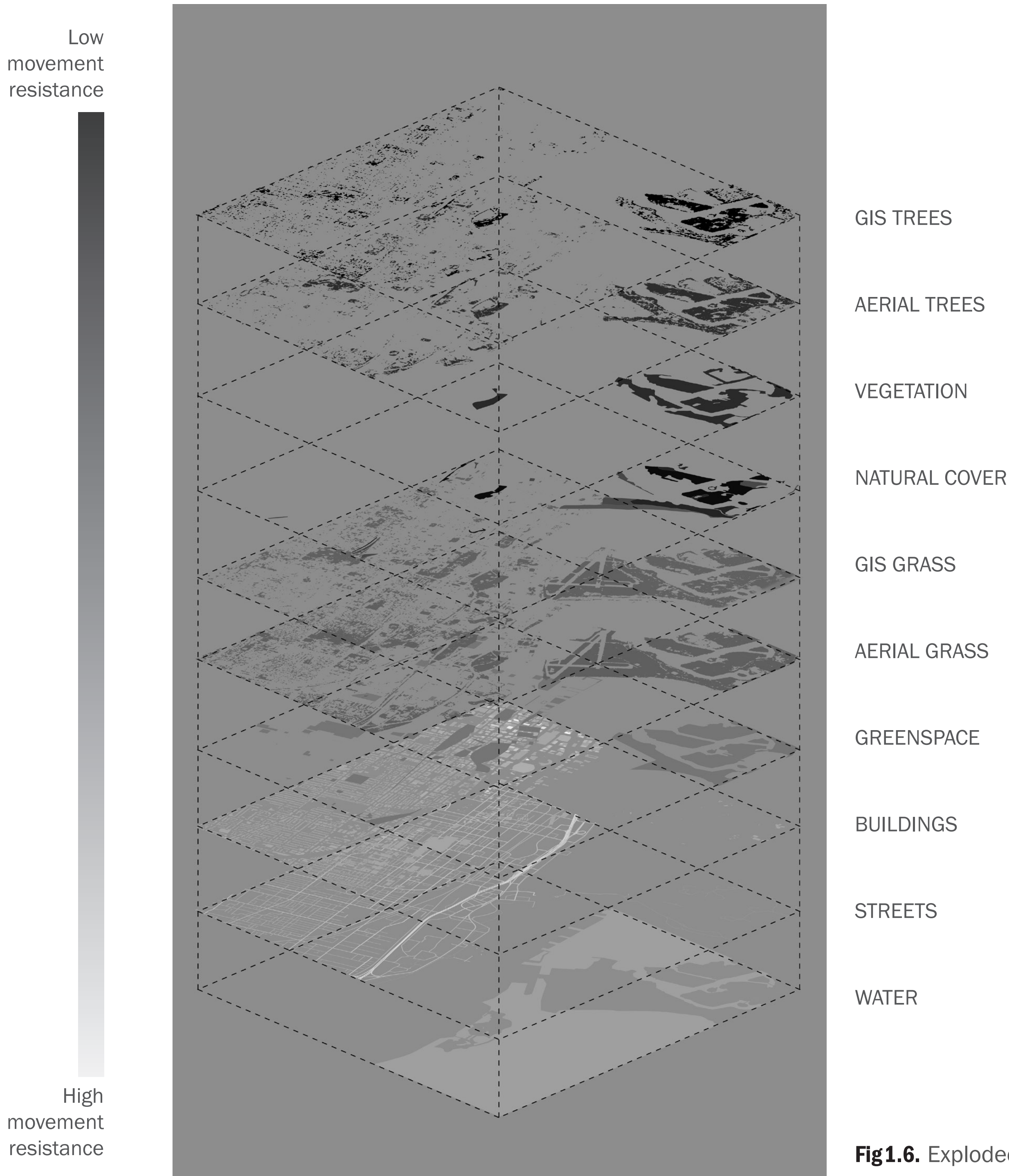


Fig 1.6. Exploded resistance and accommodation layers

Low movement resistance

Fig 1.7. Resistance map of West Downtown Toronto

High movement resistance

NETWORK STUDY 02

[input]
The resistance map is the only input for this study.

[process]
This study begins by sampling the resistance map image and pulling a grid of values based on the ability of each sample point to support or resist bird movement, with higher values relating to better habitat. Any points over a certain value are identified as patches and are subsequently connected to their nearest neighbours. Any connection that is over the maximum bird movement threshold is then removed. To adjust the remaining connections to favour paths of lower resistance, the paths are assigned control points that sample the resistance strength of their surrounding fabric and move towards values of lower resistance. Now when the path is redrawn through the control points, it avoids areas of strong resistance.

For the final map, this process is run using multiple patch thresholds, with thicker lines connecting stronger patches. These paths can also be coloured according to the connection length and resistance met along the path. Here red shows the highest resistance and orange, the lowest.

[evaluation]
This network study begins to illustrate bird movement in urban fabric and can be useful in informing interventions to improve the network. However, there are some flaws with this type of network.

The first issue is that connecting any point within a specific distance, and then simply distorting the path if it met resistance leaves connections where they may not be possible. Another issue is that the more a path is distorted the less accurate the distortion becomes, leaving inaccurate paths in extreme areas. To combat this, the third network study develops an agent-based approach rather than using nearest neighbour connections.

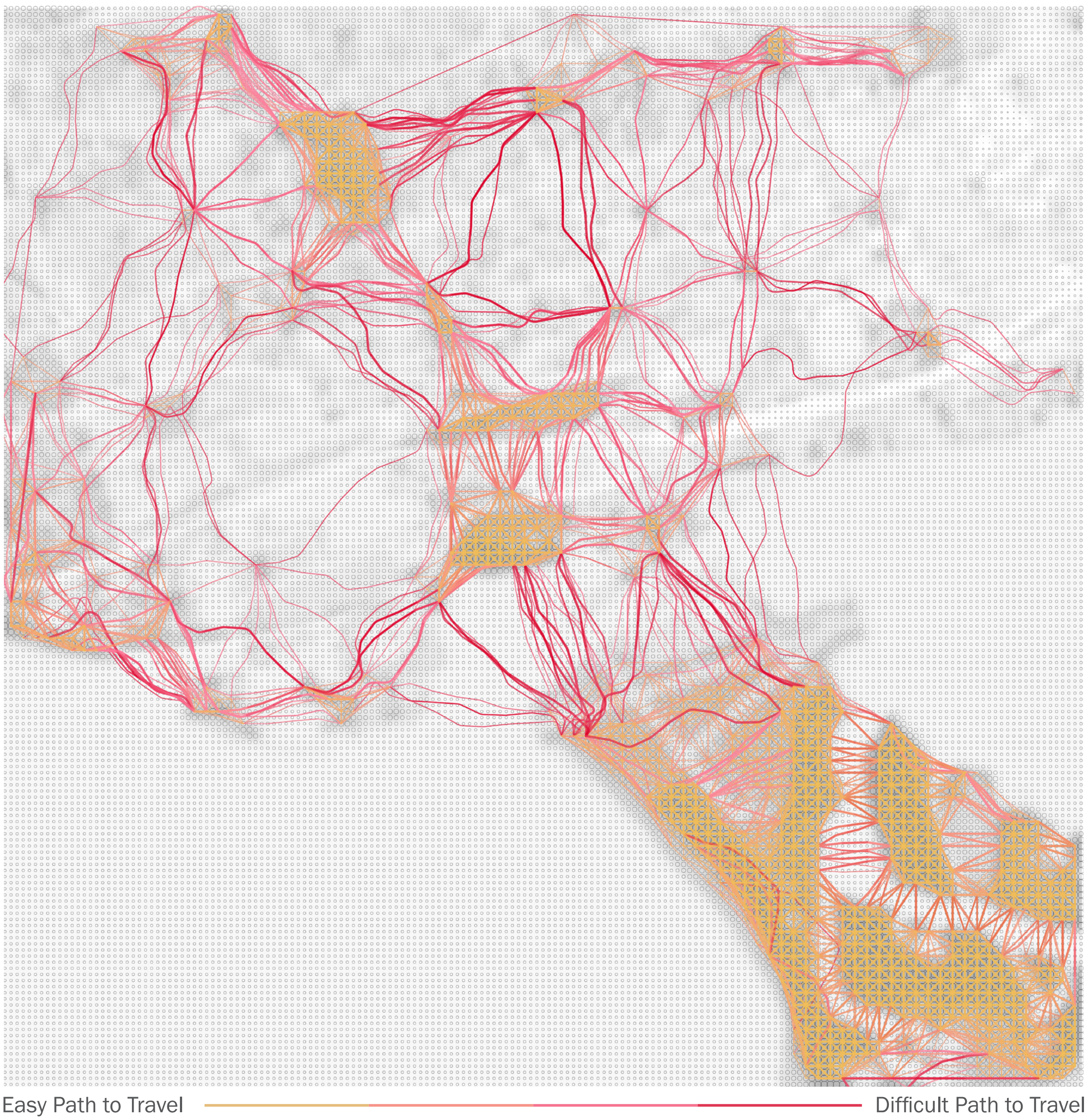
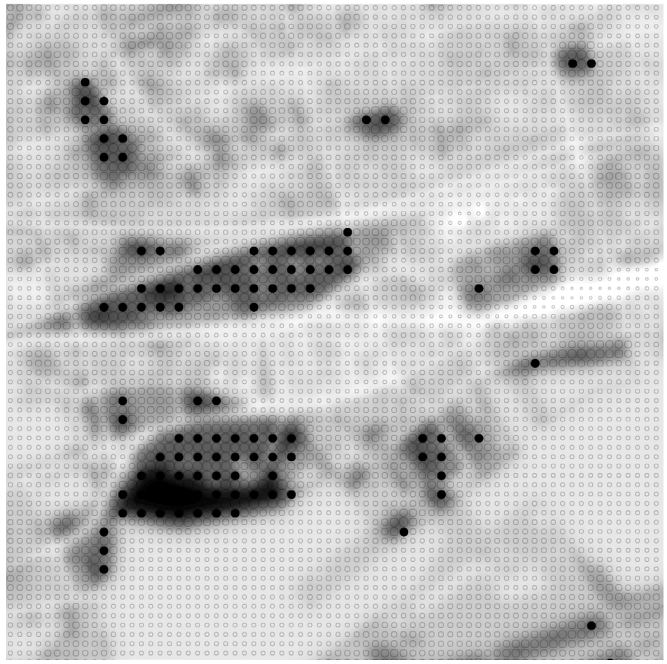


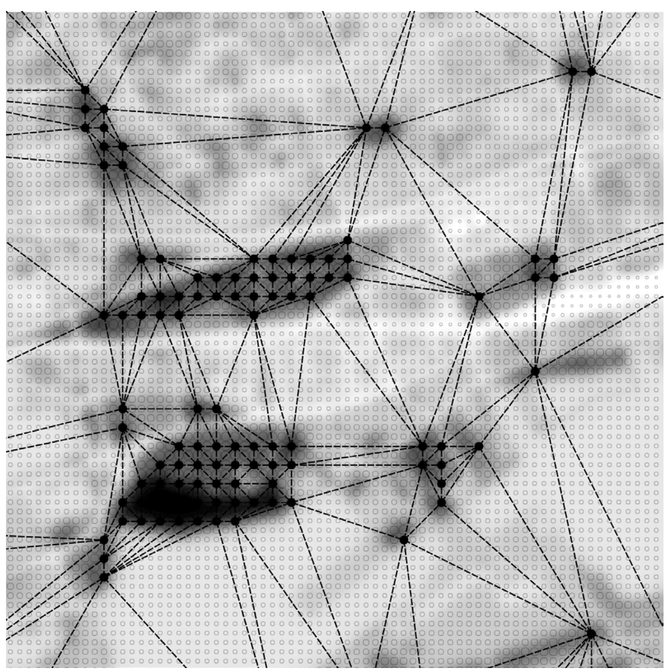
Fig 1.8. Nearest neighbour network with paths adjusted for fabric resistance

1



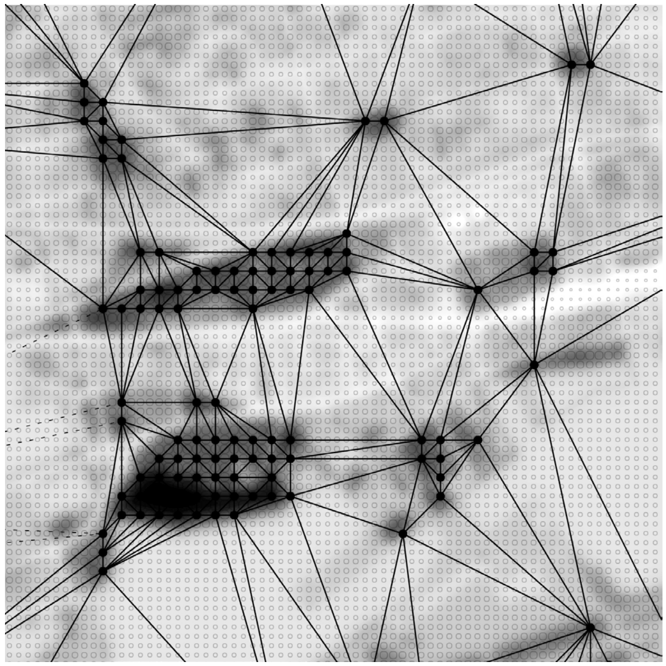
• Patch Point

2



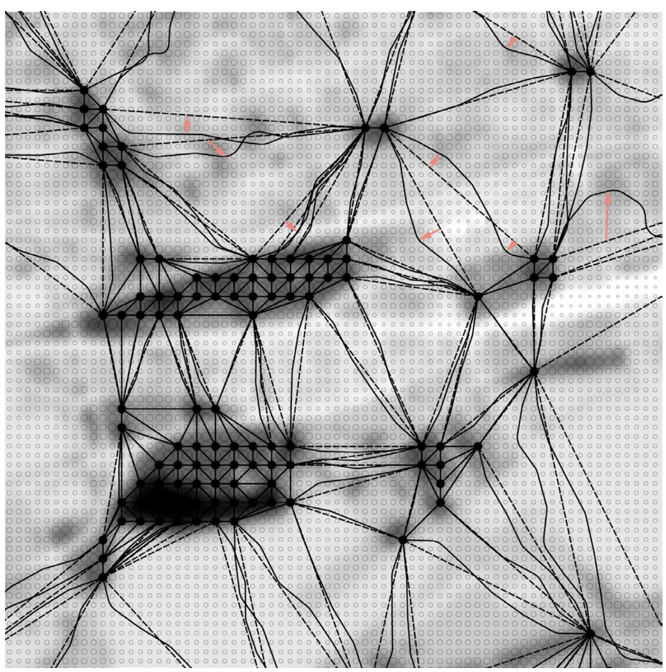
— Connection

3



— — Connection > 1000 m

4



Connection Distortion

Fig 1.9. Nearest neighbour network building process

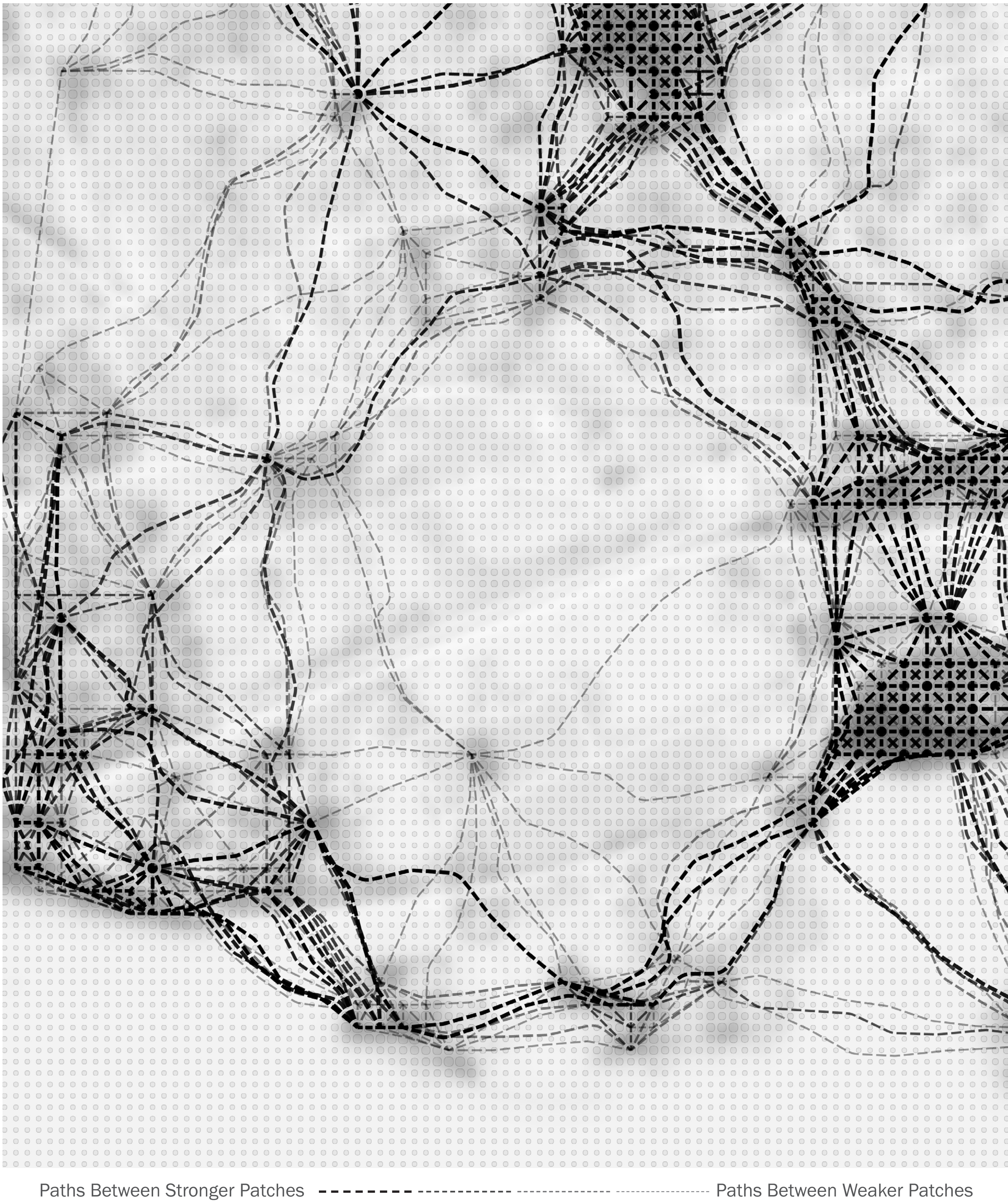

Paths Between Stronger Patches
Paths Between Weaker Patches

Fig 1.10. Nearest neighbour network – Detail

NETWORK STUDY 03

[input]
Again, the resistance map is the only input for this study.

[process]
The resistance map is sampled and this time habitat points are combined into a habitat patch polyline**.** "Agents" are then emitted outward from the patch into the matrix. As they move, these agents sense a portion of the resistance map in front of them, constantly moving forwards and towards areas that better support birds. If on their journey, one of these agents arrives at another patch, it stops moving and its path is solidified as a connection. **A**gents that do not reach a patch in 1000m of travel are disregarded. Once again, the simulation in carried out at multiple patch thresholds and coloured to illustrate connection strength.

[evaluation]
By allowing paths to emerge though agent movement, this map study offers a stronger illustration of the network. Here, key movement corridors and significant barriers in the matrix become much more prominent. However, while many corridors and paths are revealed, the number of red paths show how many of these vital connections are quite long and encounter a large amount of resistance.

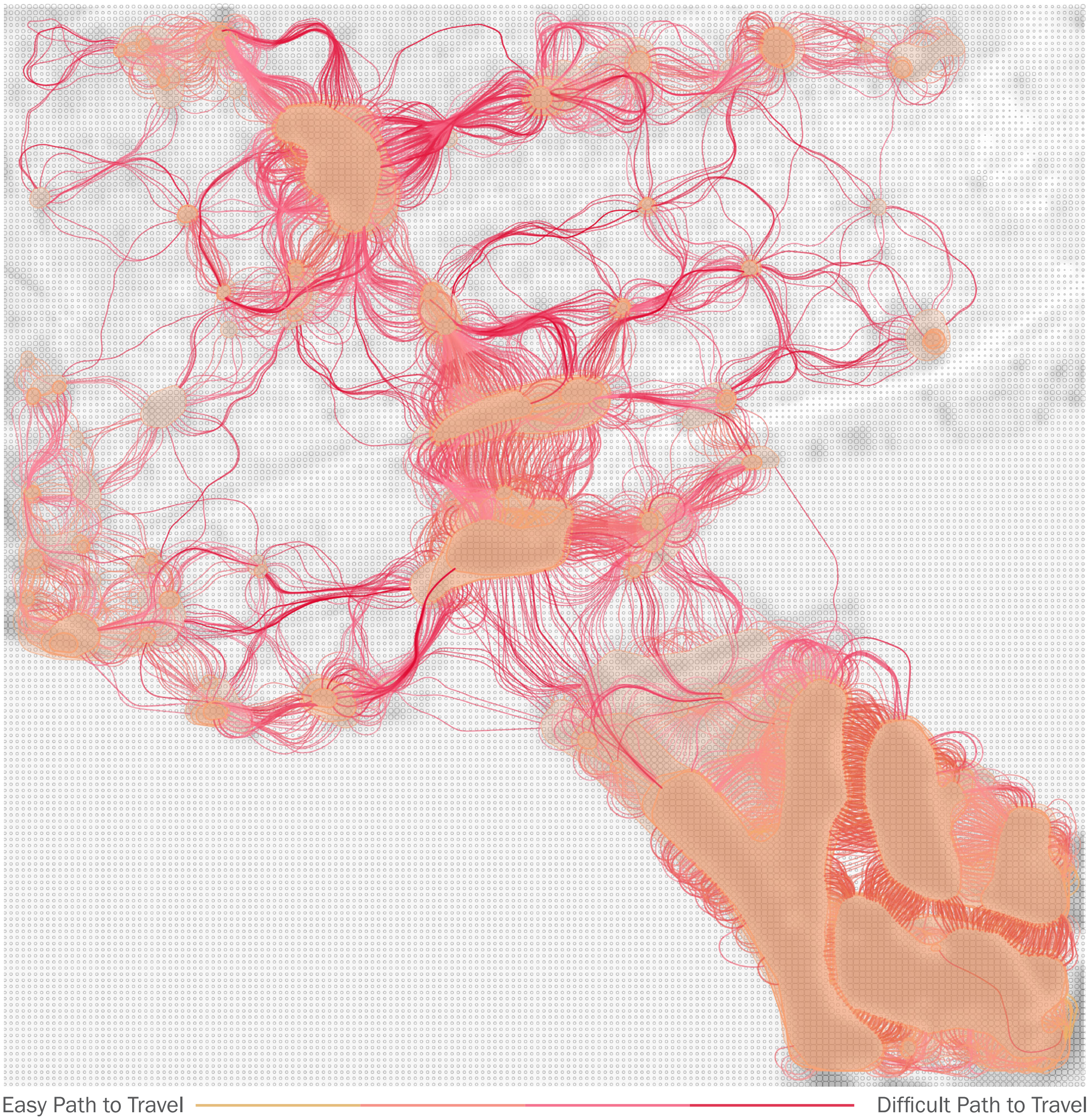
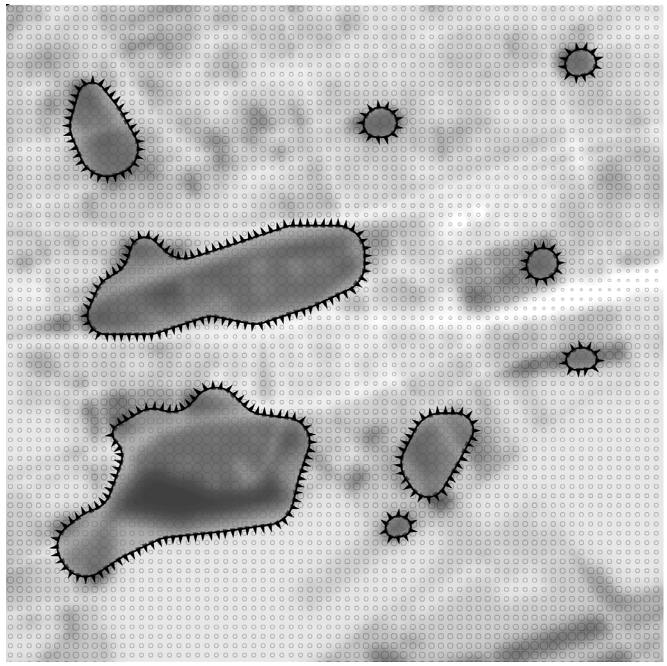


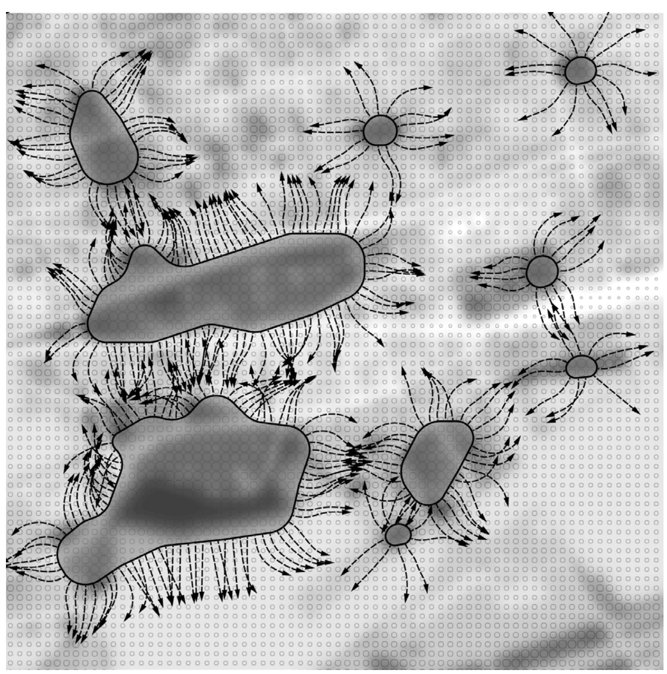
Fig 1.11. Agent driven network

1



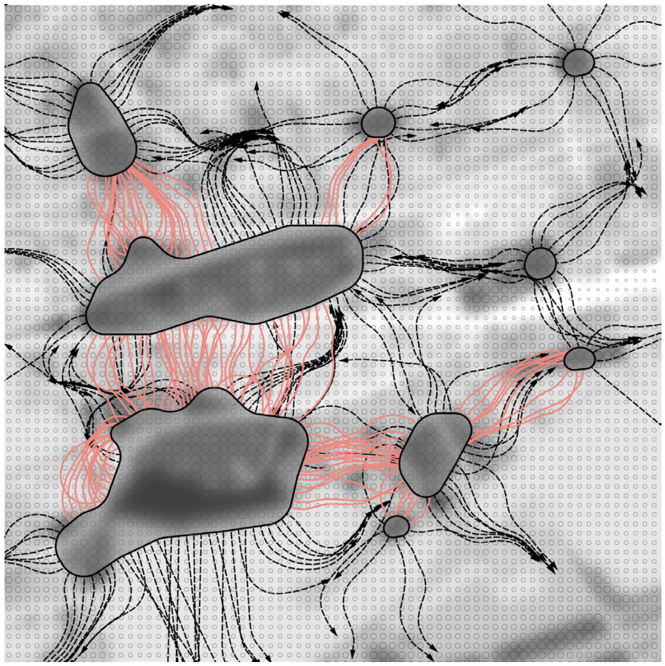
► Agent   Patch

2



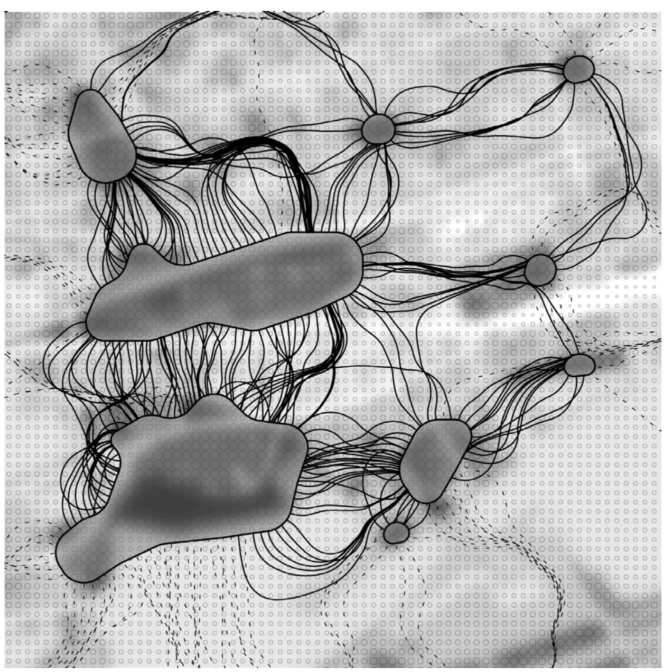
Agent Path

3



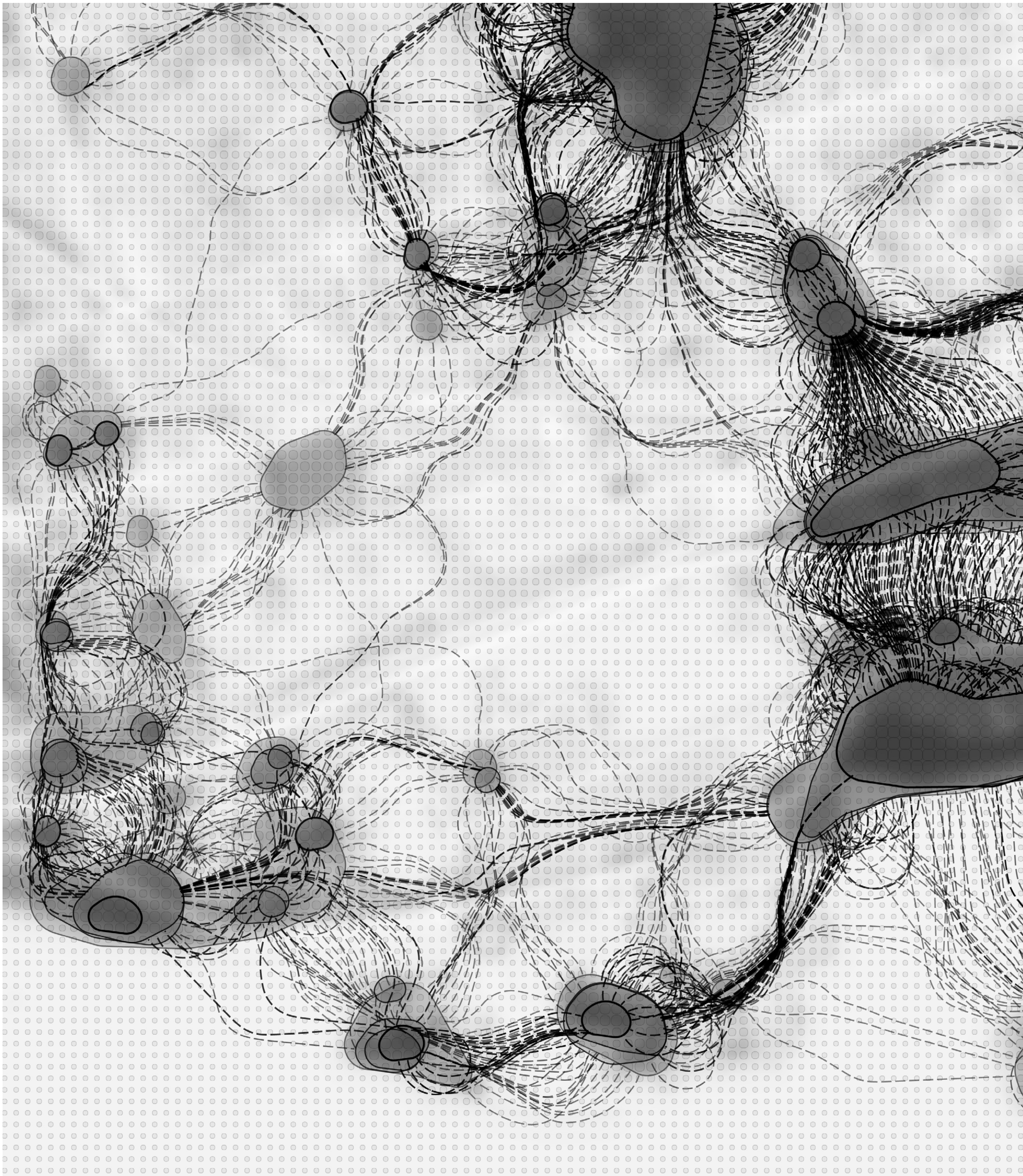
Successful Connection

4



Unsuccessful Connection

Fig 1.12. Agent network building process



Paths Between Stronger Patches ‐‐‐‐‐‐‐‐ Paths Between Weaker Patches

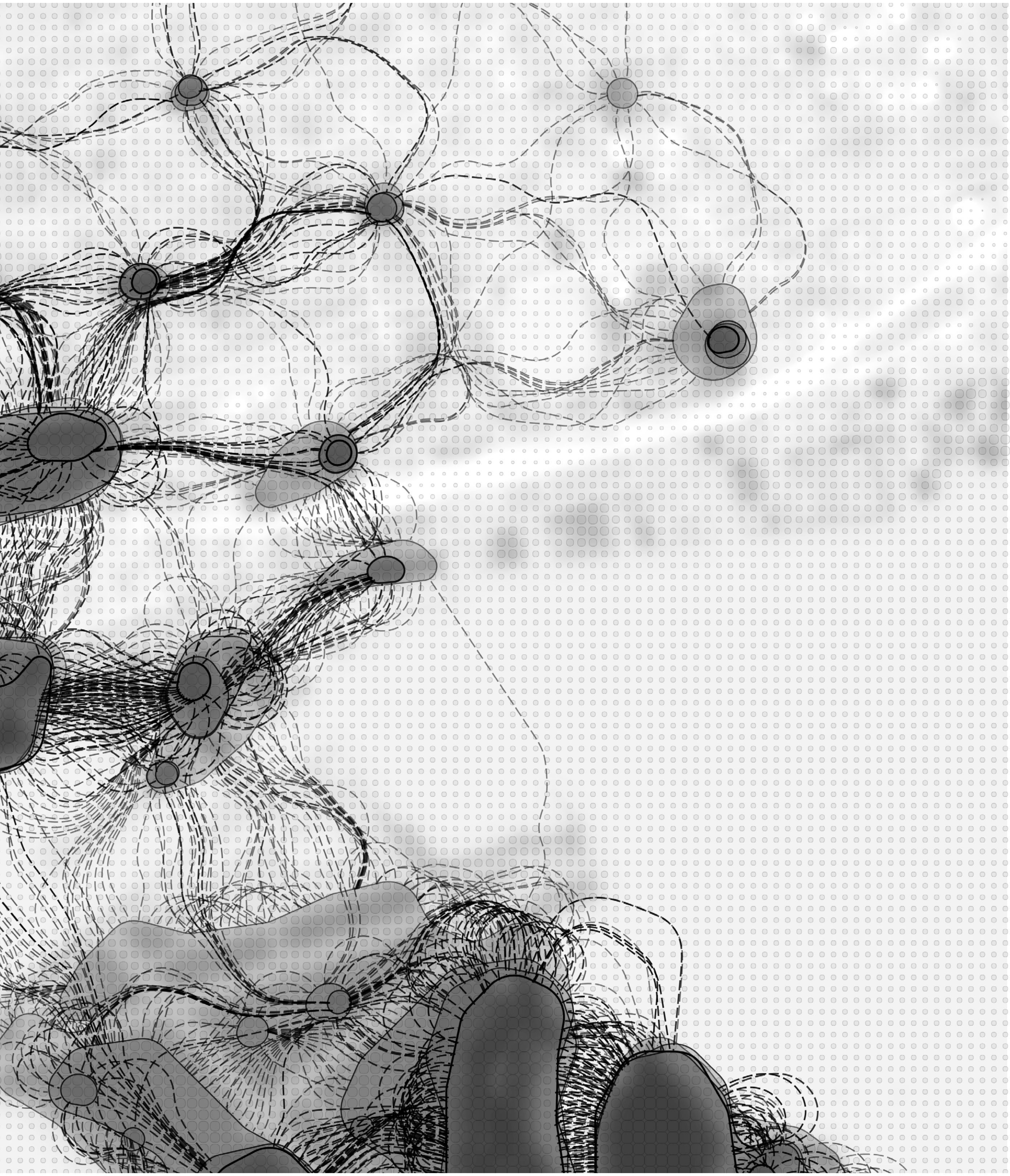


Fig 1.13. Agent network - Detail

NETWORK INTERVENTION STRATEGY

To holistically strengthen this network, four intervention types have been developed and located in the urban fabric. The intervention types are as follows:

Patch Add : Where travel distances between patches are too far, a habitat patch is added to increase stepping stone movement.

Patch Enhance: Where green space exists, but does not have the characteristics to accommodate bird populations, the qualities of the habitat are improved.

Ecotone Spread: Where strong ecological territory borders areas of high resistance, this transition is blurred to encourage species movement through the matrix and offer variation in habitat.

Matrix Smooth: Where the matrix offers high resistance along identified paths of travel and around patches, safety and accommodation of urban fabric is increased to boost willingness and ability of birds to move between patches.

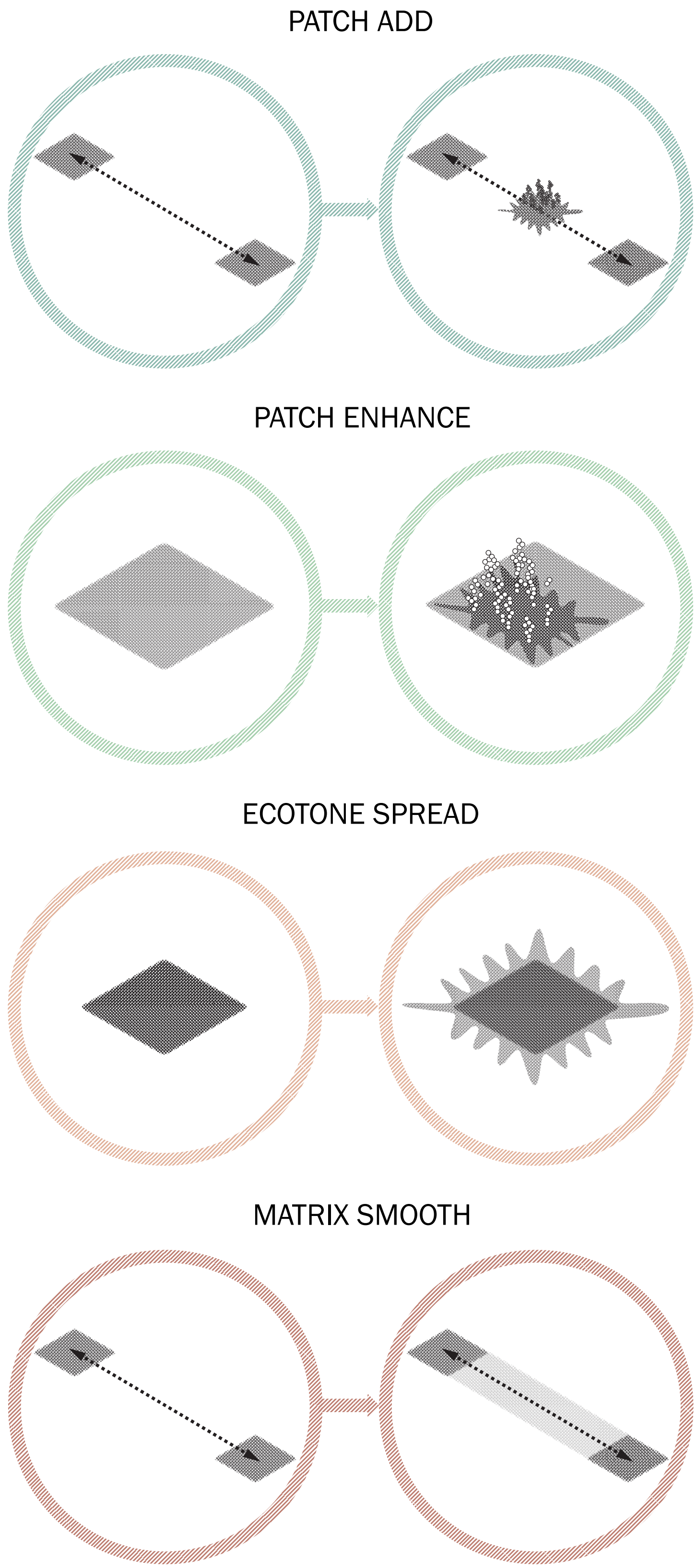


Fig 1.14. Patch network intervention strategies

[input]
To locate these interventions in this complex network, a digital tool has been developed to evaluate the network and resistance map and place these interventions accordingly.

[process]
To place *Patch Add* interventions, network paths are evaluated based on length. Where the length exceeds a specified threshold, a midpoint is placed to indicate the need for an additional patch. Closely spaced points are then conglomerated into patches that serve as intermediate stops on multiple paths of travel.

For the *Patch Enhance* interventions, to identify portions of the fabric that have potential to support bird populations but don't currently have enough vegetal cover, the tool takes the values sampled from the resistance maps and highlights those within a certain range.

To place the *Ecotone Spread* intervention sites, the resistance map is sampled, and anytime an area of very low resistance borders and area of very high resistance, an ecotone is placed to encourage birds to cross this boundary.

For the *Matrix Smooth* interventions, areas of fabric with high resistance values that are within a certain radius of a patch or path are extracted from the resistance map and highlighted.

[evaluation]
The result it a collage of intervention suggestions that act as starting points for policy makers and designers. Because these network and intervention maps are generated computationally, they can easily be updated to test the effect of these interventions or other changes in the urban fabric on the network. Now that the network has been developed and interventions suggested, it becomes advantageous to make use of the vast amounts of bird data collected by avid birders watchers. By locating this data within the network, the designers of these interventions can easily access this data to inform their design decisions.

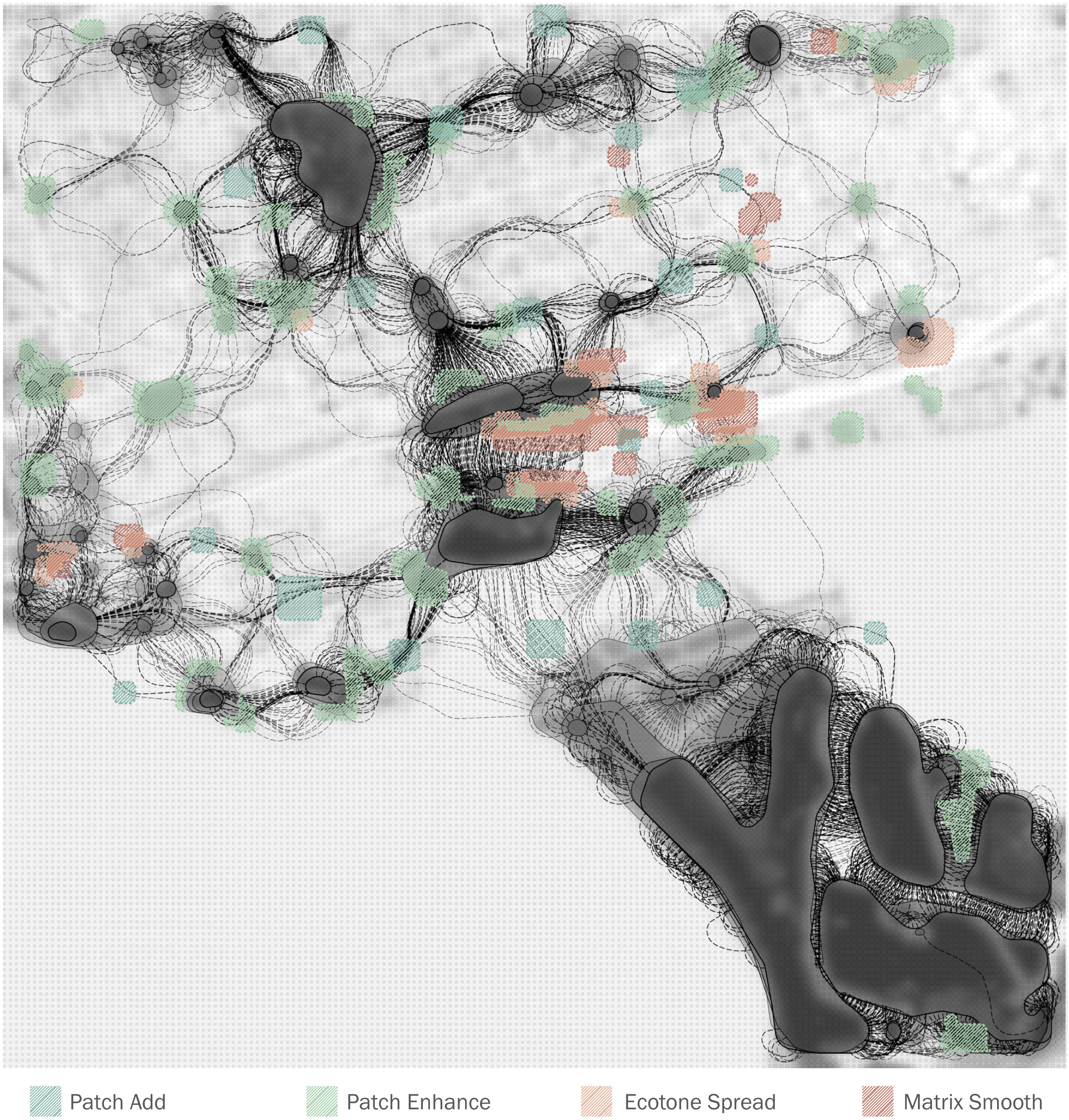
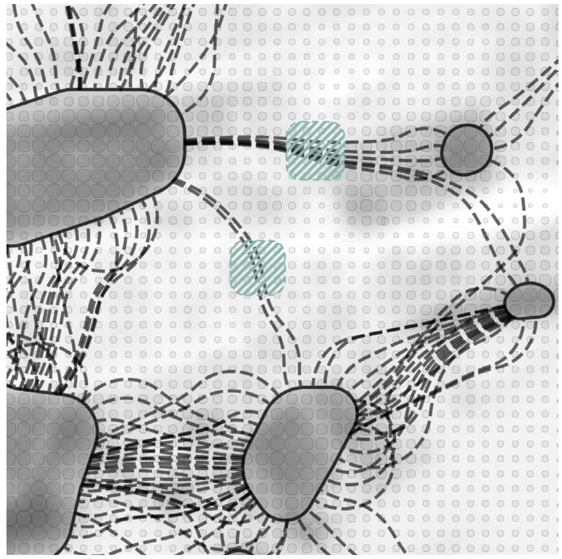


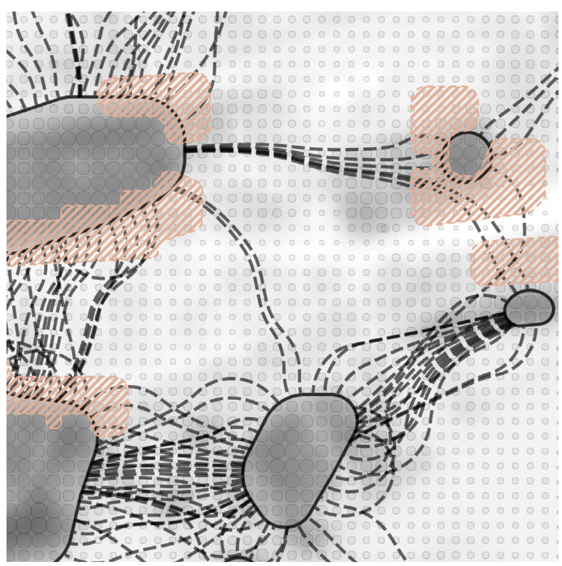
Fig 1.15. Interventions located using the network and resistance map

PATCH ADD



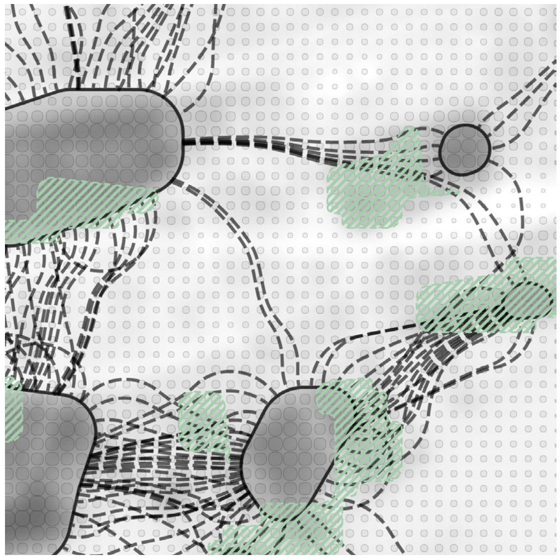
Added when path is longer than 400m

ECOTONE SPREAD



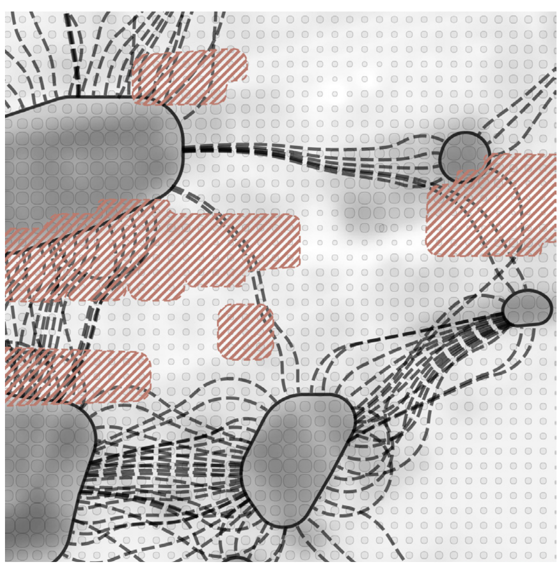
Added when very high resistance map values are in close proximity to very low values

PATCH ENHANCE



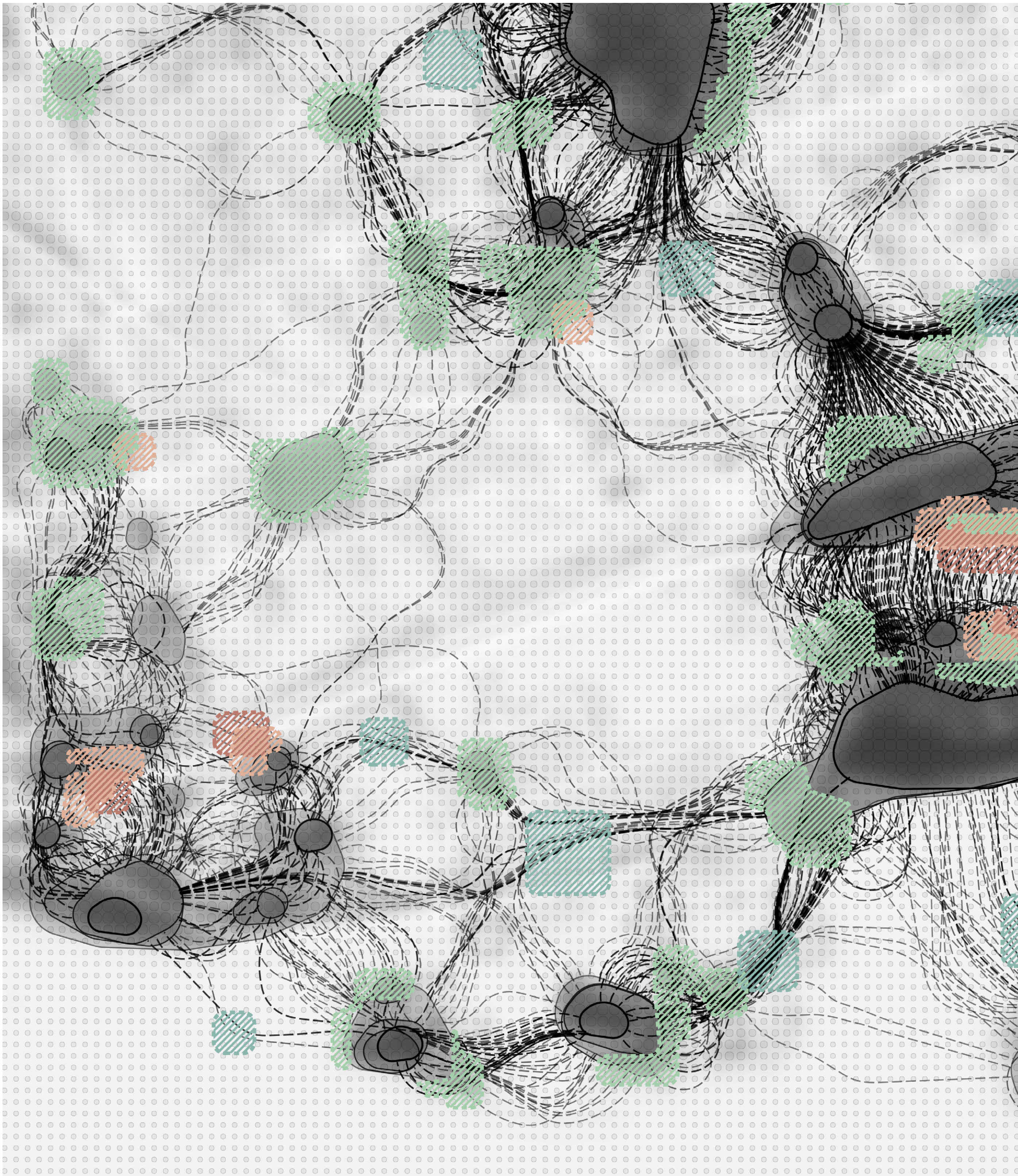
Added when resistance map values are between the patch and matrix thresholds

MATRIX SMOOTH



Added when high resistance values intersect paths and patches

Fig 1.16. Intervention placement process



Patch Add
Patch Enhance
Ecotone Spread
Matrix Smooth

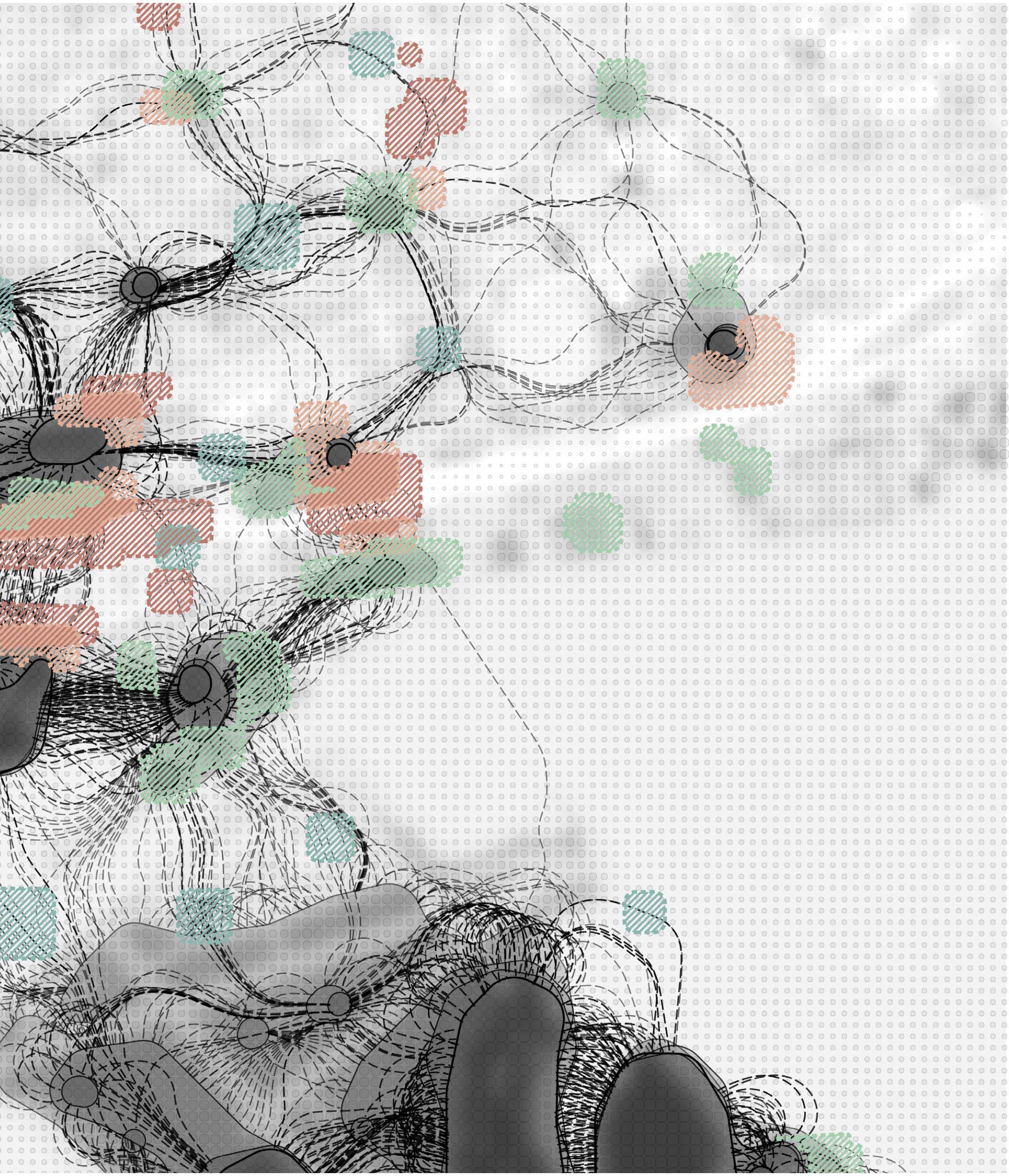


Fig 1.17. Intervention locations - Detail

DATA VISUALIZATION

[input]

The data visualized was acquired from the Online database eBird, where almost 30,000 bird sightings in this region in the past 5 years was used.[33] Each sighting entry contains key data items including sighting coordinates, species, number of birds, and date. This data was supplemented by adding data reflecting design parameters for each species. For each entry, the species' habitat, food, nesting, behaviour, conservation, and size, as gathered from the Cornell Lab of Ornithology's Bird Guide, was added.[34]

[process]

Species Map

This first data visualization map shows all the species recorded at each sighting location. To achieve this, sightings recorded in the same location were grouped, and any sighting of the same species was combined, with the species numbers being added. The sightings were then sorted based on how recent the last species sighting occurred. Each group of sightings is graphically represented as a circle, with the radius of the circle representing the number of species seen and the species names and number of sightings recorded along the edge.

Habitat Map

The second map records the habitat types of the birds seen in each location. After the data is grouped by sighting location, it is sorted by habitat type, and the number of species requiring each habitat is calculated. A circle is drawn based on the number of habitat types required by the birds at each location, with the colour of the circle representing the dominant habitat type. The habitats and species number per habitat are listed along the circle edge.

33 eBird Basic Dataset. Version: EBD_relNov-2017. Cornell Lab of Ornithology, Ithaca, New York. November 2017.

34 Cornell Lab of Ornithology, "All about Birds, Bird Guide," Cornell University, (accessed Feb, 2017).

[evaluation]

These visualizations of birds sightings in downtown Toronto allow conclusions to be drawn, such as the sheer number of species in the island, the importance of bird watching along the waterfront, and how preferred habitats types vary based on location in the fabric.

In addition to these visualizations, this tool is important in developing a work-flow to geographically group data and combine or sort it based different species parameters. This is key in the next step of assigning this data to the previously developed patch networks, so that as interventions are placed and designed they can quickly pull species data based on the intervention's connectivity to nearby patches.

Fig 1.18. Snapshot of sighting data

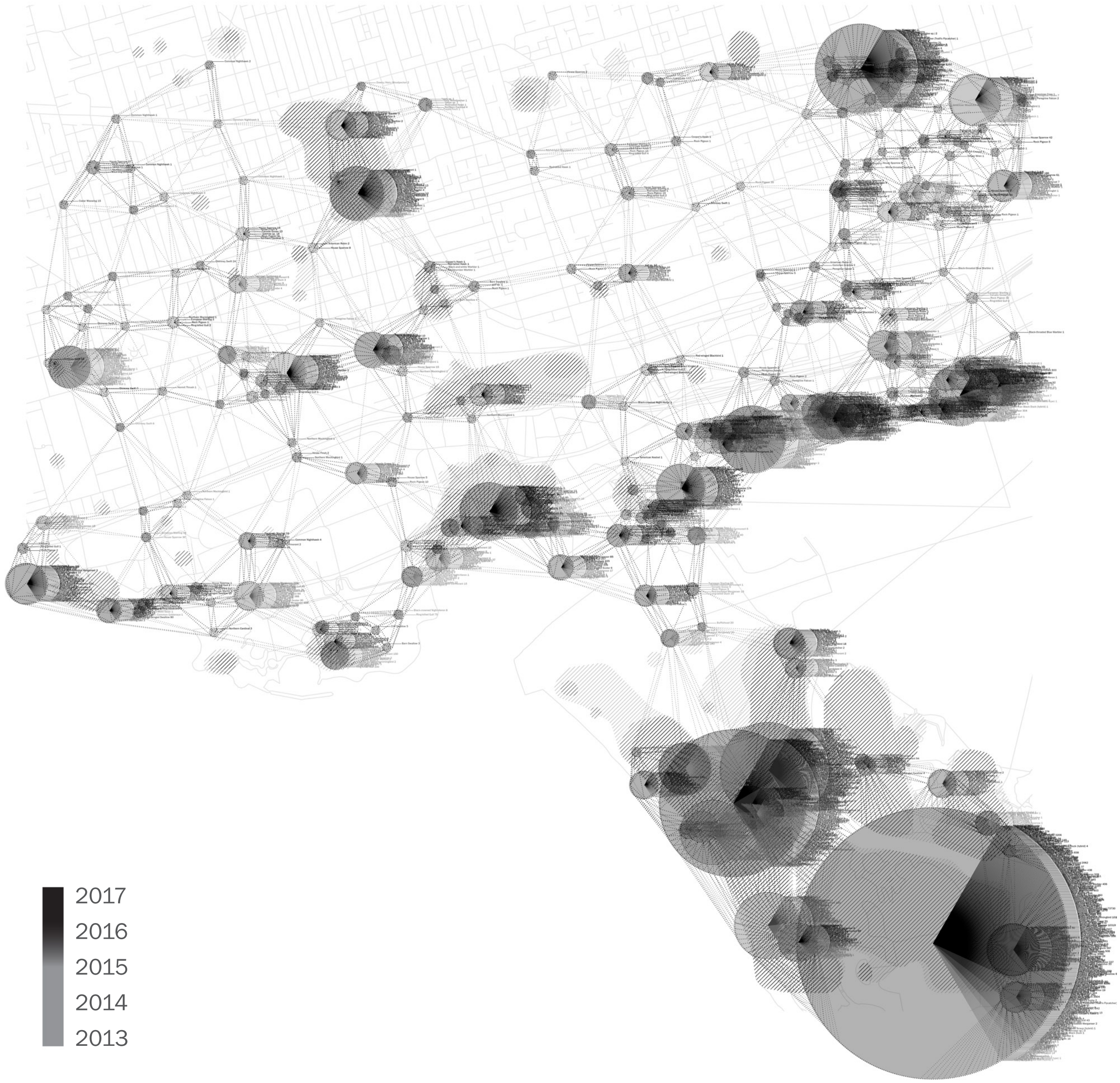
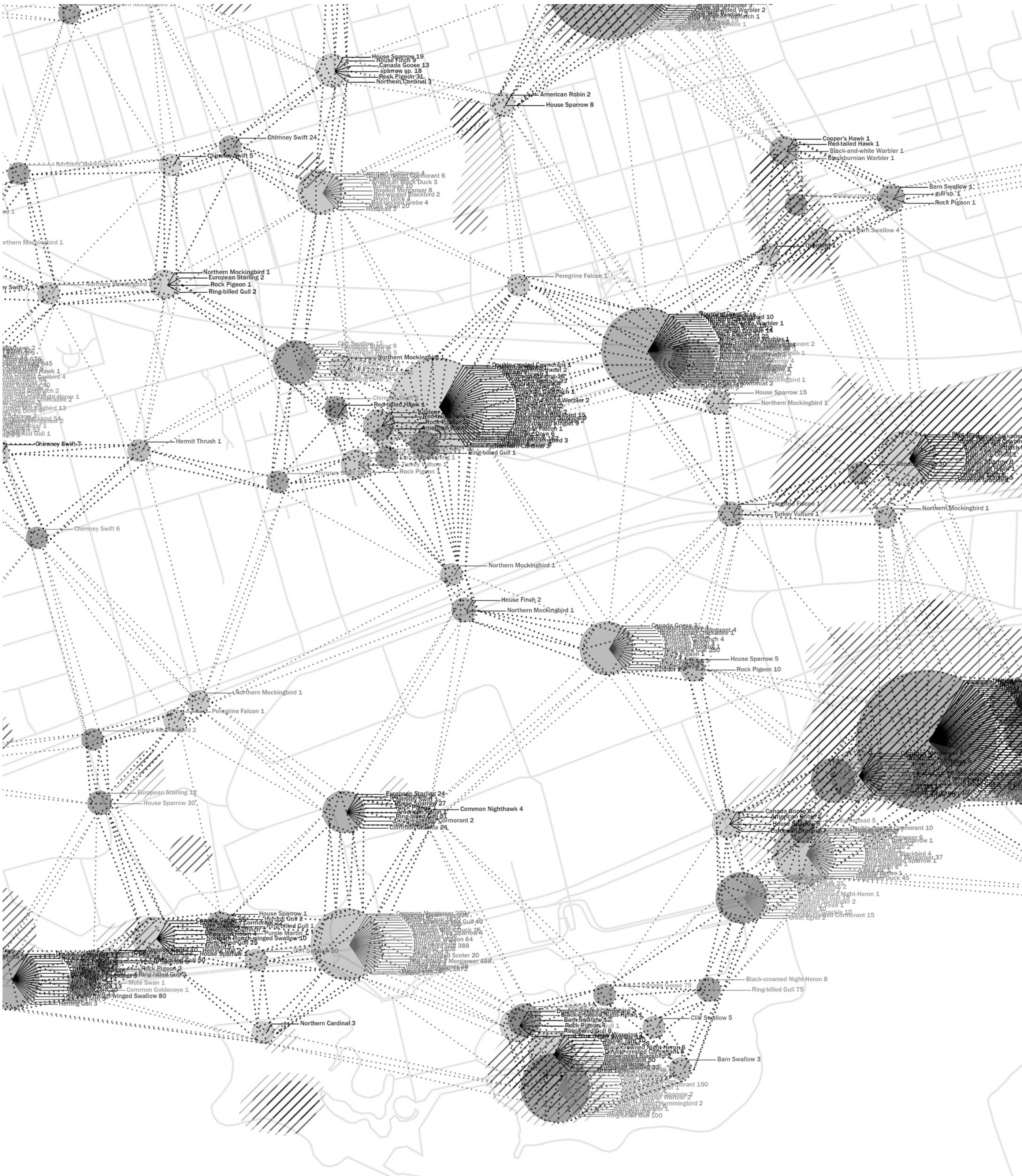


Fig 1.19. Bird sightings in the past 5 years - By species

Fig 1.20. Bird sightings in the past 5 years - By habitat


House Sparrow 19
House Finch 9
Canada Goose 13
sparrow sp. 18
Rock Pigeon 31
Northern Cardinal 3
American Robin 2
House Sparrow 8
Chimney Swift 24
Chimney Swift 5
Cooper's Hawk 1
Red-tailed Hawk 1
Black-and-white Warbler 1
Blackburnian Warbler 1
Barn Swallow 1
gull sp. 1
Rock Pigeon 1
Barn Swallow 4
Northern Mockingbird 1
European Starling 2
Rock Pigeon 1
Ring-billed Gull 2
Peregrine Falcon 1
House Sparrow 15
Northern Mockingbird 1
Red-tailed Hawk 1
Rock Pigeon 1
Ring-billed Gull 1
Hermit Thrush 1
Chimney Swift 7
Chimney Swift 6
Peregrine Falcon 1
Turkey Vulture 1
Northern Mockingbird 1
Northern Mockingbird 1
House Finch 2
Northern Mockingbird 1
House Sparrow 5
Rock Pigeon 10
Northern Mockingbird 1
Peregrine Falcon 1
European Starling 12
House Sparrow 30
European Starling 24
Common Nighthawk 4
Canada Goose 6
Double-crested Cormorant 10
Black-crowned Night-Heron 1
House Sparrow 1
Northern Cardinal 3
Black-crowned Night-Heron 8
Ring-billed Gull 75
Cliff Swallow 5
Barn Swallow 3
Ring-billed Gull 100
Mute Swan 1
Common Goldeneye 1
Herring Gull 3

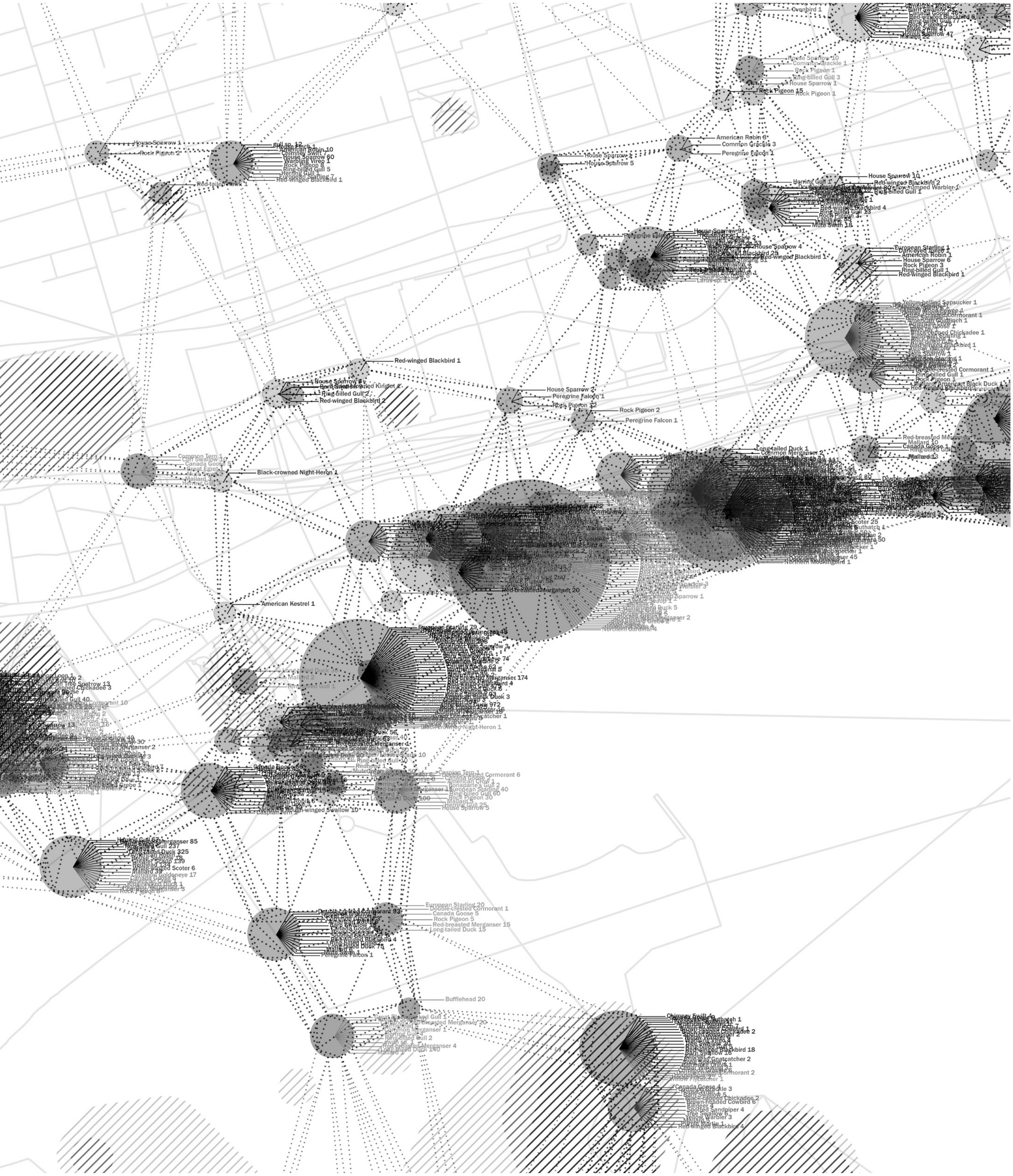
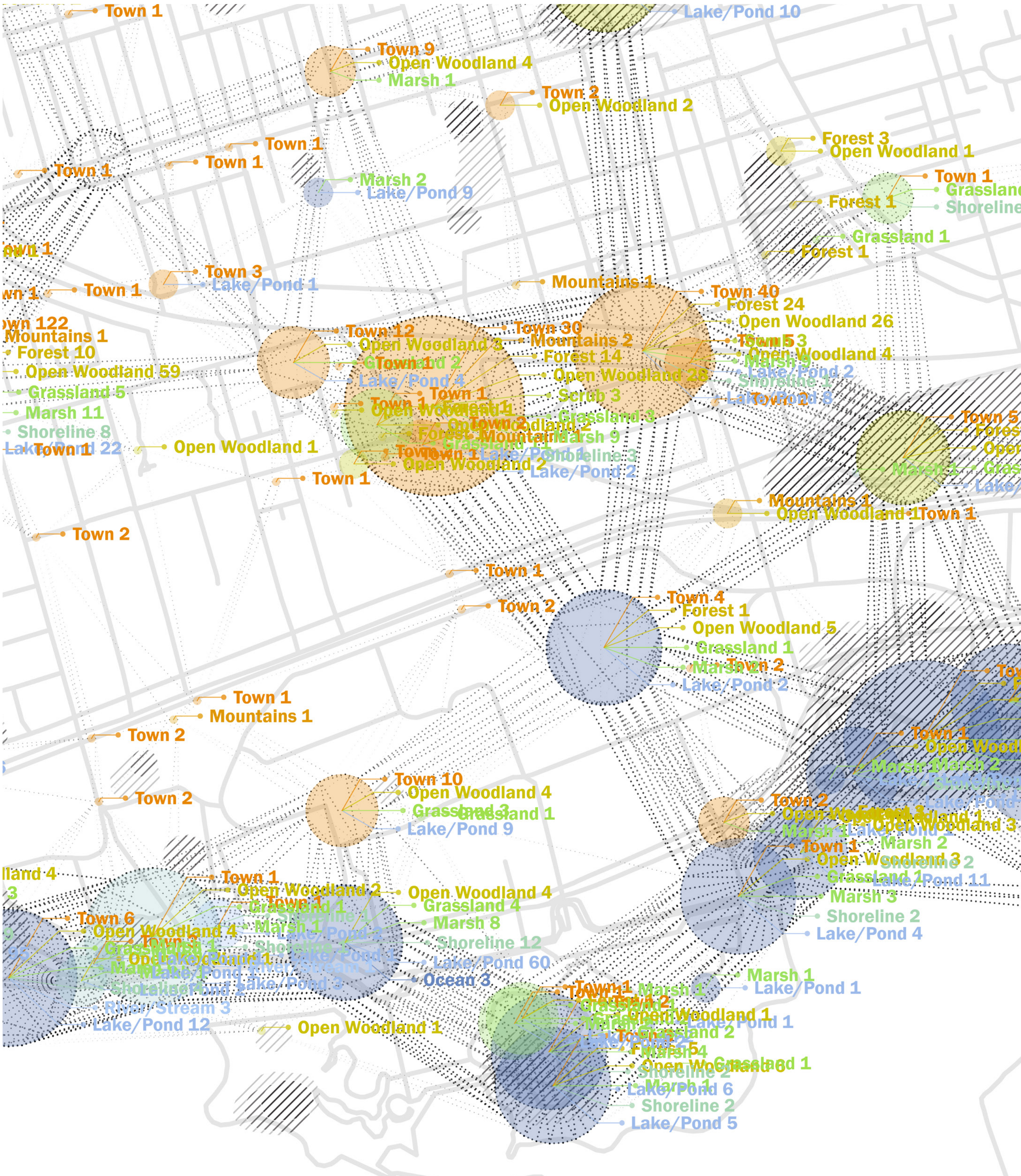


Fig 1.21. Sightings by species - Detail



Town 1
Lake/Pond 10
Town 9
Open Woodland 4
Marsh 1
Town 2
Open Woodland 2
Town 1
Town 1
Town 1
Marsh 2
Lake/Pond 9
Forest 3
Open Woodland 1
Town 1
Forest 1
Grassland 1
Forest 1
Town 3
Lake/Pond 1
Town 1
Mountains 1
Town 40
Forest 24
Open Woodland 26
Town 12
Open Woodland 3
Mountains 2
Forest 14
Open Woodland 28
Mountains 1
Forest 10
Open Woodland 59
Grassland 5
Marsh 11
Shoreline 8
Open Woodland 1
Lake/Pond 4
Town 1
Scrub 3
Grassland 3
Marsh 9
Open Woodland 4
Lake/Pond 2
Town 1
Town 5
Open Woodland 2
Lake/Pond 2
Mountains 1
Town 2
Town 1
Town 2
Town 4
Forest 1
Open Woodland 5
Grassland 1
Lake/Pond 2
Town 1
Mountains 1
Town 2
Town 2
Town 10
Open Woodland 4
Lake/Pond 9
Town 2
Town 1
Marsh 2
Open Woodland 3
Marsh 3
Shoreline 2
Lake/Pond 4
Lake/Pond 11
Town 1
Open Woodland 2
Open Woodland 4
Grassland 4
Marsh 8
Shoreline 12
Lake/Pond 60
Ocean 3
Town 6
Open Woodland 4
River/Stream 3
Lake/Pond 12
Open Woodland 1
Marsh 1
Lake/Pond 1
Lake/Pond 6
Shoreline 2
Lake/Pond 5

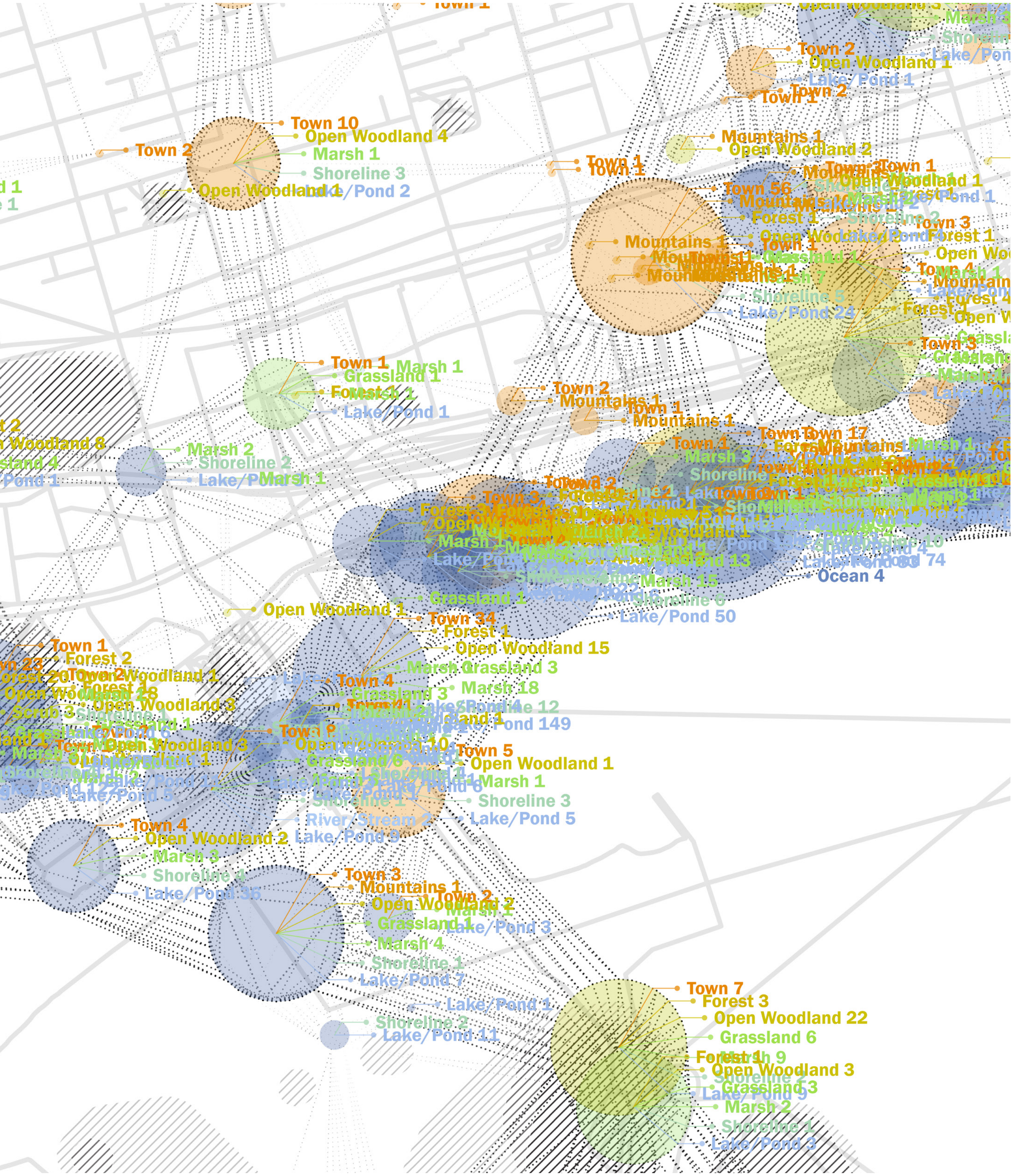


Fig 1.22. Sightings by habitat - Detail

DATA INTEGRATION

By locating bird sighting data within the network, the designers of these interventions can easily access information in local bird species and their habitat requirements to inform their design decisions.

[input]
The dataset from the previous visualization study is used. This data is located within the agent network, and the resistance map is used to inform new connections.

[process]
To begin integrating data and the patch network, any geographic group of sightings that is inside or within a certain distance of a patch is grouped and stored in reference to the patch. The remaining sighting groups are tested for their distance to each other and then combined if they are close enough. Any sighting location that has five or more unique species and is not in or near a patch is considered an important sighting location. While the birds seen here are not occupying a defined habitat patch, it is important to note their existence in the fabric. To determine the sighting location's connectivity in the habitat network, agents are expelled, and connections are made to any habitat patch they reach, as per *Network Study 03*.

Now that all significant bird sightings are assigned to either a patch, or a sighting location, and these patches and locations have agent lines connecting them where possible, this network can be simplified and evaluated based on connectivity. Here, any patch connected by a least one agent line is considered connected, and a simple edge is drawn, representing this connectivity. Now, all the data is stored in the form of a graph, where there is a list of bird species and their attributes at each node, and each edge signifies that those patches are connected.

[evaluation]
While less rich and complex than the previously illustrated networks, this graph structure offers a different set of advantages. These advantages include the ability to mathematically test the effect of an intervention on the connectivity of the network, as well as quickly access large amounts of species data based on this connectivity.

To create more accurate network connectivity analysis, a weighted graph could be developed as a next step. Here, the edges would be assigned values based on the strength of the connections, rather than all the connections being treated equally.

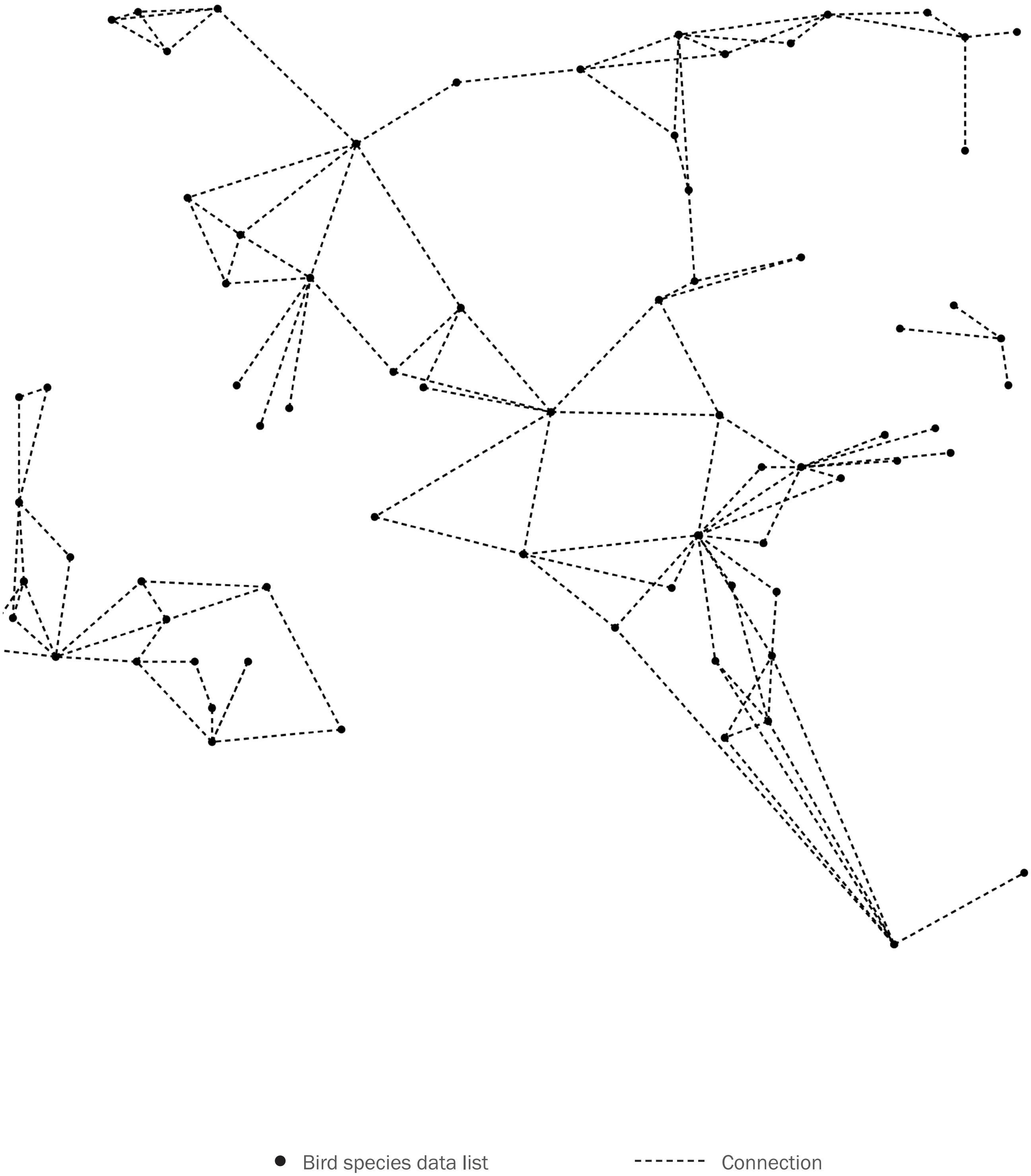
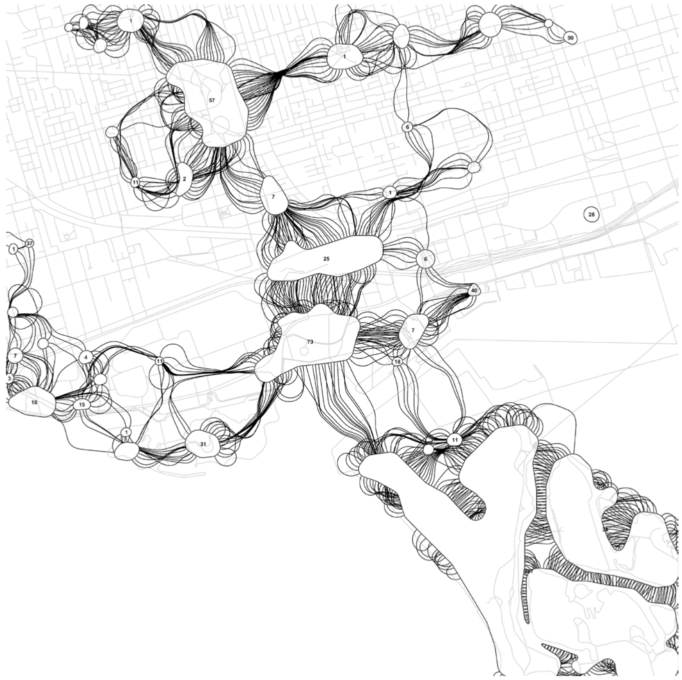
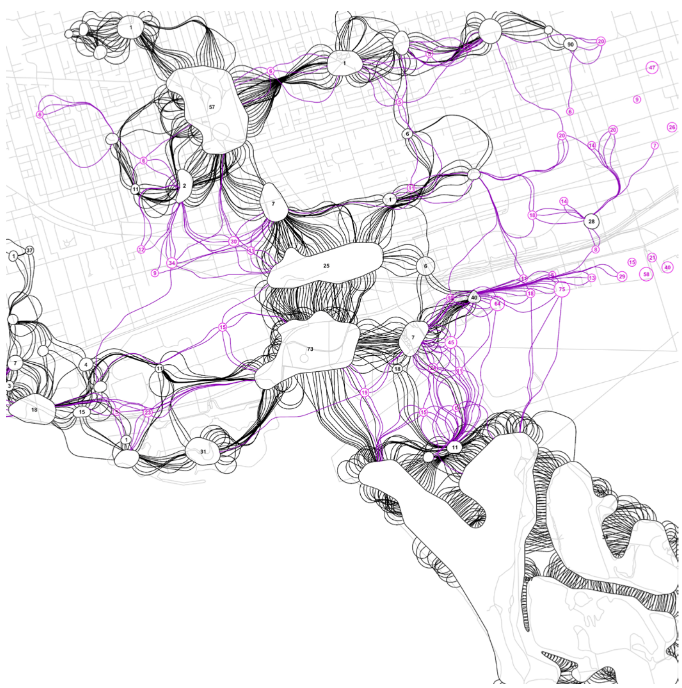


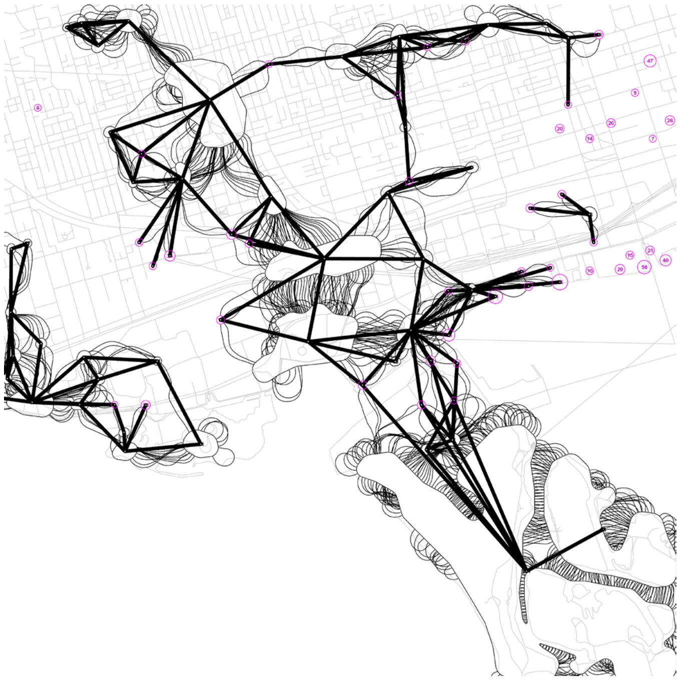
Fig 1.23. Graph data structure



Number of species seen in habitat patches



Locations with many sightings connected to nearby habitats



Data network based on patch and sighting connectivity

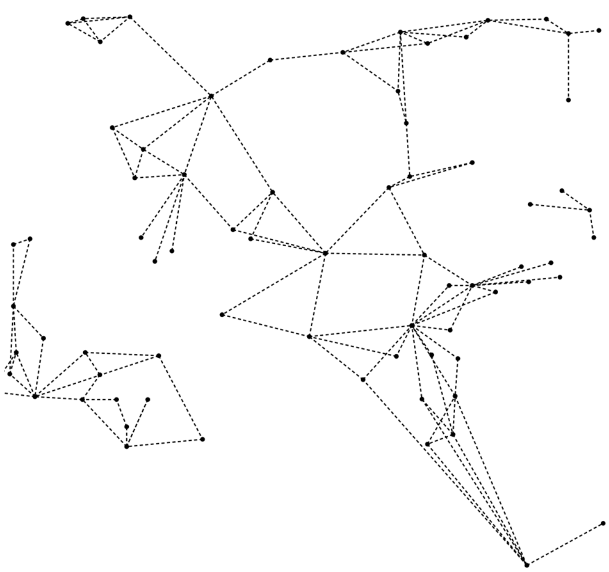


Fig 1.24. Merging patch network and sighting data process

• Bird species data list ------- Connection

PART II

3D NETWORK DEVELOPMENT
INTERVENTION MASSING

Part II sees the fabric sensing and network building strategies developed in Part I adapted for three-dimensional fabric. In addition, examples of the intervention typologies outlined in Part I are explored using example sites. Specific attention is given to a *Patch Enhance* intervention case study located in CityPlace's Canoe Landing Park. At this phase, an evolutionary solver is used to optimize a massing envelope for this intervention that generates the most connectivity in the region, before more detailed habitat composition is explored in Part III.

FABRIC SELECTION

The portion of fabric selected to test intervention strategies and three-dimensional networks stretches from the waterfront to King Street and from Spadina Ave to Strachan Ave. This area includes several major parks and heavy residential development, and is key in linking the island and waterfront ecosystems to the Garrison Creek series of green spaces, which are tracings of where a creek system used to run through Toronto. This represents a key opportunity to expose Toronto's downtown residents, who use Garrison Creek parks heavily, to regional bird species.

This Toronto Island to Garrison Creek connection is illustrated in the City of Toronto's Proposed Downtown Plan where they locate a ring of connected greenspace called a "core circle" in the city, saying "Connecting these large natural features creates a continuous and connected circular network around Downtown, builds on Toronto's strong identity as a "city within a park" and provides opportunities to acknowledge our history and natural setting."[35] While in this report the City of Toronto focuses on connecting these greenspaces with circulation infrastructure for urbanites, if these green spaces are to provide urban biophilia, they need to be connected for regional species as well. To ensure this green loop is connected for birds as well as people, the location where the circle crosses heavy development is a key area of study, and network studies can offer a much more robust examination than this green ring diagram.

35 City of Toronto, *Proposed Downtown Plan*, 2017.

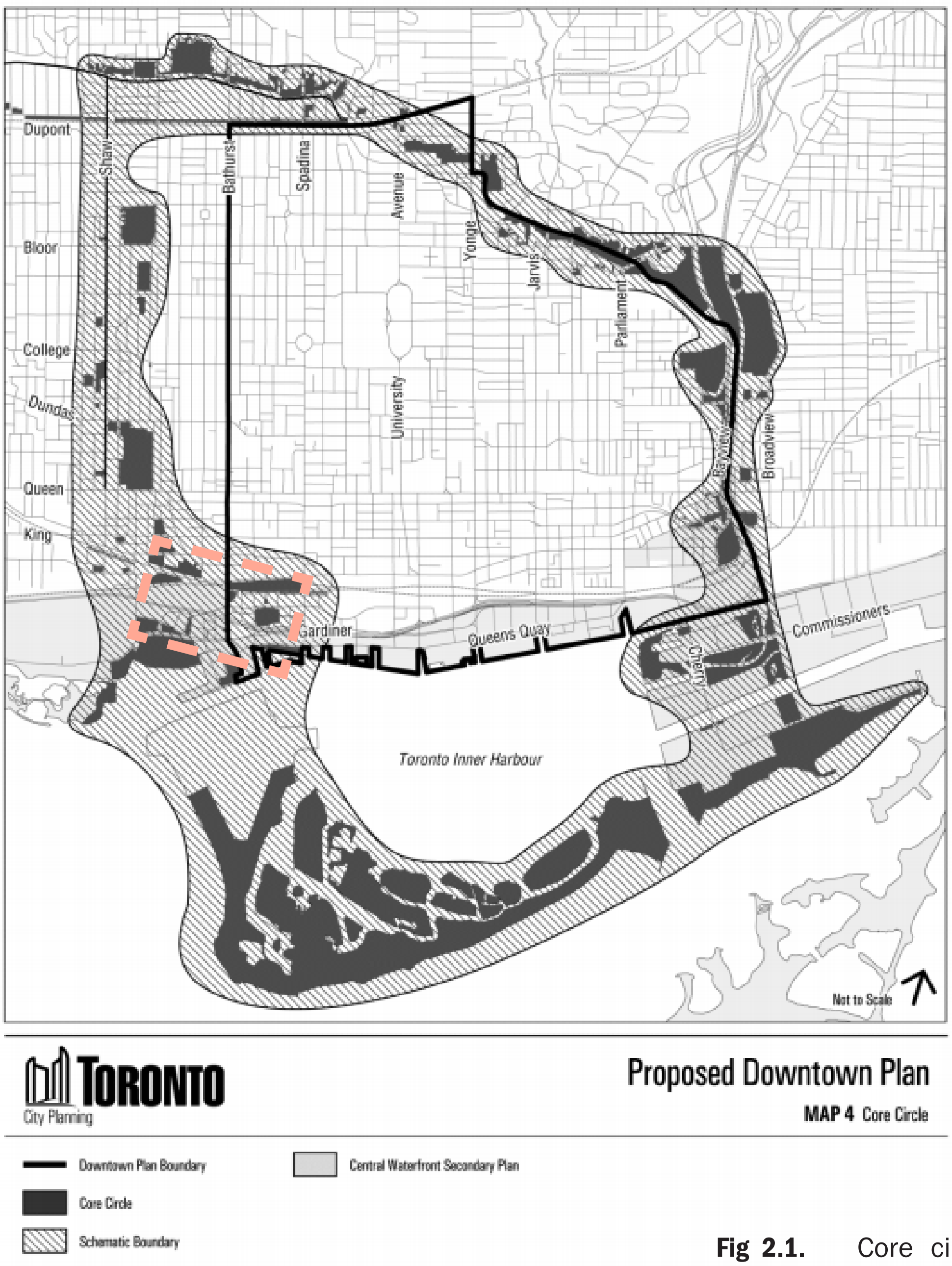
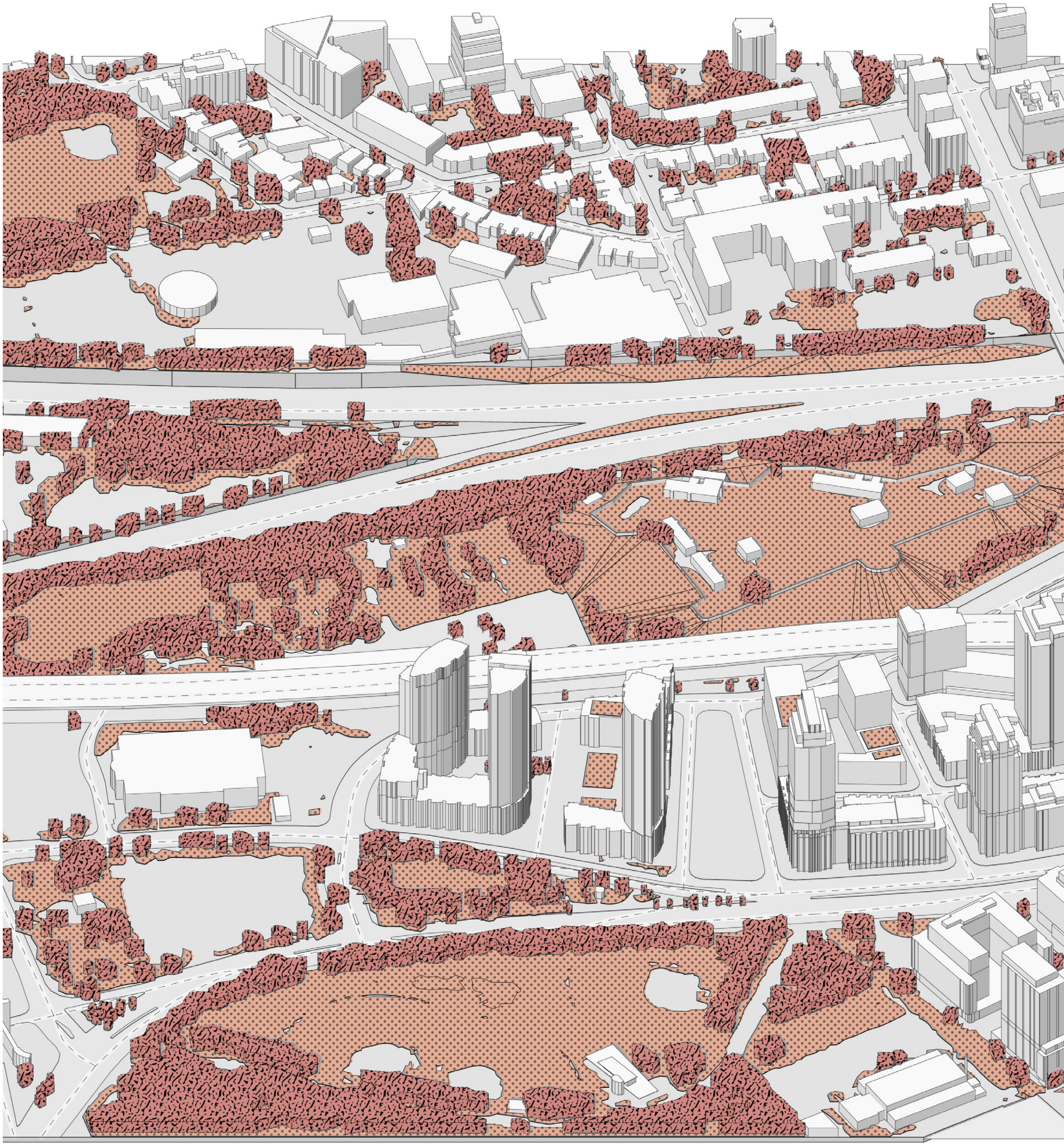
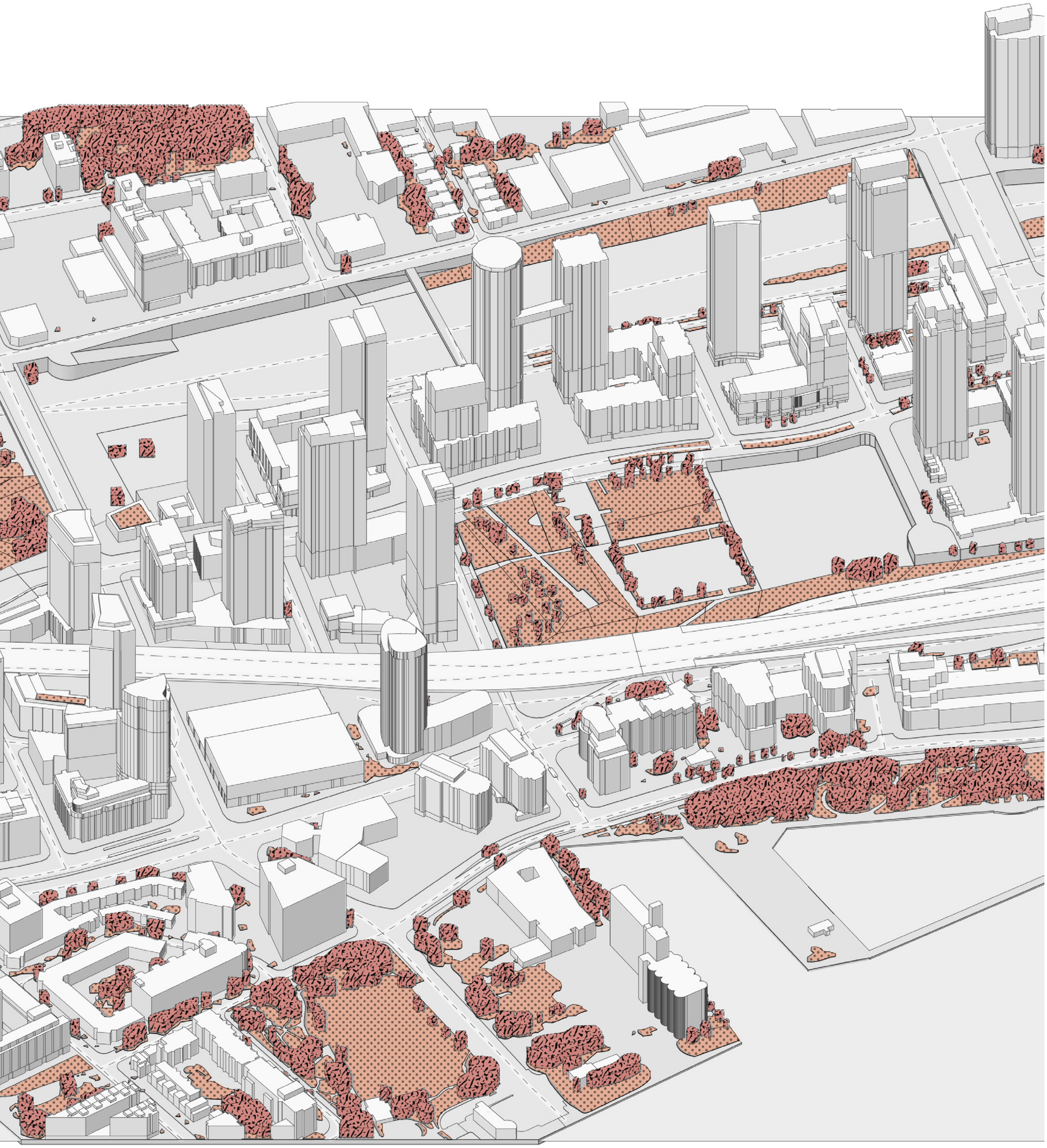


Fig 2.1. Core circle, City of Toronto - Proposed Downtown Plan, 2017



Tree canopy



Grass cover

Fig 2.2. 3-D Fabric Model

INTERVENTION EXPLORATION

To begin analysing this piece of 3D fabric, the patch intervention locations and paths from the 2D studies in Part 1 are directly imported and overlaid on the 3-D fabric model. This allows insight on which intervention suggestions should be explored further. To illustrate the intervention typologies introduced in Part I, four locations were chosen for closer examination. While these interventions would not necessarily be initially carried out in such close proximity, locating them beside each other illustrates their importance as a cohesive system.

The first study location is on top of a low building where a patch add can maximize connectivity and bird penetration in the surrounding residential development.

The second location, which will be explored in more detail, is a patch enhance to allow Canoe Landing park to connect existing green spaces and act as an amenity to the surrounding residential neighborhood and proposed community center and school.

The third location is the edge of Fort York, where the park is sunken below street level, and borders heavy development. Here the script located an ecotone spread and matrix smooth to encourage movement.

The final location is between Fort York and Coronation Park, where busy streets and large glassy building mass calls for a matrix smooth

These four interventions are schematically explored, then, to further inform these interventions, networks are calculated in three dimensions.

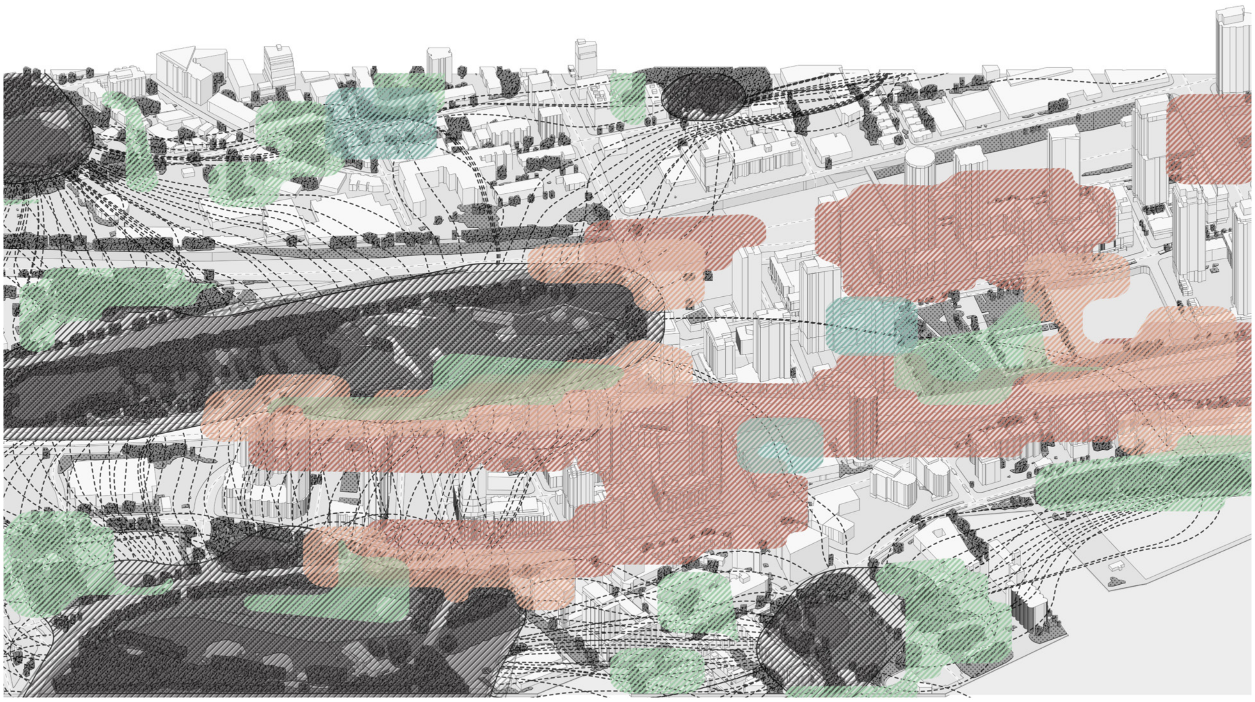
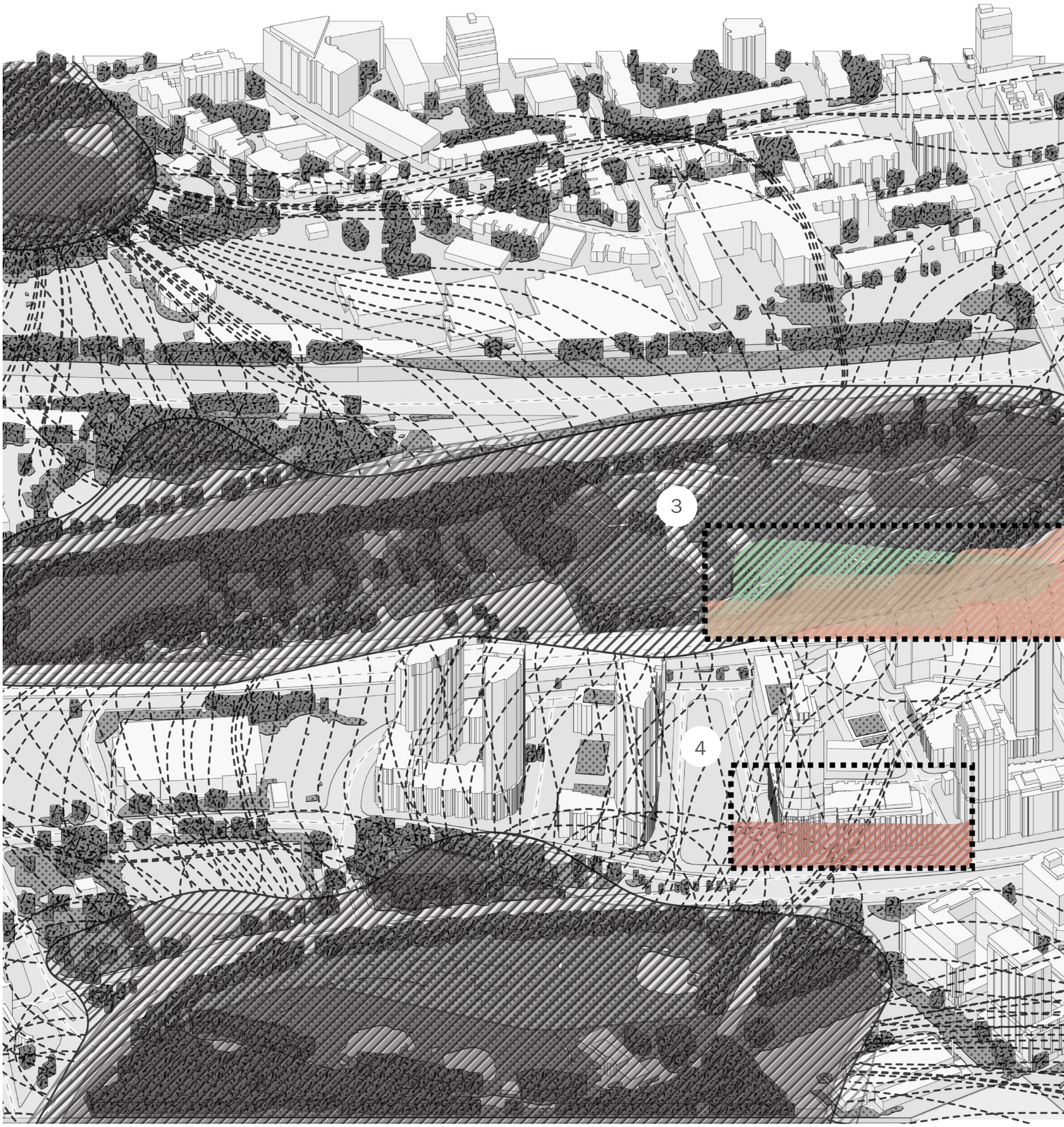


Fig 2.3. Imported 2-D paths, patches, and interventions



Patch Add

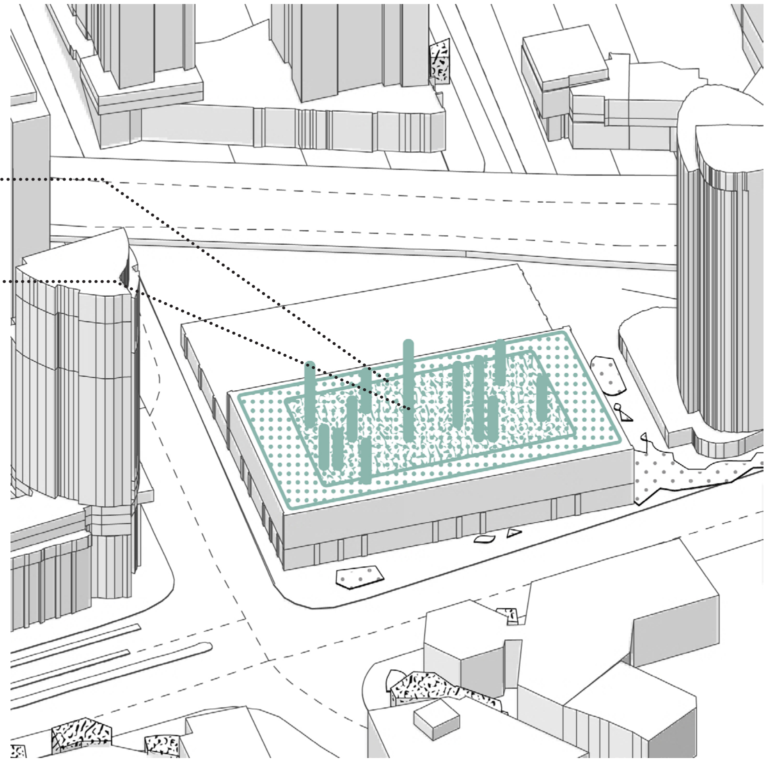
Patch Enhance

Ecotone Spread

Matrix Smooth

Fig 2.4. Selected interventions for further investigation

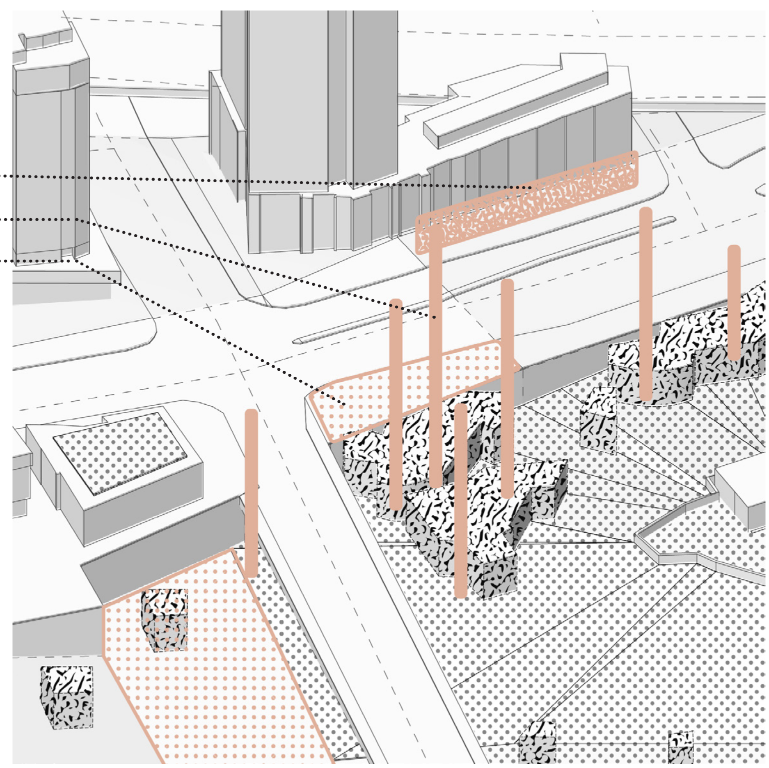
1



PATCH ADD

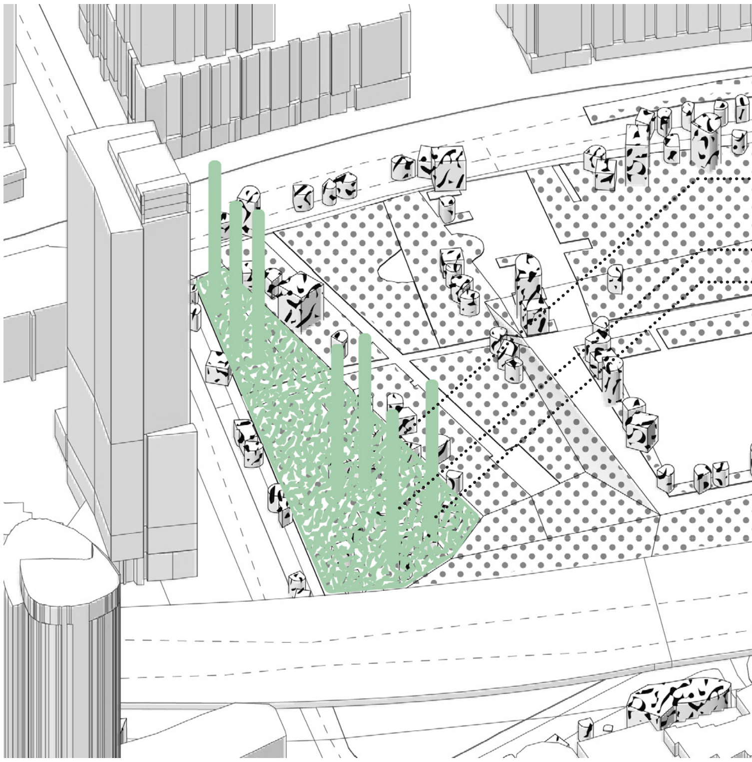
- Add green roof in accordance with City of Toronto's Guidelines for Biodiversity Green Roofs
- If possible add height and cavities
- Choose plants that attract birds and pollinators

3



ECOTONE SPREAD

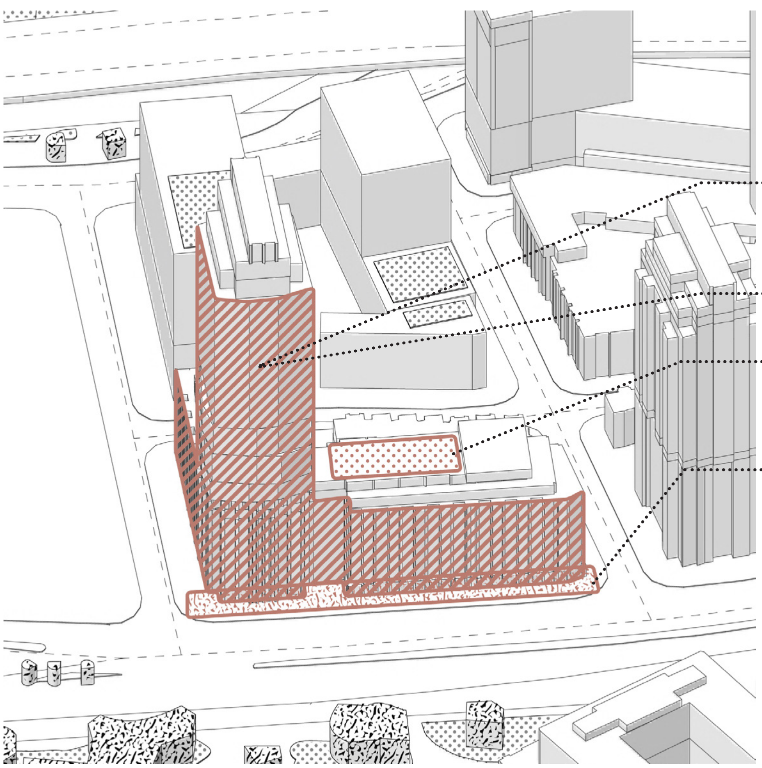
- Add street trees and shrubs
- Add height to increase sight lines
- Replace paving with permeable paving and natural cover where possible



2

PATCH ENHANCE

- Increase variety of vertical structure
- Increase height and surface area
- Add nesting and perching opportunity
- Choose plants that attract birds and pollinators



4

MATRIX SMOOTH

- Retrofit or include bird frit as outlined in Toronto's Bird friendly guidelines
- Include more frit when located near patches and paths
- Green roof in accordance with City of Toronto's Guidelines for Biodiverse Green Roofs
- Add street trees and shrubbery

Fig 2.5. Schematic intervention strategies

BUILDING A 3D NETWORK

To create 3-D networks in urban fabric, the resistance layers, fabric sensing, and nearest neighbour network building is adapted from Part I for this context.

[input]
The digital fabric model is built using 2-D and 3-D information from the City of Toronto's open data. The 2-D information is extruded and located in space. Using the same principles of the resistance layers in Part I, each layer of this digital model is evaluated based on its ability to accommodate or resist bird movement. These model layers are the input for the network building process.

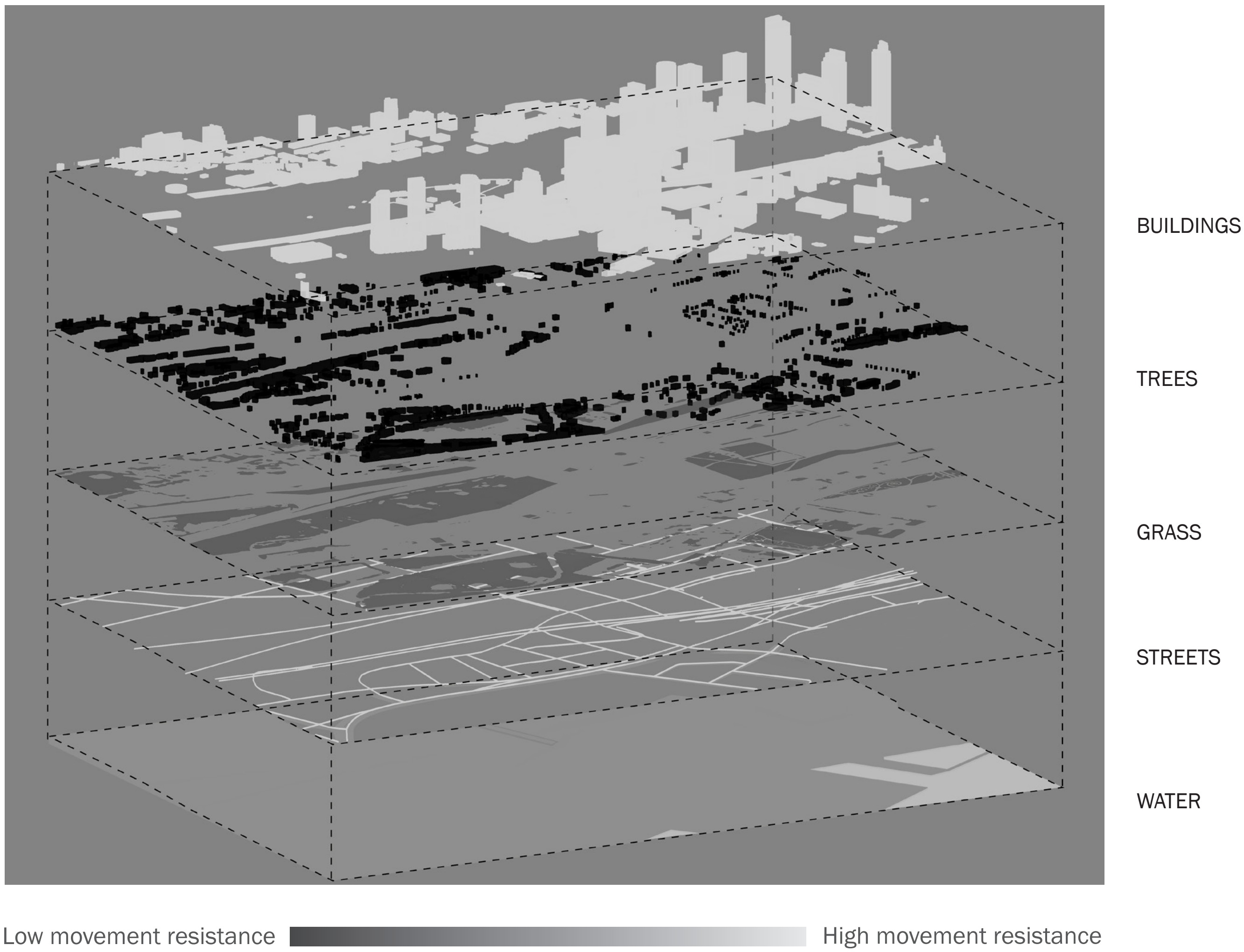


Fig 2.6. Exploded 3-D resistance and accommodation layers

[process]

To begin, a 3-D grid of sample points are placed in the fabric. Each point measures its distance to the nearest element on each resistance layer, before performing a series of calculations to weight the effect of these elements and arrive at an overall accommodation value for each point. As seen in Part I, the higher the value, the more the location in the fabric accommodates bird's habitation, and the lower, the more it resists it. To locate the nodes of the 3-D network, points that have high accommodation values are isolated. These points are then interconnected based on their nearest neighbours, and any connections that are above the distance threshold, or are interrupted by the fabric are removed. The remaining connections represent the 3-D avian movement network.

[evaluation]

When carried out at the scale of this piece of fabric, it can be seen that connections are currently lacking between the waterfront parks and Garrison Creek parks. However, when the previously explored interventions are added with optimized height and massing, these patches become much more connected, and birds are able to penetrate residential developments. This optimization is explored in the following study.

While these 3-D networks can illustrate bird movement in a vertical city, and help tune interventions to maximize connectivity, there are many advancements that could be made in this process. The first advancement would be adding more layers that affect bird movement in the 3D input model to make fabric sensing more robust. In addition, to avoid generically extruding tree canopy, recent advancement in Waveform Airborne Lidar to generate 3-D vegetation structure could be employed.[36] Finally, computing limitations are encountered when working in 3-D space. Because of this, the resolution of sample points is limited, and agent networks weren't simulated. In continuing studies of 3D networks, these limitations would need to be overcome.

36 Stefano Casalegno et al., "Ecological Connectivity in the Three-Dimensional Urban Green Volume using Waveform Airborne Lidar," *Scientific Reports* 7 (April 2017, 2017).

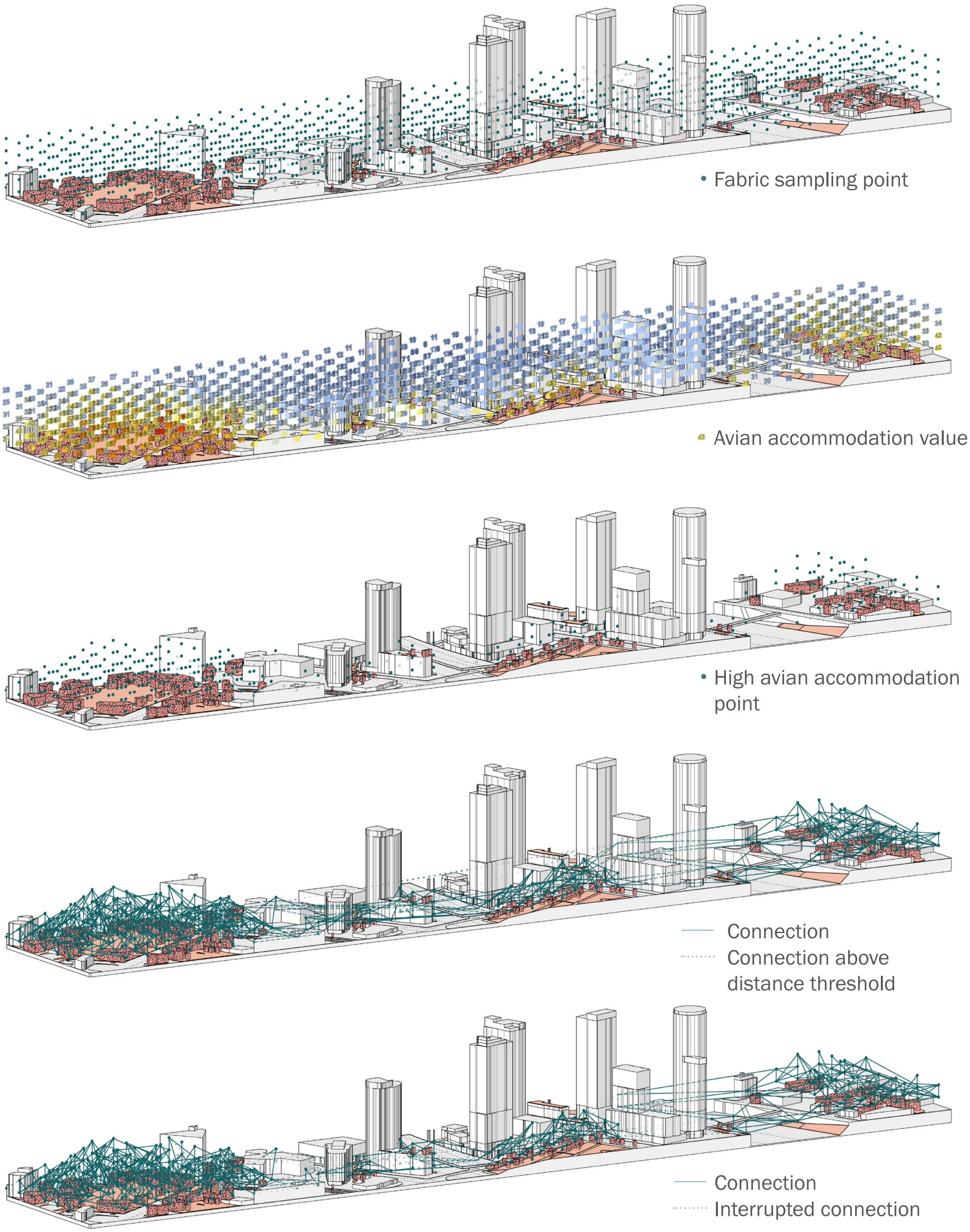
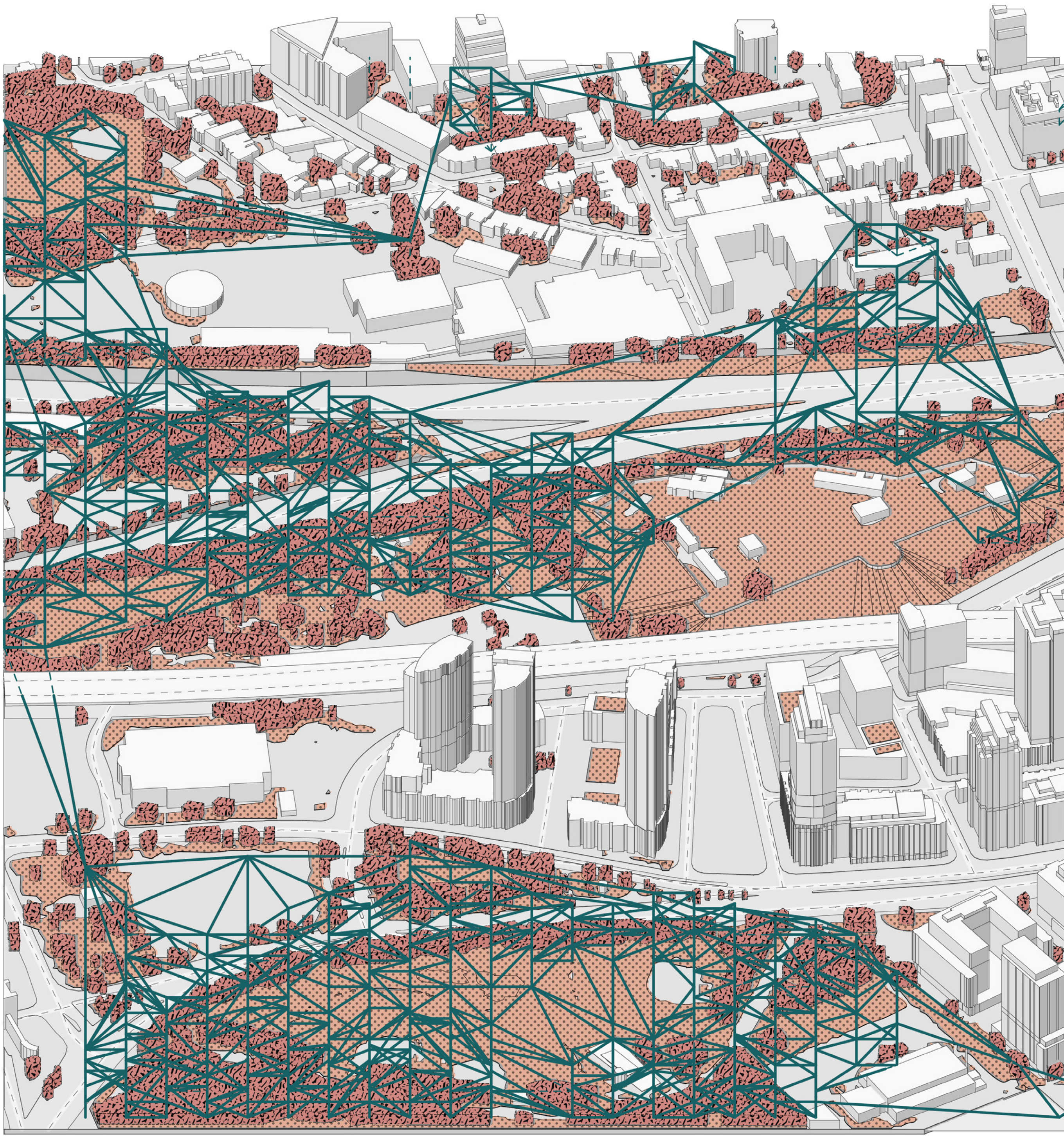


Fig 2.7. 3-D network development process



Connection network

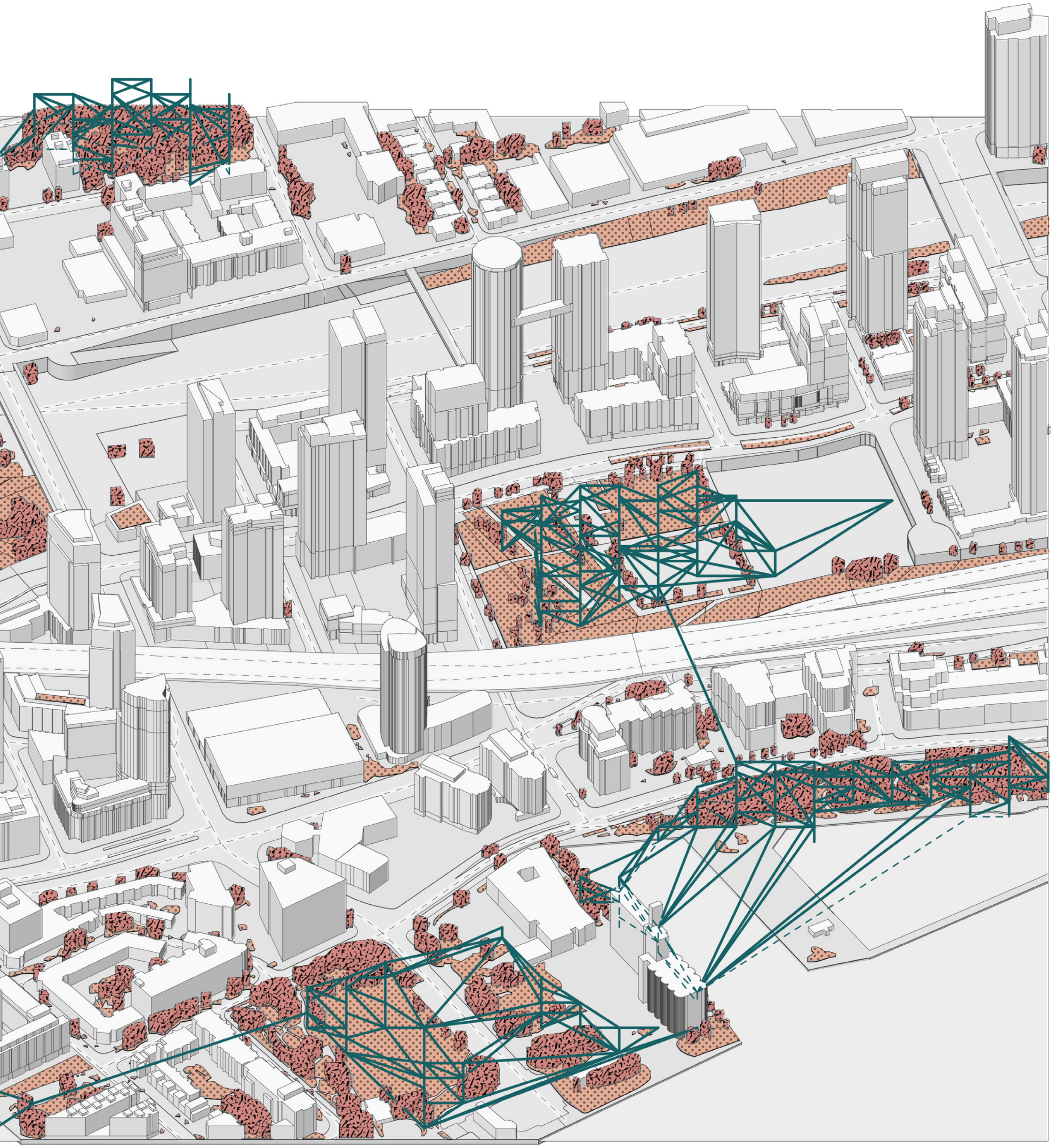
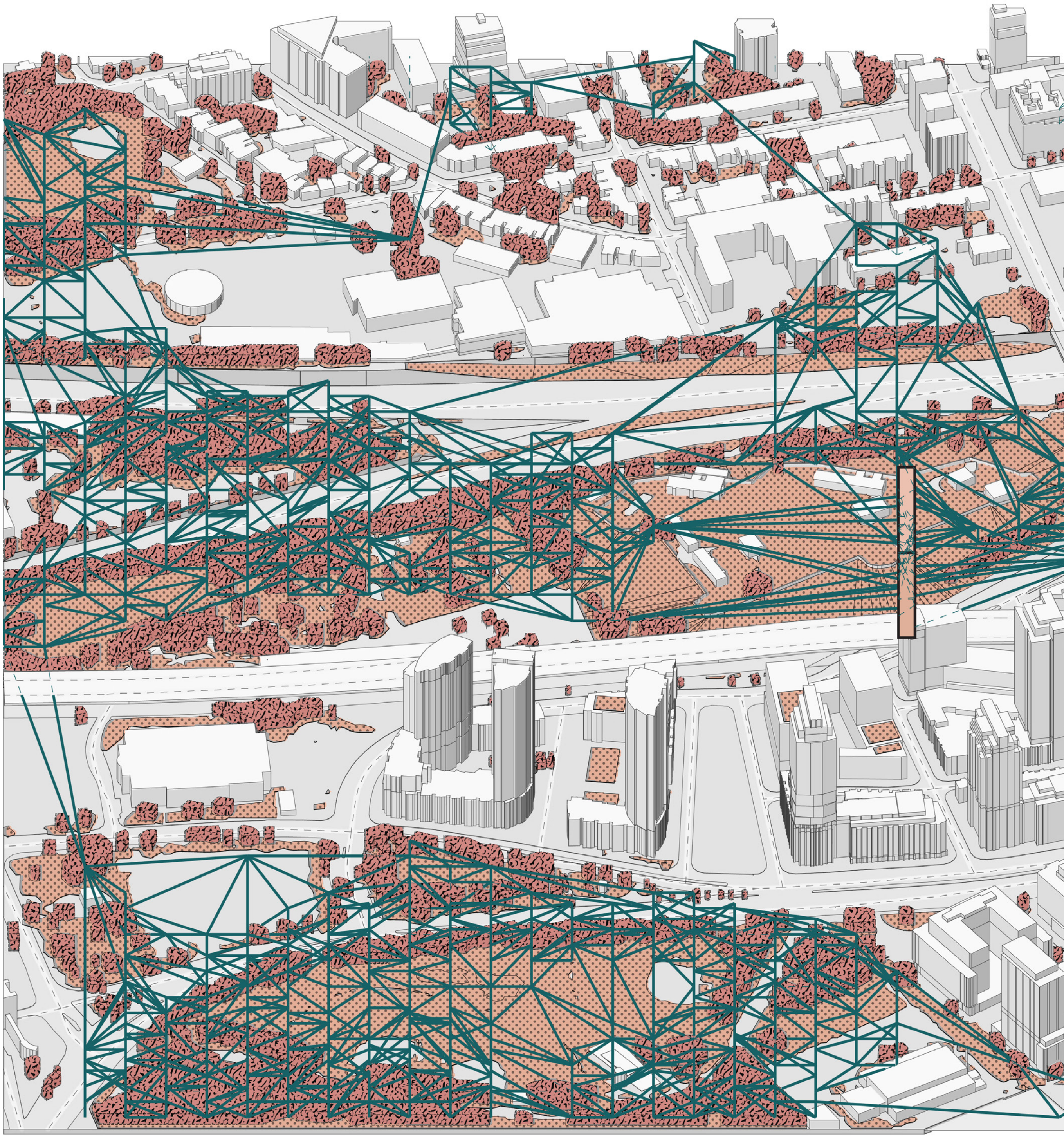


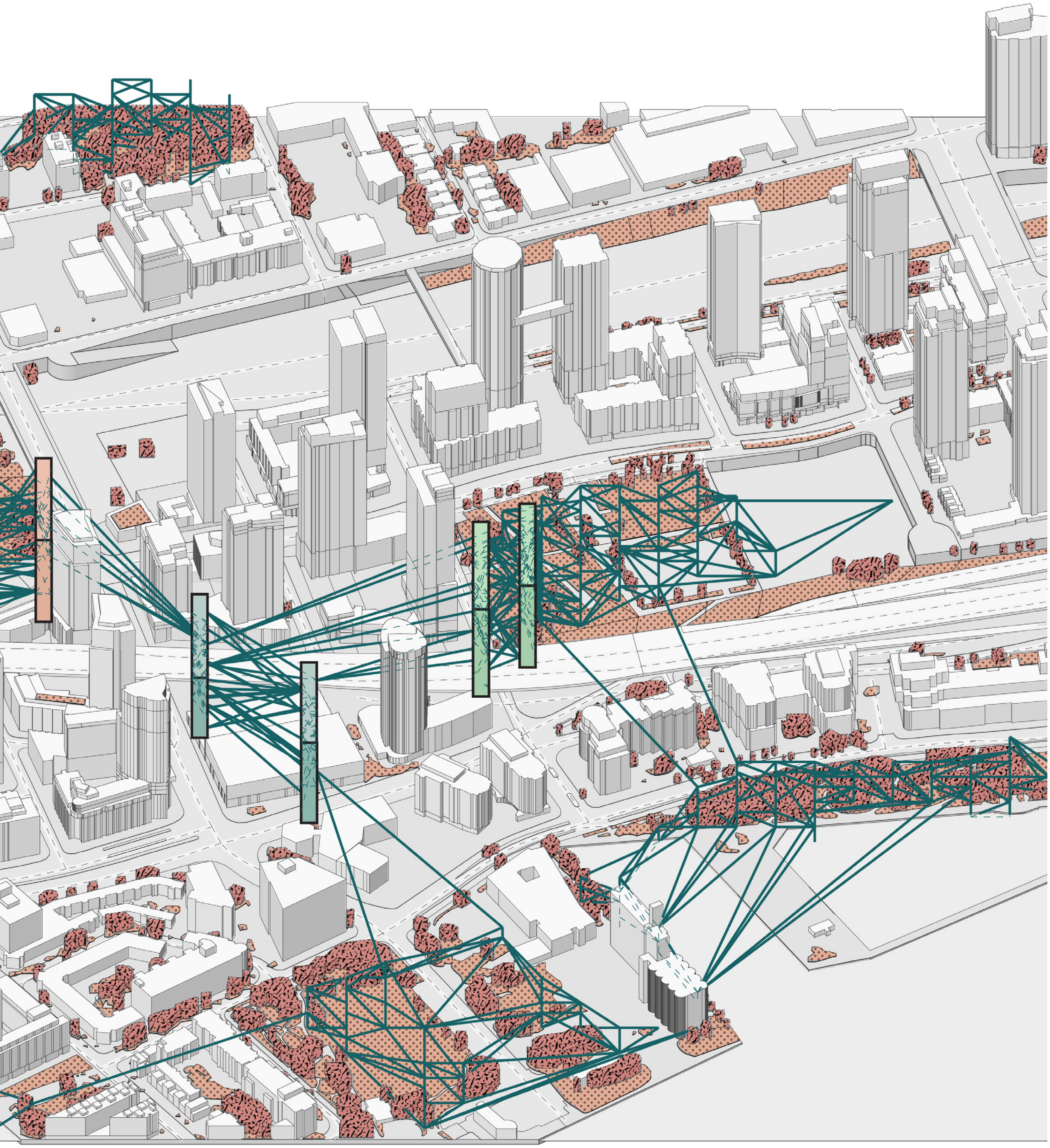
Fig 2.8. Existing 3-D bird movement network



Optimized Patch Add

Optimized Patch Enhance

Optimized Ecotone Spread



Connection network

Fig 2.9. 3-D bird movement network with proposed interventions

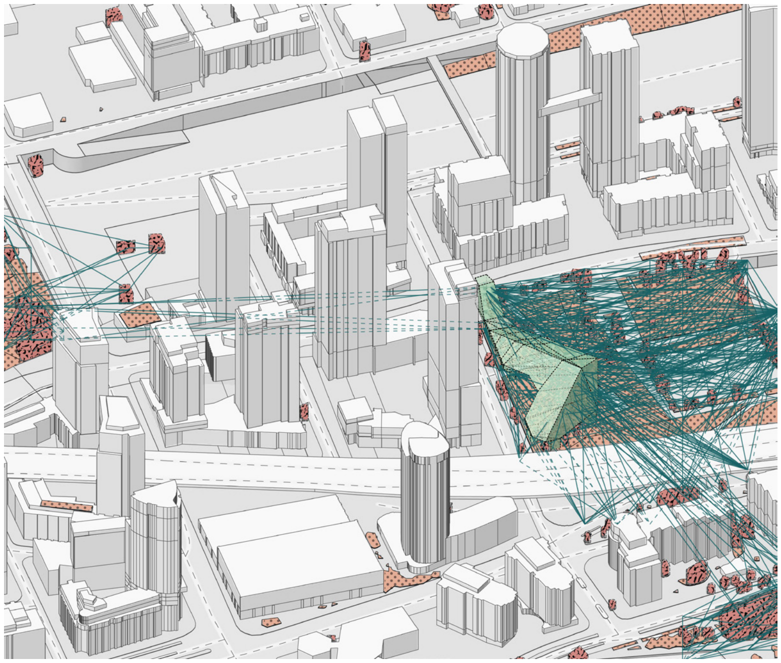
MASSING OPTIMIZATION

[input]
To begin testing an intervention envelope, or massing, a bounding box of possible volume is located on the site. The 3D network points and connections are used to test how interventions affect the network's connectivity.

[process]
This optimization of the intervention envelope comes from an evolutionary solver which rapidly generates massings within the given region. With each massing, the amount of fragmented network the intervention connects is measured, before moving on to the next. Through this process of testing hundreds of massings, the solver learns which are most effective in generating connectivity.

To design what could be referred to as the zoning envelope for the *Patch Enhance* intervention, this optimization was considered as well as the intervention's context. Based on the optimization, this envelope features height at the north and south sides to increase connections to Fort York and the Spadina Quay Wetlands. The envelope is also raised to accommodate existing trees and pathways, and slopes down in locations to respect neighbouring buildings and park sight-lines.

[evaluation]
By combining the rapid network testing tool with a designer's hand, an intervention envelope can be developed that is well adapted to complex ecological and urban dynamics in a dense vertical city.



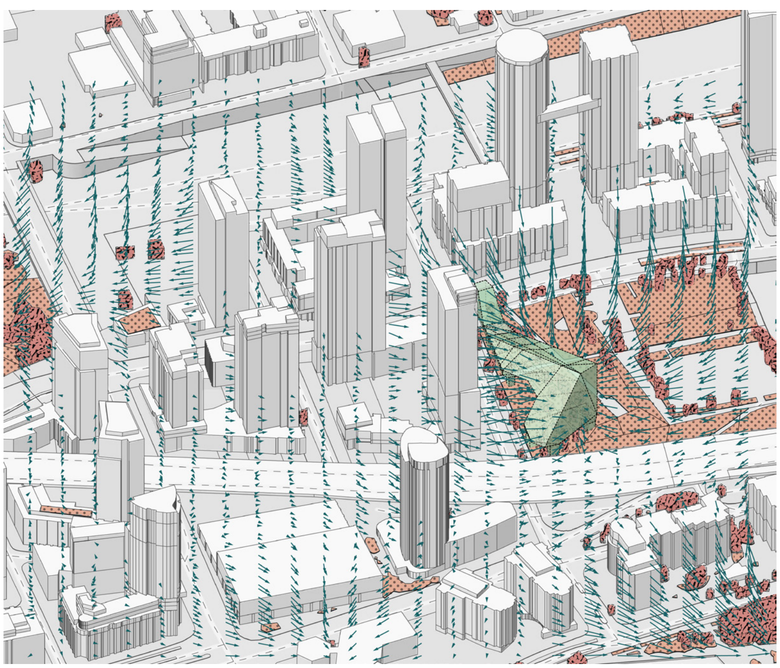
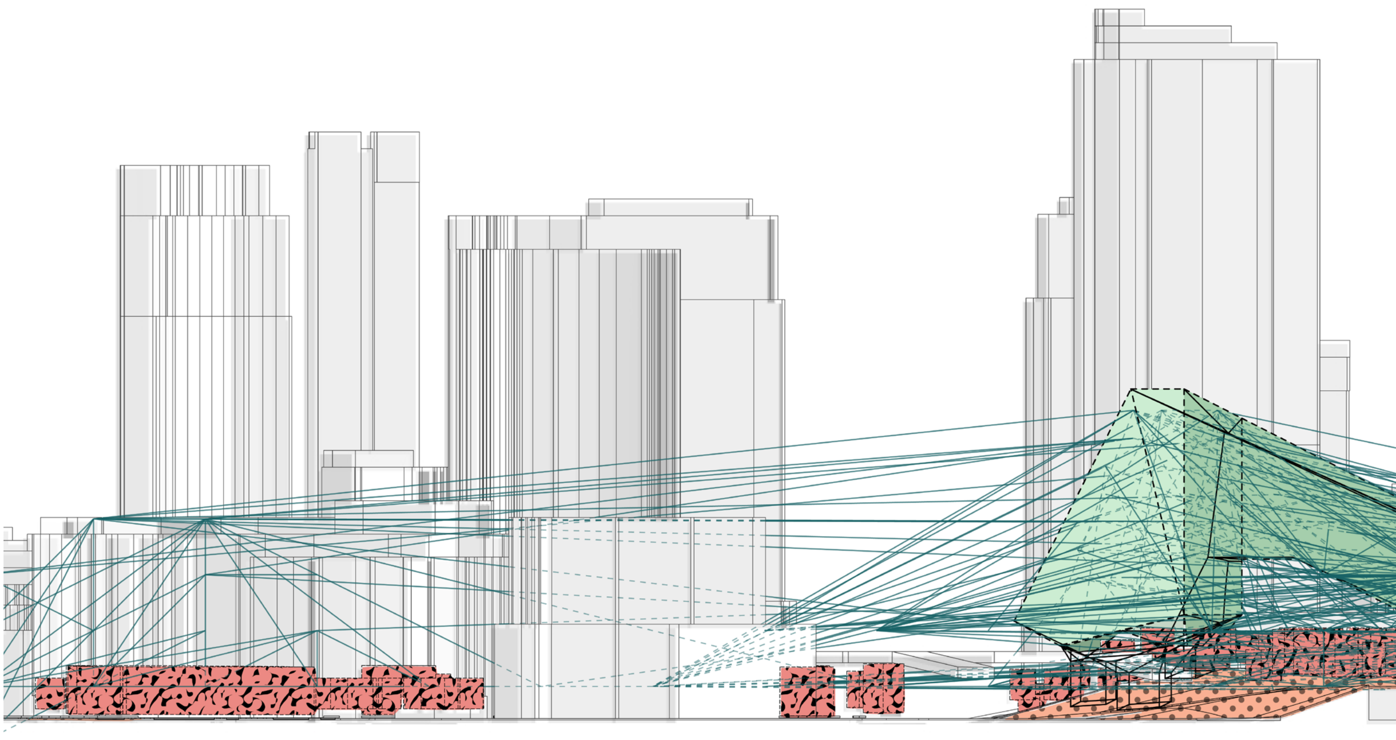


Fig 2.10. Patch enhance envelope with effect on local network and movement vectors – Axonometrics



Optimized Patch Enhance envelope

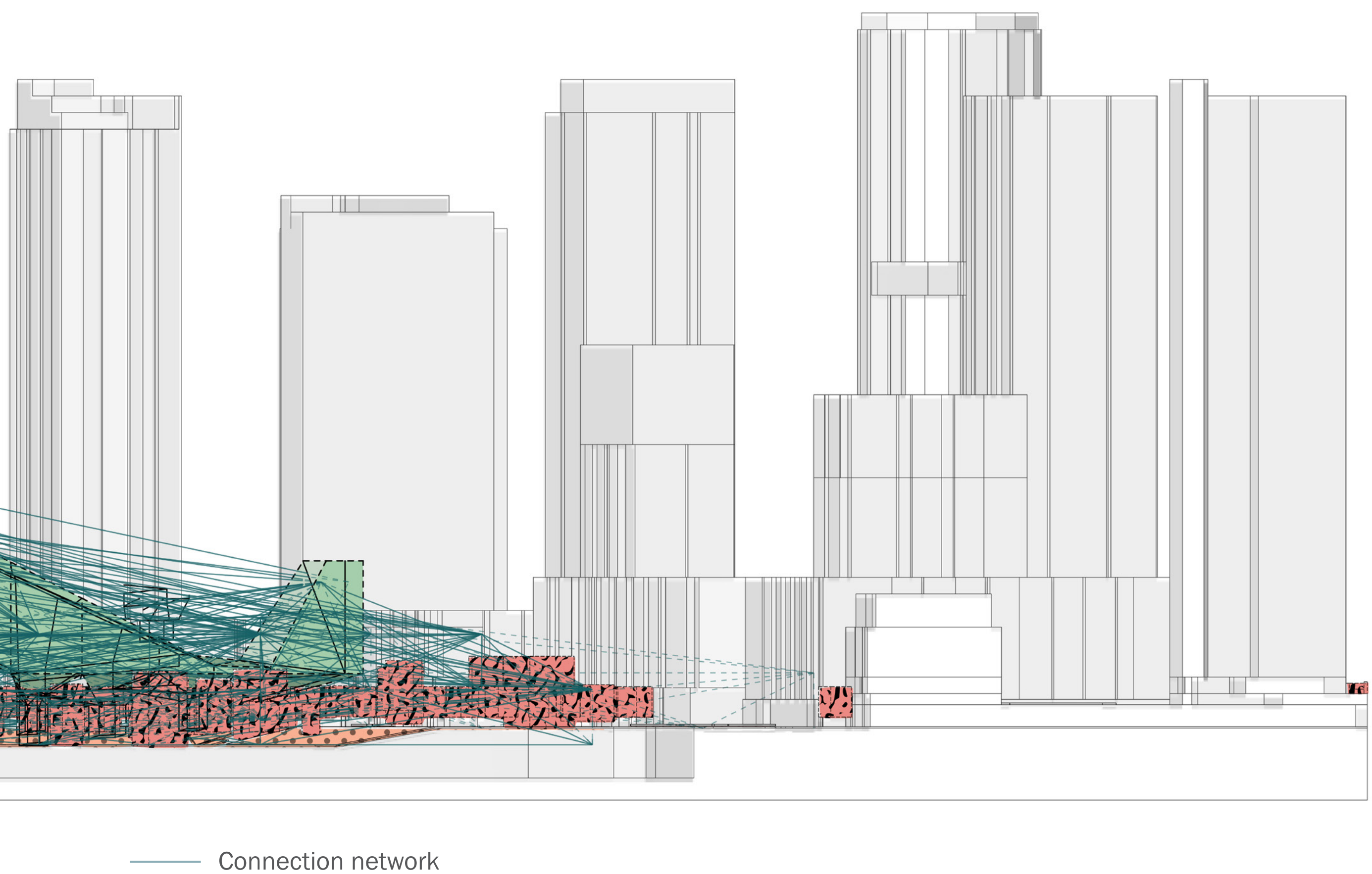


Fig 2.11. Patch enhance envelope with effect on local network– Section

PART III

HABITAT COMPOSITION ASSEMBLIES

Part III continues the *Patch Enhance* intervention introduced in Part II. This exploration speculates on how the data gathered from the network in Part I can be synthesized to generate a novel avian habitat that accommodates all species in the surrounding network. To design an artificial habitat scaffold, the composition of natural habitats is analyzed, deconstructed, and replicated using an assemblage of parametrically-generated assemblies.

FORMAL APPROACH

The design of this artificial habitat takes formal cues from Reaction Diffusion models, which represent two entangled systems that occupy the same space and react with each other to create an intricate interface. While this is an apt metaphor for an intervention that curates human and avian interaction within a dense urban environment, this system was selected because its constant variation provides a multiplicity of micro-environments and protected areas for plants and bird species, while creating a sense of wonder and exploration for human occupants. The correlation between variation in habitat structure and biodiversity is well documented in landscape ecology, and by housing diverse bird species in a captivating form, this intervention seeks to invoke the biophilic sense of wonder Timothy Beatley discusses. To ensure this formal approach specifically attracts target species, data gathered from the network will be used to digitally curate the habitat structure, plant selection, and nesting opportunities.

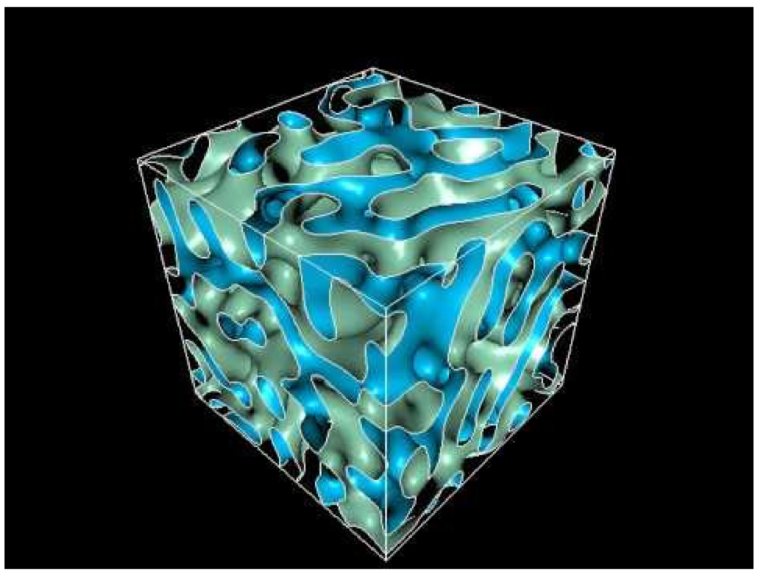


Fig 3.1. Reaction Diffusion simulation

HABITAT STRUCTURE

To guide the composition of this artificial habitat, it is important to examine vertical structure. The vertical structure of a habitat is essentially the contents and arrangement of its layers. In this study, different types of avian habitats are broken into elements. This was achieved by compiling imagery to analyse habitats, before re-drawing them using hatches for each element type. Each habitat type can be composed using a mixture of these nine elements:

- Ground Litter
- Grass
- Shrub
- Understory
- Canopy
- Overstory
- Cliff
- Gravel
- Water

Once this method of representing habitat structure is established, it can be schematically applied to the intervention massing to begin testing habitat compositions for this *Patch Enhance* intervention.

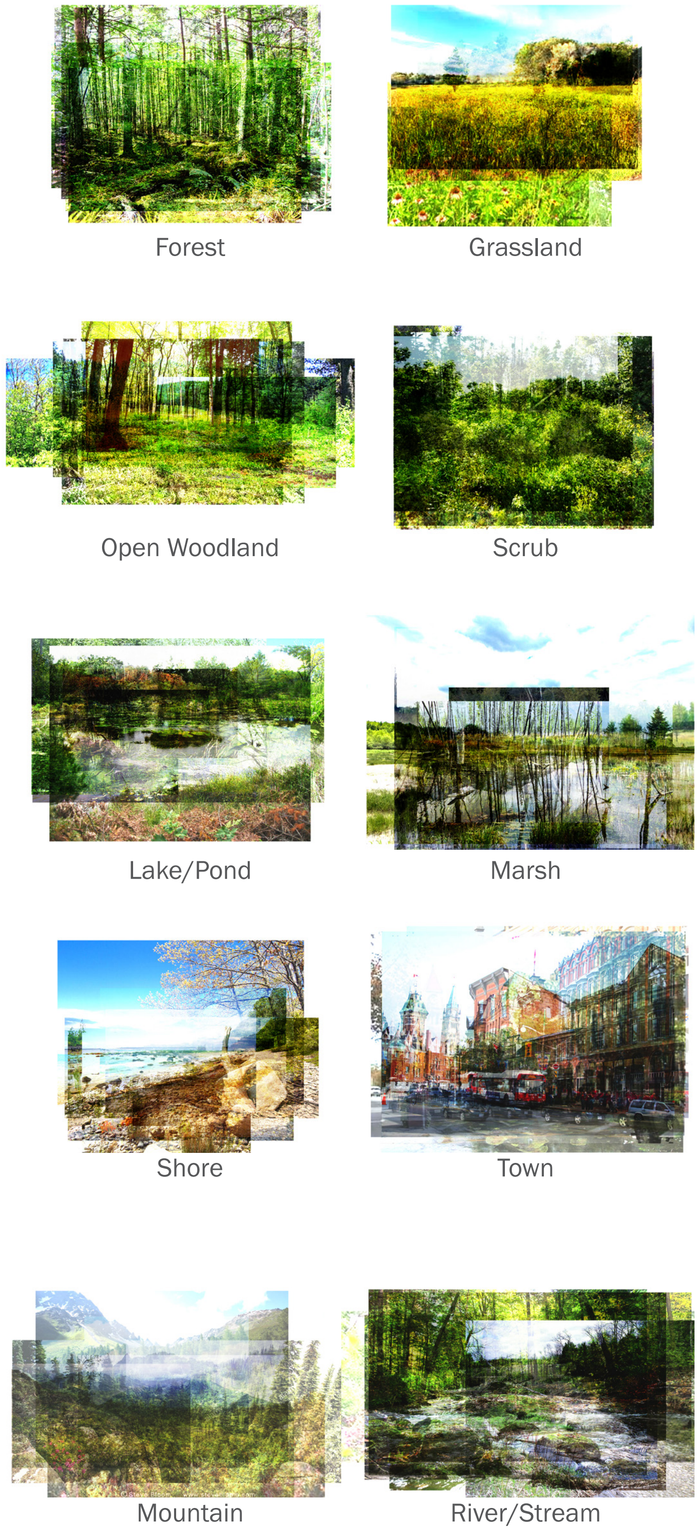
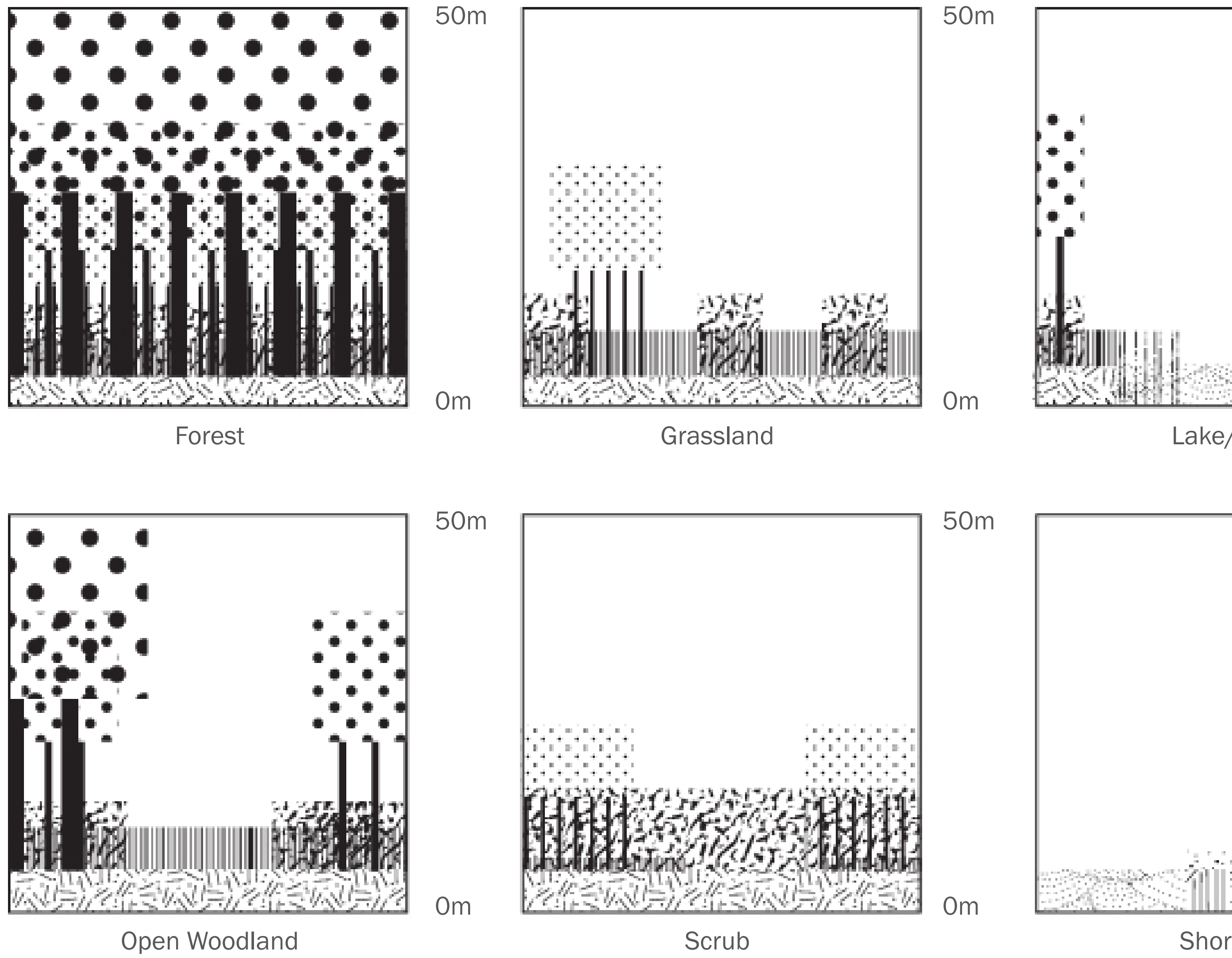
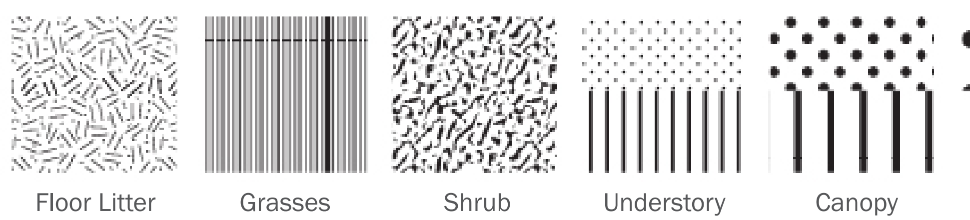


Fig 3.2. Habitat photo compilations

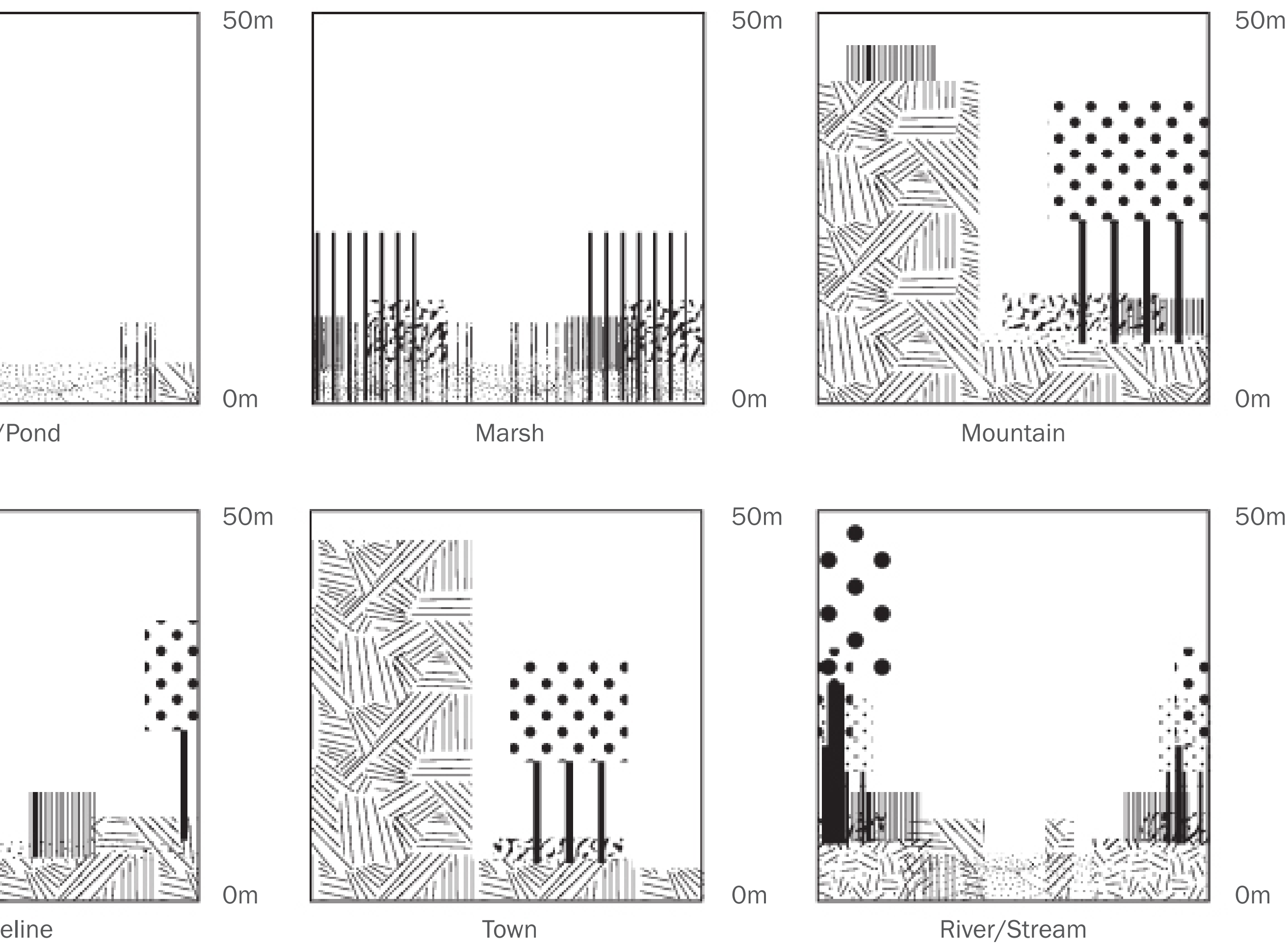
HABITAT



ELEM



T TYPES



ENTS

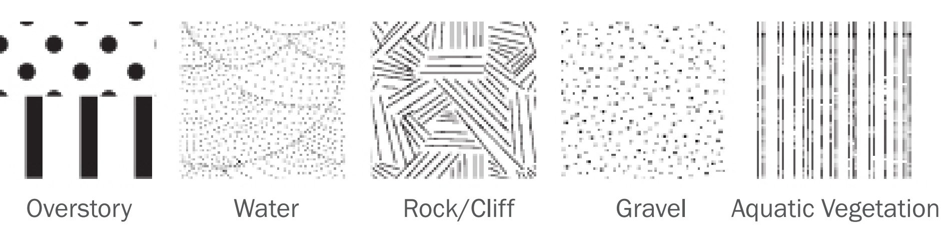
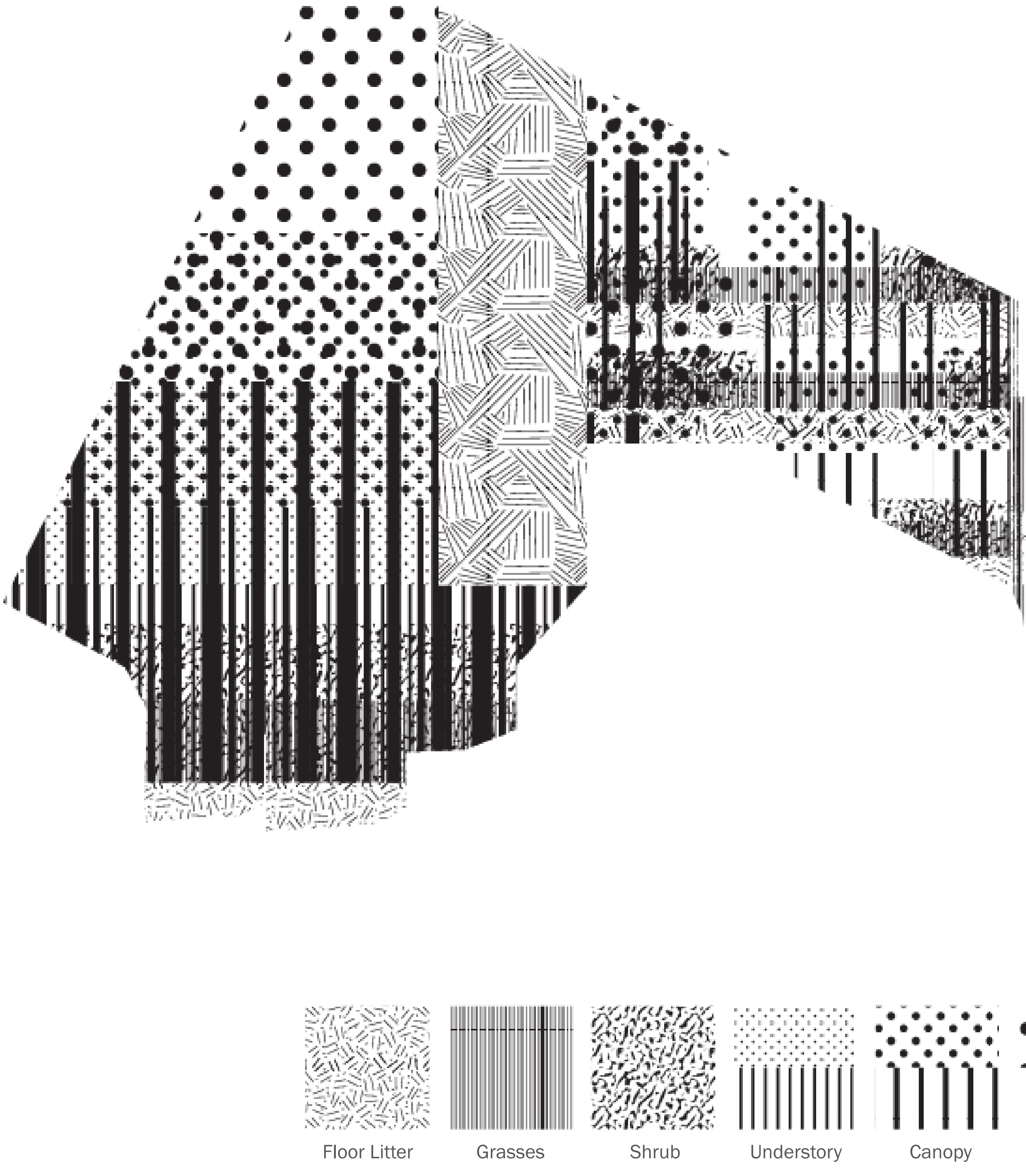


Fig 3.3. Habitat vertical structure analysis using elements as building blocks


Floor Litter
Grasses
Shrub
Understory
Canopy

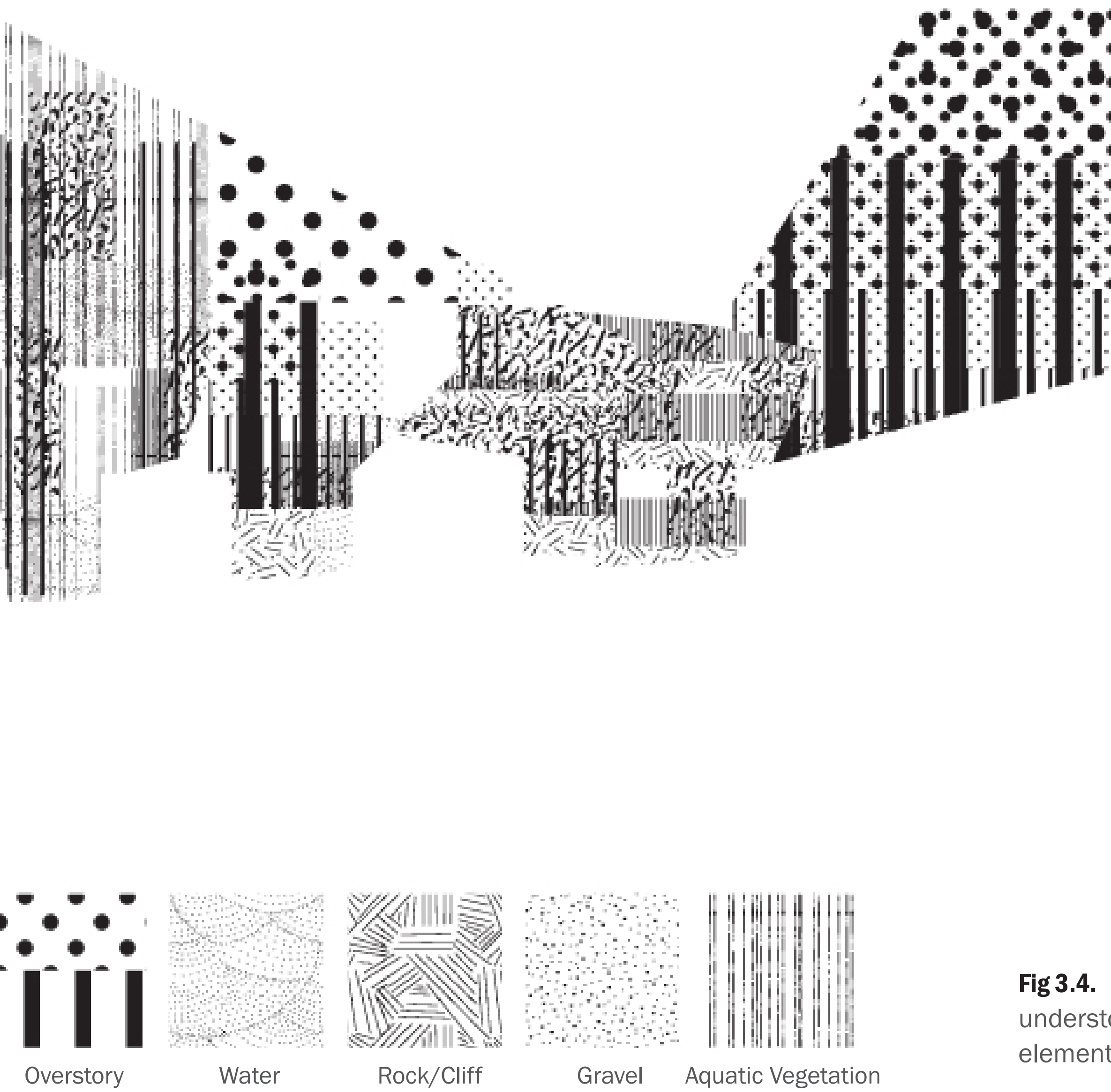


Fig 3.4. Habitat intervention understood as a collage of elements

HABITAT COMPOSITION

[input]

To begin composing this habitat, the intervention location is placed in the network graph to retrieve the bird species recorded at the intervention location, as well as in neighbouring patches. The species lists from first and second-degree connections are analysed to create a habitat breakdown outlining the amount of each habitat required at the intervention.

[process]

To begin, the zoning envelope is broken into habitats based on the breakdown, the envelope height, and logical adjacencies. The habitats are then creating by arranging the elements according to the vertical structures outlined in the previous study. To create these elements with tangible geometries, the reaction diffusion algorithm is tuned using different values for verticality, amount of branching, density, and thickness. The resulting geometries have specific attributes that mimic the core habitat elements. The tuned geometries then fill these element regions, and human circulation in woven through the spaces created.

[evaluation]

When applied at scale, this generates a habitat with the ability to support large and diverse populations of birds and act as a key component in an avian habitat network.

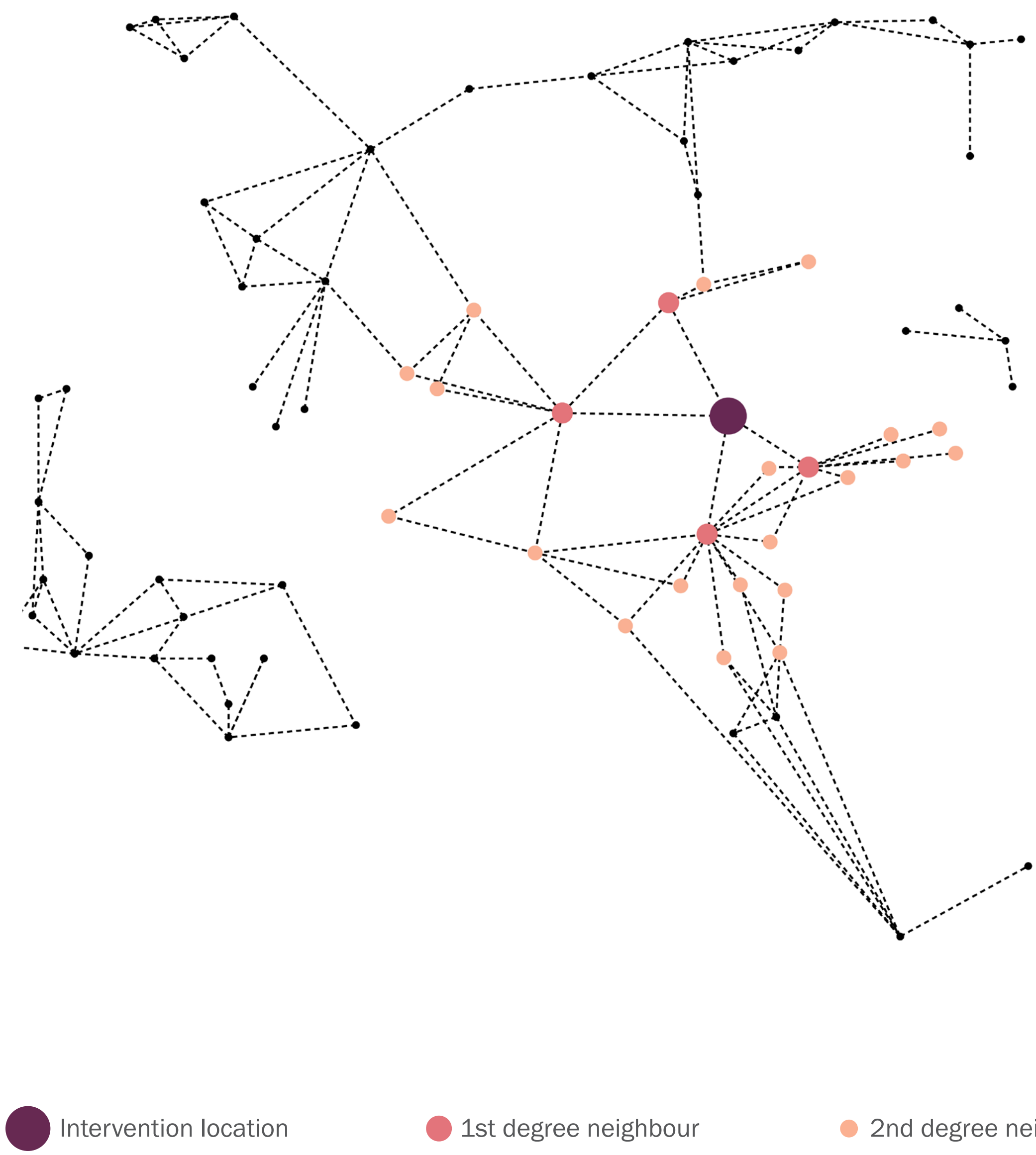


Fig 3.5. Accessing species data sets based on intervention connectivity

HABITAT BREAKDOWN

Forest - 28%
Grassland - 6 %
Lake/Pond - 23 %
Marsh - 7 %
Mountains - 1%
Ocean - 1%
Open Woodland - 20%
River/Stream - 1 %
Scrub - 6%
Shoreline - 6%
Town - 4%

NESTING BREAKDOWN

Building - 3%
Burrow - 3%
Cavity - 25%
Cliff - 2%
Floating - 4%
Ground - 35%
Shrub - 10%
Tree - 27%

LOCATED AT INTERVENTION

White-throated Sparrow	1	Forest	Seeds	Ground	Ground For	Least Conc	17	21
Bufflehead	6	Lake/Pond	Insects	Cavity	Surface Div	Least Conc	37	55
Greater Scaup	2	Lake/Pond	Insects	Ground	Surface Div	Least Conc	57	75
Canada Goose	1	Marsh	Seeds	Ground	Ground For	Least Conc	85	150
Swamp Sparrow	6	Marsh	Insects	Shrub	Ground For	Least Conc	13	18
House Sparrow	17	Town	Seeds	Cavity	Ground For	Least Conc	16	22

ONE CONNECTION AWAY

Barn Swallow	59	Grassland	Insects	Building	Aerial Fora	Least Conc	17	31
Eastern Phoebe	36	Open Woodland	Insects	Building	Fly Catchin	Least Conc	15	27
Rock Pigeon	23	Town	Seeds	Building	Ground For	Least Conc	33	58
Bank Swallow	37	Lake/Pond	Insects	Burrow	Aerial Fora	Least Conc	13	27
Belted Kingfisher	5	Lake/Pond	Fish	Burrow	Aerial Dive	Least Conc	31	54
Northern Rough-winged Swallow	38	River/Stream	Insects	Burrow	Aerial Fora	Least Conc	13	28
Black-capped Chickadee	4	Forest	Insects	Cavity	Foliage Gle	Least Conc	13	18
Downy Woodpecker	2	Forest	Insects	Cavity	Bark Forag	Least Conc	16	27
Hairy Woodpecker	1	Forest	Insects	Cavity	Bark Forag	Least Conc	22	37
Red-breasted Nuthatch	1	Forest	Insects	Cavity	Bark Forag	Least Conc	11	19
White-breasted Nuthatch	1	Forest	Insects	Cavity	Bark Forag	Least Conc	13	23
Winter Wren	9	Forest	Insects	Cavity	Ground For	Least Conc	10	14
Yellow-bellied Sapsucker	1	Forest	Insects	Cavity	Bark Forag	Least Conc	20	37
Bufflehead	12	Lake/Pond	Insects	Cavity	Surface Div	Least Conc	37	55
Common Goldeneye	5	Lake/Pond	Insects	Cavity	Surface Div	Least Conc	45	80
Common Merganser	86	Lake/Pond	Fish	Cavity	Surface Div	Least Conc	2	86
Hooded Merganser	4	Lake/Pond	Fish	Cavity	Surface Div	Least Conc	45	63
Purple Martin	13	Lake/Pond	Insects	Cavity	Aerial Fora	Least Conc	19	40
Tree Swallow	25	Lake/Pond	Insects	Cavity	Aerial Fora	Least Conc	13	32
American Kestrel	1	Open Woodland	Insects	Cavity	Soaring	Least Conc	26	55
Carolina Wren	1	Open Woodland	Insects	Cavity	Ground For	Least Conc	13	29
European Starling	30	Town	Insects	Cavity	Ground For	Least Conc	21	35
House Sparrow	30	Town	Seeds	Cavity	Ground For	Least Conc	16	22
Peregrine Falcon	2	Mountains	Birds	Cliff	Aerial Dive	Least Conc	45	105
Turkey Vulture	3	Open Woodland	Carrion	Cliff	Soaring	Least Conc	72	174
American Coot	1	Lake/Pond	Plants	Floating	Surface Div	Least Conc	40	60
Canvasback	1	Lake/Pond	Plants	Floating	Surface Div	Least Conc	52	85
Horned Grebe	1	Lake/Pond	Insects	Floating	Surface Div	Vulnerable	35	60
Redhead	155	Lake/Pond	Plants	Floating	Surface Div	Least Conc	48	77
Red-necked Grebe	5	Lake/Pond	Fish	Floating	Surface Div	Least Conc	50	75
Great Black-backed Gull	5	Shoreline	Omnivore	Gound	Ground For	Least Conc	75	155
Black-and-white Warbler	4	Forest	Insects	Ground	Bark Forag	Least Conc	12	20
Orange-crowned Warbler	3	Forest	Insects	Ground	Foliage Gle	Least Conc	12	19
Tennessee Warbler	6	Forest	Insects	Ground	Foliage Gle	Least Conc	12	20
White-throated Sparrow	85	Forest	Seeds	Ground	Ground For	Least Conc	17	21
Killdeer	6	Grassland	Insects	Ground	Ground For	Least Conc	24	47
Savannah Sparrow	3	Grassland	Insects	Ground	Ground For	Least Conc	12	21
Snowy Owl	1	Grassland	Mammals	Ground	Aerial Dive	Least Conc	61	134
American Black Duck	4	Lake/Pond	Insects	Ground	Dabbler	Least Conc	55	90
Common Loon	1	Lake/Pond	Fish	Ground	Surface Div	Least Conc	75	115
Double-crested Cormorant	729	Lake/Pond	Fish	Ground	Surface Div	Least Conc	80	120
Lesser Scaup	2	Lake/Pond	Insects	Ground	Surface Div	Least Conc	35	72
Long-tailed Duck	137	Lake/Pond	Insects	Ground	Surface Div	Vulnerable	48	72
Mallard	147	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	57	92
Mallard x American Black Duck (h	1	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	57	92
Mute Swan	22	Lake/Pond	Plants	Ground	Dabbler	Least Conc	140	218
Red-breasted Merganser	29	Lake/Pond	Fish	Ground	Surface Div	Least Conc	58	70
Red-throated Loon	1	Lake/Pond	Fish	Ground	Surface Div	Least Conc	60	110
Ring-billed Gull	95	Lake/Pond	Omnivore	Ground	Ground For	Least Conc	48	111
Trumpeter Swan	5	Lake/Pond	Plants	Ground	Dabbler	Least Conc	148	203
White-winged Scoter	31	Lake/Pond	Insects	Ground	Surface Div	Least Conc	53	80
Brant	3	Marsh	Plants	Ground	Ground For	Least Conc	62	1200
Canada Goose	46	Marsh	Seeds	Ground	Ground For	Least Conc	85	150
Gadwall	3	Marsh	Plants	Ground	Dabbler	Least Conc	52	84
Virginia Rail	1	Marsh	Insects	Ground	Probing	Least Conc	24	35
American Tree Sparrow	12	Open Woodland	Seeds	Ground	Ground For	Least Conc	14	24
Brewster's Warbler (hybrid)	1	Open Woodland	Insects	Ground	Foliage Gle	Least Conc	13	26
Hermit Thrush	2	Open Woodland	Insects	Ground	Ground For	Least Conc	16	27
Palm Warbler	2	Open Woodland	Insects	Ground	Ground For	Least Conc	13	20
Eastern Towhee	4	Scrub	Omnivore	Ground	Ground For	Least Conc	19	24
Field Sparrow	3	Scrub	Insects	Ground	Ground For	Least Conc	13	20
Lincoln's Sparrow	7	Scrub	Insects	Ground	Ground For	Least Conc	14	18
White-crowned Sparrow	10	Scrub	Insects	Ground	Ground For	Least Conc	15	22
Wilson's Warbler	2	Scrub	Insects	Ground	Foliage Gle	Least Conc	11	16
Caspian Tern	3	Shoreline	Fish	Ground	Aerial Dive	Least Conc	50	130
Herring Gull	3	Shoreline	Omnivore	Ground	Ground For	Least Conc	61	142
Spotted Sandpiper	14	Shoreline	Small Anim	Ground	Probing	Least Conc	19	29
Wilson's Plover	1	Shoreline	Insects	Ground	Probing	Least Conc	18	38
Black-throated Blue Warbler	7	Forest	Insects	Shrub	Foliage Gle	Least Conc	12	18
Red-winged Blackbird	220	Marsh	Insects	Shrub	Ground For	Least Conc	20	36
Swamp Sparrow	2	Marsh	Insects	Shrub	Ground For	Least Conc	13	18

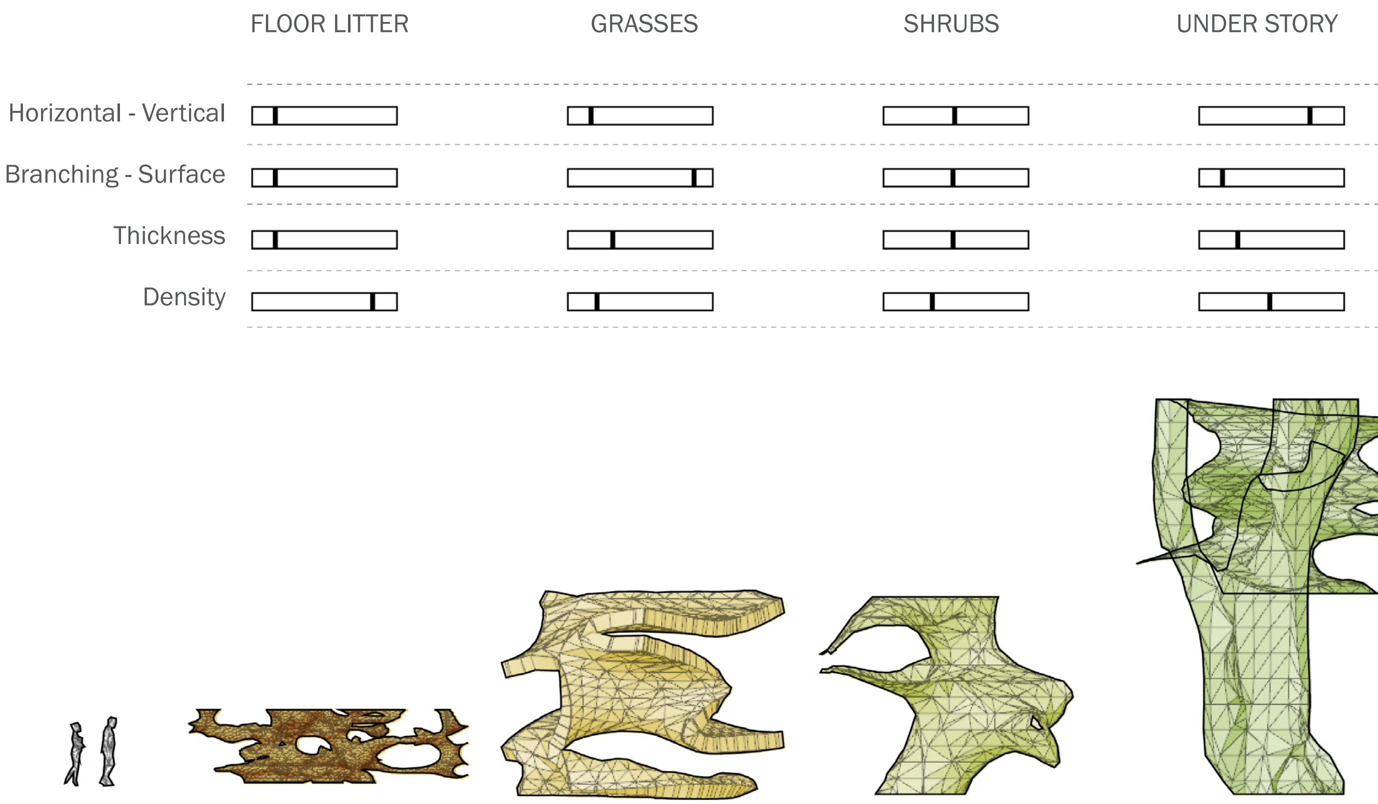
American Goldfinch	132	Open Woodland	Seeds	Shrub	Foliage Gle	Least Conc	12	20
Chipping Sparrow	7	Open Woodland	Seeds	Shrub	Ground For	Least Conc	13	21
Gray Catbird	8	Open Woodland	Insects	Shrub	Ground For	Least Conc	22	27
Northern Cardinal	4	Open Woodland	Seeds	Shrub	Ground For	Least Conc	22	28
Song Sparrow	11	Open Woodland	Insects	Shrub	Ground For	Least Conc	15	20
Yellow Warbler	24	Open Woodland	Insects	Shrub	Foliage Gle	Least Conc	12	18
Clay-colored Sparrow	1	Scrub	Seeds	Shrub	Foliage Gle	Least Conc	13	21
Common Yellowthroat	1	Scrub	Insects	Shrub	Foliage Gle	Least Conc	12	17
American Redstart	1	Forest	Insects	Tree	Foliage Gle	Least Conc	12	17
Bay-breasted Warbler	79	Forest	Insects	Tree	Foliage Gle	Least Conc	14	21
Blackburnian Warbler	6	Forest	Insects	Tree	Foliage Gle	Least Conc	11	20
Blue Jay	28	Forest	Omnivore	Tree	Ground For	Least Conc	27	38
Blue-gray Gnatcatcher	8	Forest	Insects	Tree	Foliage Gle	Least Conc	10	16
Blue-headed Vireo	3	Forest	Insects	Tree	Foliage Gle	Least Conc	14	22
Broad-winged Hawk	1	Forest	Mammals	Tree	Aerial Dive	Least Conc	38	90
Brown Creeper	2	Forest	Insects	Tree	Bark Forag	Least Conc	13	19
Cape May Warbler	5	Forest	Insects	Tree	Foliage Gle	Least Conc	12	20
Cooper's Hawk	1	Forest	Birds	Tree	Aerial Fora	Least Conc	38	75
Eastern Wood-Pewee	4	Forest	Insects	Tree	Flycatching	Least Conc	15	25
Golden-crowned Kinglet	2	Forest	Insects	Tree	Foliage Gle	Least Conc	10	16
Magnolia Warbler	3	Forest	Insects	Tree	Foliage Gle	Least Conc	12	18
Red-eyed Vireo	29	Forest	Insects	Tree	Foliage Gle	Least Conc	12	24
Ruby-crowned Kinglet	10	Forest	Insects	Tree	Foliage Gle	Least Conc	10	17
Scarlet Tanager	1	Forest	Insects	Tree	Foliage Gle	Least Conc	16	27
Sharp-shinned Hawk	2	Forest	Birds	Tree	Aerial Dive	Least Conc	29	49
Wood Thrush	2	Forest	Insects	Tree	Ground For	Least Conc	20	32
Yellow-rumped Warbler	52	Forest	Insects	Tree	Foliage Gle	Least Conc	13	21
Brown-headed Cowbird	2	Grassland	Seeds	Tree	Ground For	Least Conc	20	36
Osprey	1	Lake/Pond	Fish	Tree	Aerial Dive	Least Conc	56	165
American Crow	8	Open Woodland	Omnivore	Tree	Ground For	Least Conc	45	90
American Robin	197	Open Woodland	Insects	Tree	Ground For	Least Conc	25	35
Baltimore Oriole	2	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	18	26
Common Grackle	7	Open Woodland	Omnivore	Tree	Ground For	Least Conc	31	41
Mourning Dove	2	Open Woodland	Seeds	Tree	Ground For	Least Conc	28	45
Olive-sided Flycatcher	1	Open Woodland	Insects	Tree	Flycatching	Near Threa	19	35
Red-tailed Hawk	1	Open Woodland	Small Anim	Tree	Soaring	Least Conc	50	125
Warbling Vireo	32	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	12	22
House Finch	3	Town	Seeds	Tree	Ground For	Least Conc	13	22

TWO CONNECTIONS AWAY

Semipalmated Sandpiper	1	Shoreline	Insects	Ground	Ground For	Near Threa	14	29
Spotted Sandpiper	29	Shoreline	Small Anim	Ground	Probing	Least Conc	19	29
tern sp.	3	Shoreline	Fish	Ground	Aerial Dive	Least Conc	34	77
Wilson's Plover	3	Shoreline	Insects	Ground	Probing	Least Conc	18	38
Alder/Willow Flycatcher (Traill's F	1	Marsh	Insects	Scrub	Flycatching	Least Conc	15	22
Alder Flycatcher	5	Scrub	Insects	Scrub	Flycatching	Least Conc	15	22
Black-throated Blue Warbler	51	Forest	Insects	Shrub	Foliage Gle	Least Conc	12	18
Gray-cheeked Thrush	7	Forest	Insects	Shrub	Ground For	Least Conc	16	28
Swainson's Thrush	13	Forest	Insects	Shrub	Foliage Gle	Least Conc	17	30
Red-winged Blackbird	1223	Marsh	Insects	Shrub	Ground For	Least Conc	20	36
Swamp Sparrow	23	Marsh	Insects	Shrub	Ground For	Least Conc	13	18
American Goldfinch	308	Open Woodland	Seeds	Shrub	Foliage Gle	Least Conc	12	20
Chestnut-sided Warbler	24	Open Woodland	Insects	Shrub	Foliage Gle	Least Conc	10	19
Chipping Sparrow	70	Open Woodland	Seeds	Shrub	Ground For	Least Conc	13	21
Gray Catbird	58	Open Woodland	Insects	Shrub	Ground For	Least Conc	22	27
Indigo Bunting	2	Open Woodland	Insects	Shrub	Foliage Gle	Least Conc	12	20
Northern Cardinal	148	Open Woodland	Seeds	Shrub	Ground For	Least Conc	22	28
Prairie Warbler	1	Open Woodland	Insects	Shrub	Foliage Gle	Least Conc	11	20
Song Sparrow	77	Open Woodland	Insects	Shrub	Ground For	Least Conc	15	20
Yellow Warbler	196	Open Woodland	Insects	Shrub	Foliage Gle	Least Conc	12	18
Brown Thrasher	12	Scrub	Omnivore	Shrub	Ground For	Least Conc	26	30
Clay-colored Sparrow	4	Scrub	Seeds	Shrub	Foliage Gle	Least Conc	13	21
Common Yellowthroat	27	Scrub	Insects	Shrub	Foliage Gle	Least Conc	12	17
Northern Mockingbird	3	Town	Omnivore	Shrub	Ground For	Least Conc	24	33
Willow Flycatcher	8	Marsh	Insects	Shrubs	Flycatching	Least Conc	15	22
American Redstart	31	Forest	Insects	Tree	Foliage Gle	Least Conc	12	17
Bald Eagle	4	Forest	Fish	Tree	Soaring	Least Conc	85	204
Bay-breasted Warbler	87	Forest	Insects	Tree	Foliage Gle	Least Conc	14	21
Blackburnian Warbler	19	Forest	Insects	Tree	Foliage Gle	Least Conc	11	20
Blackpoll Warbler	6	Forest	Insects	Tree	Foliage Gle	Least Conc	14	22
Black-throated Green Warbler	27	Forest	Insects	Tree	Foliage Gle	Least Conc	12	18
Blue Jay	1419	Forest	Omnivore	Tree	Ground For	Least Conc	27	38
Blue-gray Gnatcatcher	79	Forest	Insects	Tree	Foliage Gle	Least Conc	10	16
Blue-headed Vireo	15	Forest	Insects	Tree	Foliage Gle	Least Conc	14	22
Broad-winged Hawk	2	Forest	Mammals	Tree	Aerial Dive	Least Conc	38	90
Brown Creeper	16	Forest	Insects	Tree	Bark Forag	Least Conc	13	19
Cape May Warbler	8	Forest	Insects	Tree	Foliage Gle	Least Conc	12	20
Cerulean Warbler	2	Forest	Insects	Tree	Foliage Gle	Vulnerable	11	20
Cooper's Hawk	10	Forest	Birds	Tree	Aerial Fora	Least Conc	38	75
Eastern Wood-Pewee	8	Forest	Insects	Tree	Flycatching	Least Conc	15	25
Empidonax sp.	2	Forest	Insects	Tree	Flycatching	Least Conc	15	23
Golden-crowned Kinglet	188	Forest	Insects	Tree	Foliage Gle	Least Conc	10	16
Least Flycatcher	19	Forest	Insects	Tree	Flycatching	Least Conc	13	20
Magnolia Warbler	31	Forest	Insects	Tree	Foliage Gle	Least Conc	12	18
Northern Goshawk	1	Forest	Birds	Tree	Aerial Dive	Least Conc	58	109
Northern Parula	35	Forest	Insects	Tree	Foliage Gle	Least Conc	11	17
Philadelphia Vireo	9	Forest	Insects	Tree	Foliage Gle	Least Conc	12	20
Pine Warbler	7	Forest	Insects	Tree	Bark Forag	Least Conc	13	21
Red-eyed Vireo	48	Forest	Insects	Tree	Foliage Gle	Least Conc	12	24
Rose-breasted Grosbeak	26	Forest	Insects	Tree	Foliage Gle	Least Conc	19	31
Ruby-crowned Kinglet	94	Forest	Insects	Tree	Foliage Gle	Least Conc	10	17
Rusty Blackbird	130	Forest	Insects	Tree	Ground For	Vulnerable	23	37
Scarlet Tanager	3	Forest	Insects	Tree	Foliage Gle	Least Conc	16	27
Sharp-shinned Hawk	86	Forest	Birds	Tree	Aerial Dive	Least Conc	29	49
Wood Thrush	10	Forest	Insects	Tree	Ground For	Least Conc	20	32
Yellow-rumped Warbler	232	Forest	Insects	Tree	Foliage Gle	Least Conc	13	21
Brown-headed Cowbird	88	Grassland	Seeds	Tree	Ground For	Least Conc	20	36
Eastern Kingbird	92	Grassland	Insects	Tree	Fly Catchin	Least Conc	21	36
Bonaparte's Gull	39	Lake/Pond	Insects	Tree	Dabbler	Least Conc	32	78
Osprey	9	Lake/Pond	Fish	Tree	Aerial Dive	Least Conc	56	165
Black-crowned Night-Heron	11	Marsh	Fish	Tree	Stalking	Least Conc	62	116
Great Blue Heron	11	Marsh	Fish	Tree	Stalking	Least Conc	120	185
Great Egret	17	Marsh	Fish	Tree	Stalking	Least Conc	100	140
Green Heron	1	Marsh	Fish	Tree	Stalking	Least Conc	43	66
Solitary Sandpiper	3	Marsh	Insects	Tree	Probing	Least Conc	21	42
American Crow	86	Open Woodland	Omnivore	Tree	Ground For	Least Conc	45	90
American Robin	526	Open Woodland	Insects	Tree	Ground For	Least Conc	25	35
Baltimore Oriole	107	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	18	26
Cedar Waxwing	183	Open Woodland	Fruit	Tree	Foliage Gle	Least Conc	15	26
Common Grackle	79	Open Woodland	Omnivore	Tree	Ground For	Least Conc	31	41
Merlin	4	Open Woodland	Birds	Tree	Aerial Fora	Least Conc	27	58
Mourning Dove	75	Open Woodland	Seeds	Tree	Ground For	Least Conc	28	45
Northern Shrike	2	Open Woodland	Birds	Tree	Aerial Dive	Least Conc	23	32
Olive-sided Flycatcher	2	Open Woodland	Insects	Tree	Flycatching	Near Threa	19	35
Orchard Oriole	7	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	16	25
Pine Siskin	21	Open Woodland	Seeds	Tree	Foliage Gle	Least Conc	12	20
Red-tailed Hawk	9	Open Woodland	Small Anim	Tree	Soaring	Least Conc	50	125
Ruby-throated Hummingbird	6	Open Woodland	Nectar	Tree	Hovering	Least Conc	8	9

Canvasback	10	Lake/Pond	Plants	Floating	Surface Div	Least Conc	52	85
Horned Grebe	4	Lake/Pond	Insects	Floating	Surface Div	Vulnerable	35	60
Pied-billed Grebe	3	Lake/Pond	Insects	Floating	Surface Div	Least Conc	34	48
Redhead	399	Lake/Pond	Plants	Floating	Surface Div	Least Conc	48	77
Red-necked Grebe	244	Lake/Pond	Fish	Floating	Surface Div	Least Conc	50	75
Great Black-backed Gull	12	Shoreline	Omnivore	Gound	Ground For	Least Conc	75	155
Black-and-white Warbler	74	Forest	Insects	Ground	Bark Forag	Least Conc	12	20
Canada Warbler	4	Forest	Insects	Ground	Foliage Gle	Least Conc	13	19
Dark-eyed Junco	90	Forest	Seeds	Ground	Ground For	Least Conc	15	21
Fox Sparrow	7	Forest	Insects	Ground	Ground For	Least Conc	16	22
Mourning Warbler	1	Forest	Insects	Ground	Foliage Gle	Least Conc	12	18
Nashville Warbler	14	Forest	Insects	Ground	Foliage Gle	Least Conc	11	18
Northern Waterthrush	5	Forest	Insects	Ground	Ground For	Least Conc	13	23
Orange-crowned Warbler	12	Forest	Insects	Ground	Foliage Gle	Least Conc	12	19
Ovenbird	16	Forest	Insects	Ground	Ground For	Least Conc	12	23
Tennessee Warbler	9	Forest	Insects	Ground	Foliage Gle	Least Conc	12	20
Veery	11	Forest	Insects	Ground	Ground For	Least Conc	17	28
warbler sp. (Parulidae sp.)	172	Forest	Insects	Ground	Foliage Gle	Least Conc	13	19
White-throated Sparrow	1176	Forest	Seeds	Ground	Ground For	Least Conc	17	21
Yellow-bellied Flycatcher	1	Forest	Insects	Ground	Flycatching	Least Conc	14	19
American Pipit	125	Grassland	Insects	Ground	Ground For	Least Conc	15	27
Common Nighthawk	2	Grassland	Insects	Ground	Aerial Fora	Least Conc	23	55
Horned Lark	1	Grassland	Seeds	Ground	Ground For	Least Conc	18	32
Killdeer	63	Grassland	Insects	Ground	Ground For	Least Conc	24	47
Lapland Longspur	19	Grassland	Insects	Ground	Ground For	Least Conc	15	25
Northern Harrier	7	Grassland	Mammals	Ground	Soaring	Least Conc	48	110
Savannah Sparrow	36	Grassland	Insects	Ground	Ground For	Least Conc	12	21
Snowy Owl	6	Grassland	Mammals	Ground	Aerial Dive	Least Conc	61	134
American Black Duck	29	Lake/Pond	Insects	Ground	Dabbler	Least Conc	55	90
American Wigeon	2	Lake/Pond	Plants	Ground	Dabbler	Least Conc	50	84
Blue-winged Teal	2	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	38	60
Cackling Goose	1	Lake/Pond	Plants	Ground	Ground For	Least Conc	63	90
Common Loon	19	Lake/Pond	Fish	Ground	Surface Div	Least Conc	75	115
Double-crested Cormorant	10979	Lake/Pond	Fish	Ground	Surface Div	Least Conc	80	120
goose sp.	2	Lake/Pond	Plants	Ground	Ground For	Least Conc	63	90
Greater Scaup	1229	Lake/Pond	Insects	Ground	Surface Div	Least Conc	57	75
Greater/Lesser Scaup	13	Lake/Pond	Insects	Ground	Surface Div	Least Conc	57	75
Lesser Scaup	48	Lake/Pond	Insects	Ground	Surface Div	Least Conc	35	72
Long-tailed Duck	1447	Lake/Pond	Insects	Ground	Surface Div	Vulnerable	48	72
Mallard	1165	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	57	92
Mallard (Domestic type)	1	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	57	92
Mallard x American Black Duck (h	2	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	57	92
Mute Swan	180	Lake/Pond	Plants	Ground	Dabbler	Least Conc	140	218
Northern Pintail	1	Lake/Pond	Seeds	Ground	Dabbler	Least Conc	62	90
Red-breasted Merganser	889	Lake/Pond	Fish	Ground	Surface Div	Least Conc	58	70
Red-throated Loon	2	Lake/Pond	Fish	Ground	Surface Div	Least Conc	60	110
Ring-billed Gull	2773	Lake/Pond	Omnivore	Ground	Ground For	Least Conc	48	111
Ring-necked Duck	9	Lake/Pond	Plants	Ground	Surface Div	Least Conc	42	62
Trumpeter Swan	17	Lake/Pond	Plants	Ground	Dabbler	Least Conc	148	203
Tundra Swan	8	Lake/Pond	Plants	Ground	Dabbler	Least Conc	135	168
White-winged Scoter	34	Lake/Pond	Insects	Ground	Surface Div	Least Conc	53	80
Brant	3	Marsh	Plants	Ground	Ground For	Least Conc	62	1200
Canada Goose	558	Marsh	Seeds	Ground	Ground For	Least Conc	85	150
Gadwall	29	Marsh	Plants	Ground	Dabbler	Least Conc	52	84
Greater Yellowlegs	2	Marsh	Insects	Ground	Probing	Least Conc	31	60
Least Sandpiper	8	Marsh	Insects	Ground	Probing	Least Conc	14	27
Nelson's Sparrow	1	Marsh	Insects	Ground	Ground For	Least Conc	12	20
Virginia Rail	2	Marsh	Insects	Ground	Probing	Least Conc	24	35
Black Scoter	33	Ocean	Insects	Ground	Surface Div	Near Threa	48	84
Surf Scoter	5	Ocean	Insects	Ground	Surface Div	Least Conc	55	77
American Tree Sparrow	18	Open Woodland	Seeds	Ground	Ground For	Least Conc	14	24
Brewster's Warbler (hybrid)	1	Open Woodland	Insects	Ground	Foliage Gle	Least Conc	13	26
Hermit Thrush	67	Open Woodland	Insects	Ground	Ground For	Least Conc	16	27
Palm Warbler	145	Open Woodland	Insects	Ground	Ground For	Least Conc	13	20
Eastern Towhee	12	Scrub	Omnivore	Ground	Ground For	Least Conc	19	24
Field Sparrow	21	Scrub	Insects	Ground	Ground For	Least Conc	13	20
Lincoln's Sparrow	24	Scrub	Insects	Ground	Ground For	Least Conc	14	18
White-crowned Sparrow	198	Scrub	Insects	Ground	Ground For	Least Conc	15	22
Wilson's Warbler	12	Scrub	Insects	Ground	Foliage Gle	Least Conc	11	16
Caspian Tern	75	Shoreline	Fish	Ground	Aerial Dive	Least Conc	50	130
Common Tern	81	Shoreline	Fish	Ground	Aerial Dive	Least Conc	34	77
Dunlin	4	Shoreline	Insects	Ground	Probing	Least Conc	19	37
Herring Gull	244	Shoreline	Omnivore	Ground	Ground For	Least Conc	61	142
Larus sp.	7	Shoreline	Omnivore	Ground	Ground For	Least Conc	51	142
Lesser Black-backed Gull	1	Shoreline	Omnivore	Ground	Ground For	Least Conc	58	142
Piping Plover	19	Shoreline	Insects	Ground	Ground For	Near Threa	17	25
Sanderling	3	Shoreline	Insects	Ground	Probing	Least Conc	19	35
Semipalmated Plover	1	Shoreline	Insects	Ground	Ground For	Least Conc	18	28
Warbling Vireo	41	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	12	22
Yellow-throated Vireo	1	Open Woodland	Insects	Tree	Foliage Gle	Least Conc	14	23
House Finch	70	Town	Seeds	Tree	Ground For	Least Conc	13	22
Graylag Goose (Domestic type)	1	x	x	x	x	x	x	x

Fig 3.6. Species data by degree of connection


FLOOR LITTER
GRASSES
SHRUBS
UNDER STORY
Horizontal - Vertical
Branching - Surface
Thickness
Density

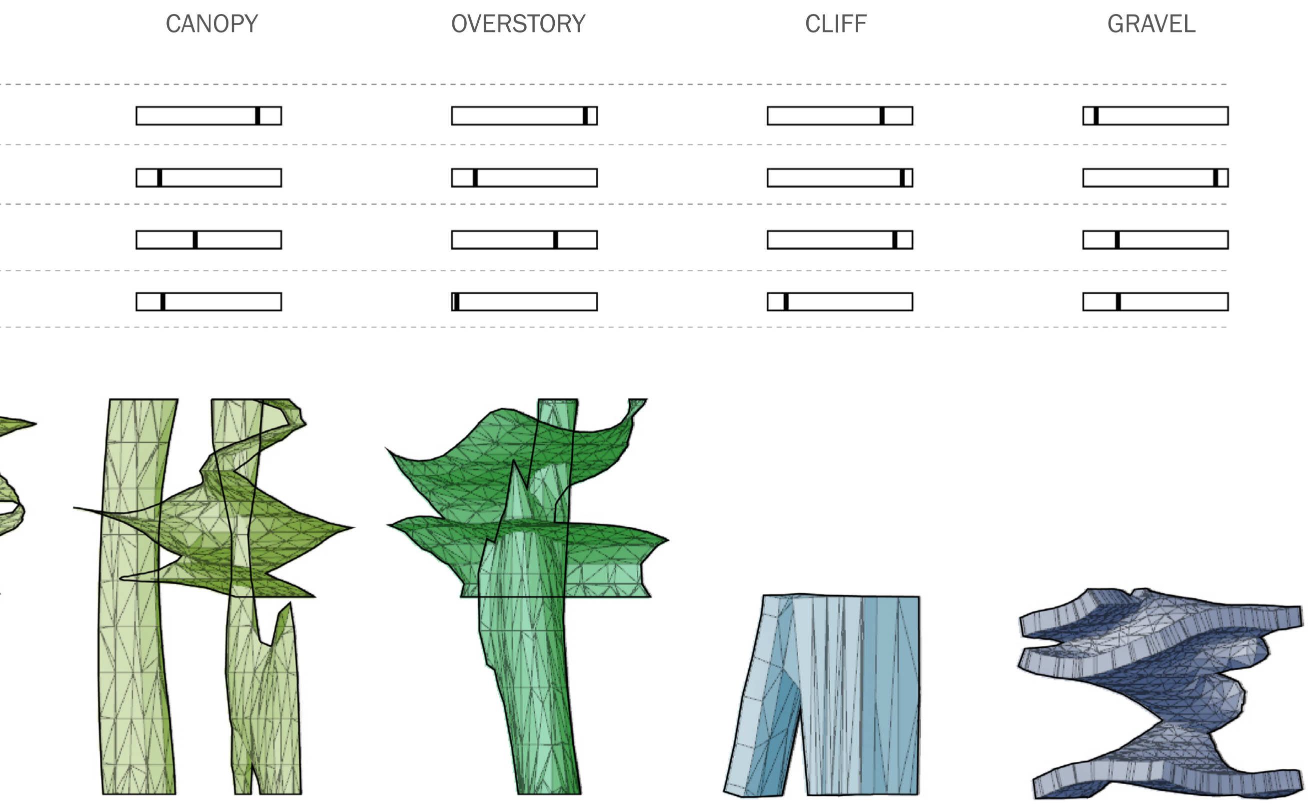
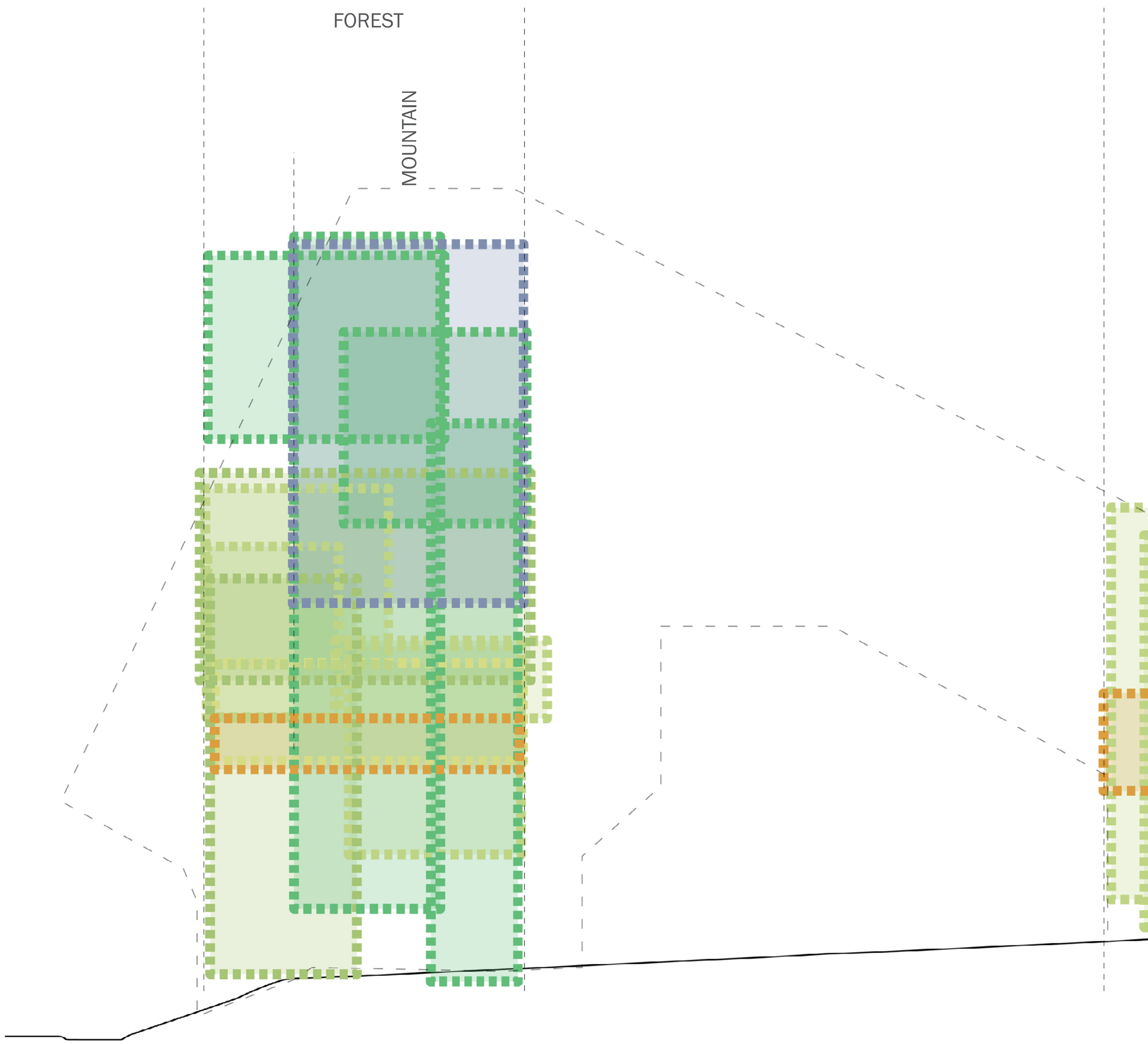


Fig 3.7. Parametrically tuned geometries simulating habitat elements


FOREST
MOUNTAIN

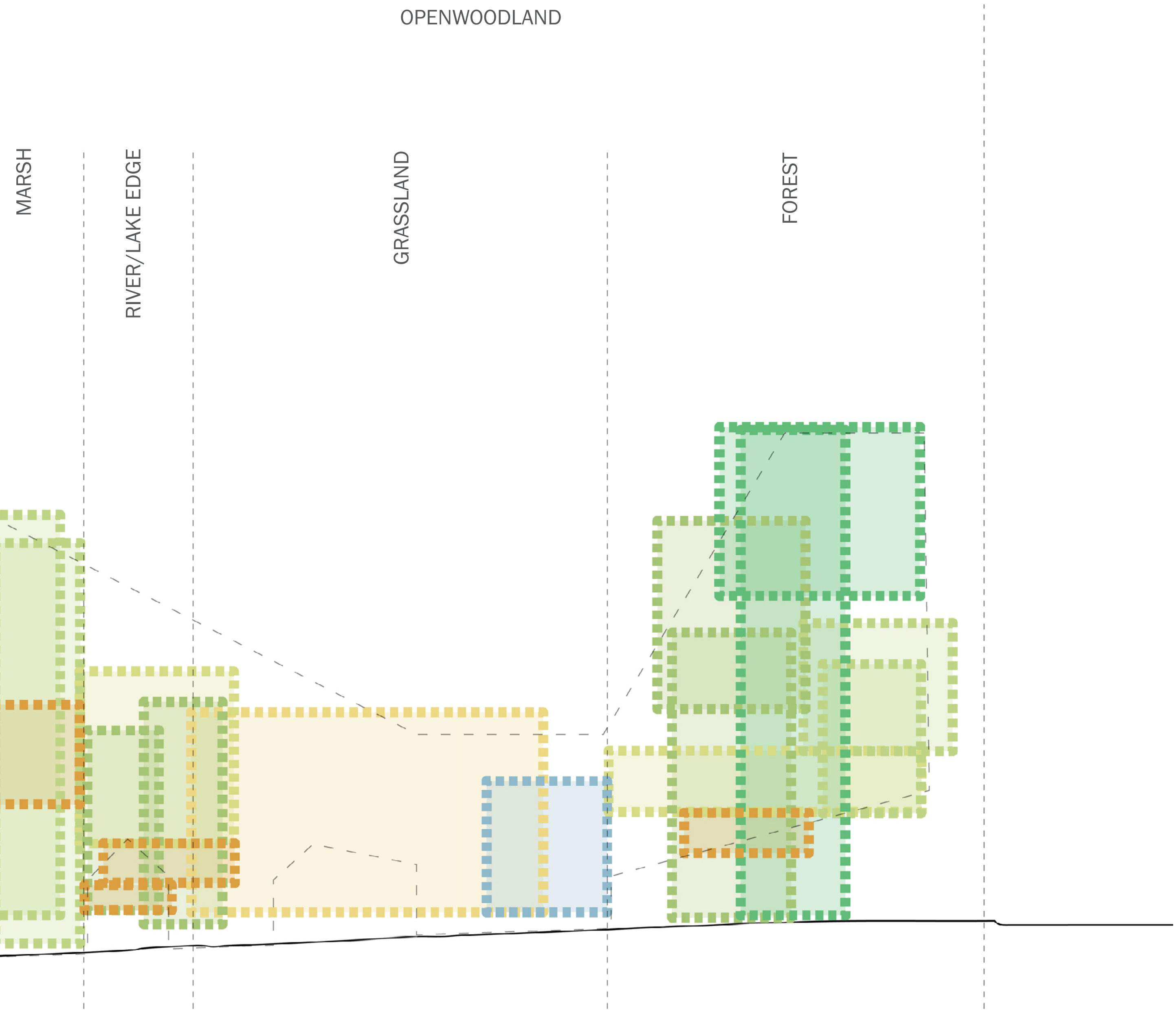
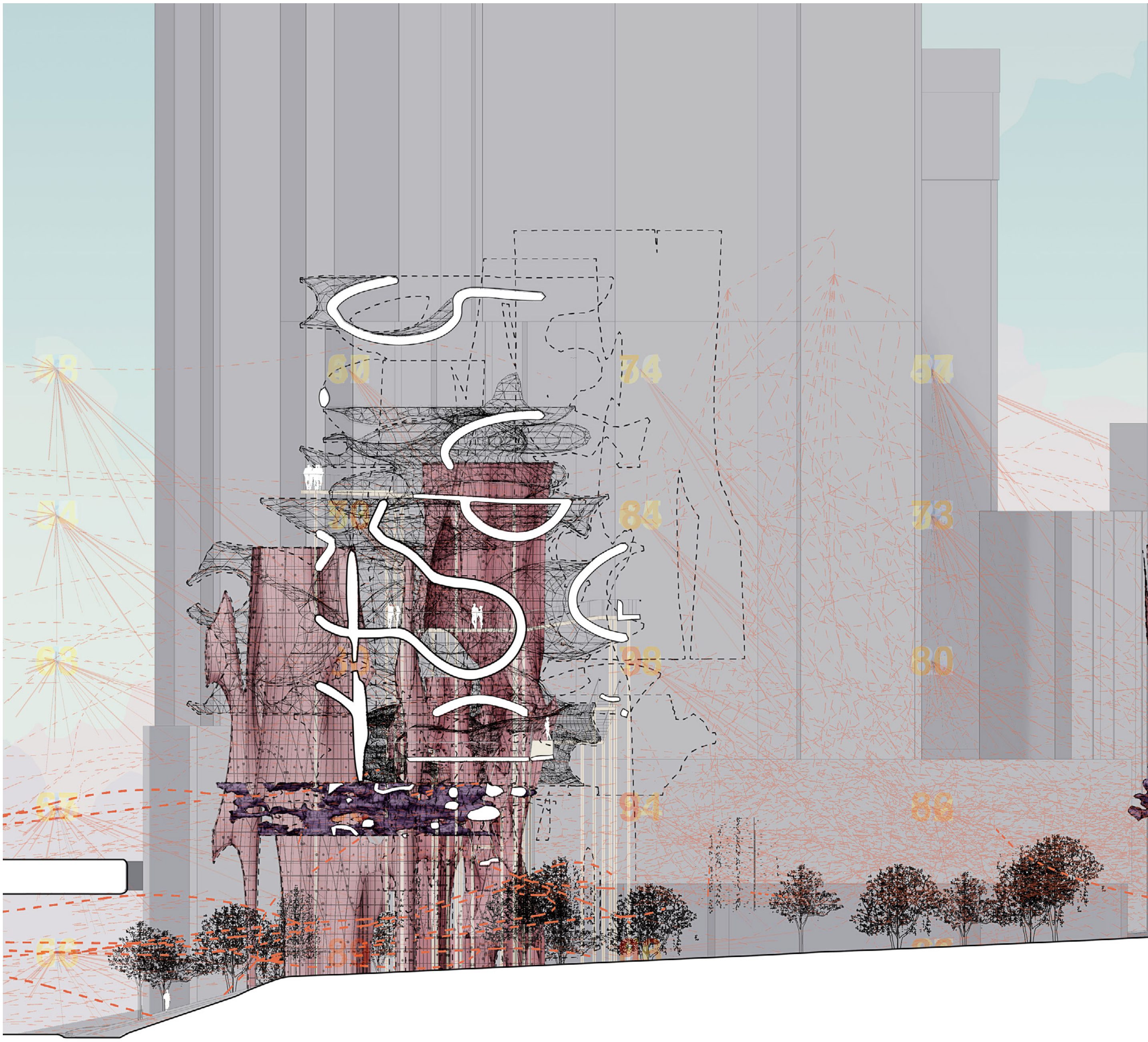


Fig 3.8. Habitat breakdown and element arrangement in intervention envelope



50 Avian accommodation value

- - - - - - - - - - Potential flight path

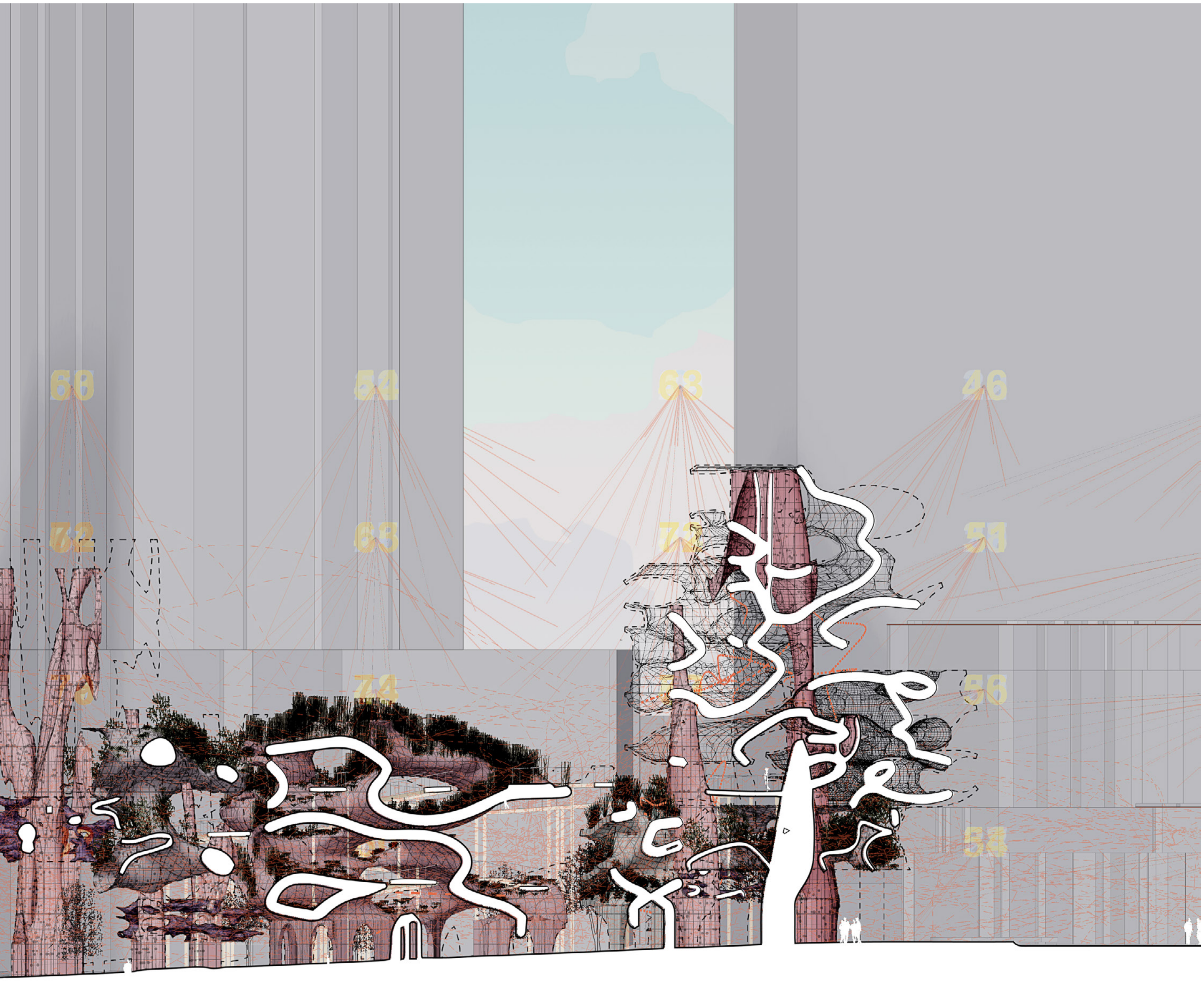


Fig 3.9. *Patch Enhance* intervention - Section

ASSEMBLY

[input]
To generate the assembly for each element in the habitat, the element geometry from the habitat compose exercise is used as a base. To inform the assembly, nesting box dimensions from the target species list, and a list of plants for each habitat type are used.

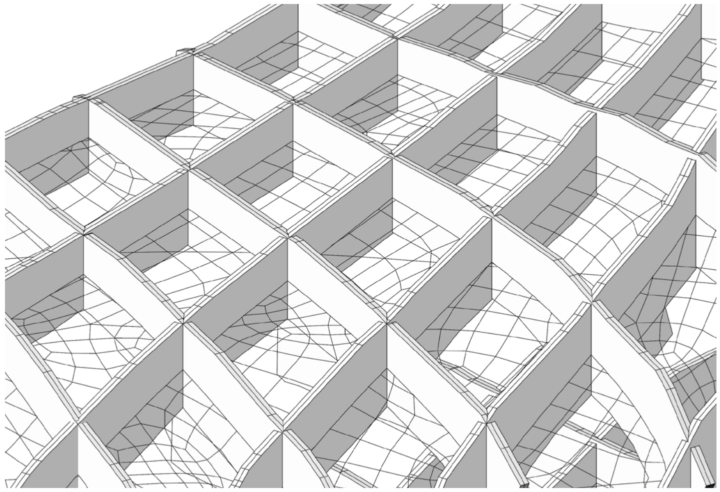
[process]
The base of the assembly is a system of laminated timber ribs that divide the volume into compartments. These ribs run through the habitat, creating structural continuity between elements. Once each element is divided into compartments, each compartment is digitally assigned as either as a perching mesh, a nesting box/ ledge, or a planter, based on its location in the habitat and its orientation.

The perching meshes are located in the upper portions of understory, canopy, and overstory elements. The mesh's density changes based on it's location in the habitat.

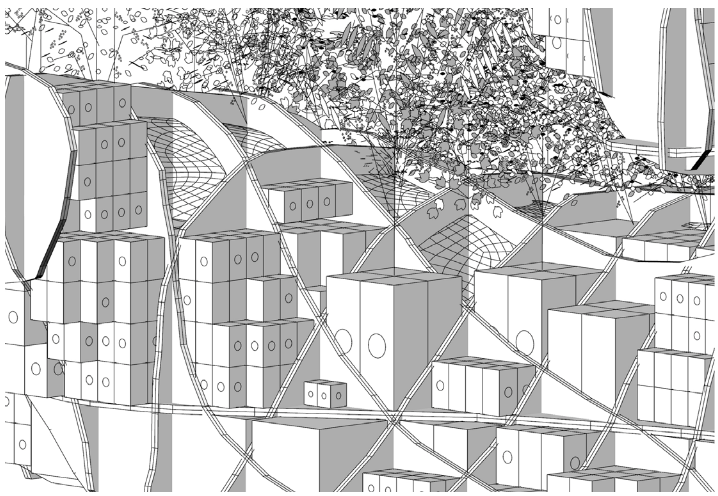
The nesting boxes or ledges are located where there are outward facing compartments in the lower portions of understory, canopy, and overstory elements, as well as floor litter, shrub, and cliff elements. To size the nesting boxes, the tool measures the compartments, compares this to the requirements of the target species, and subdivides the compartments accordingly to create the desired mix of box dimensions. Where species require a ledge, the compartment is left open, and where they require a box, one is inserted with the proper hole size.

Planters are located in grassland, shrub, gravel, and floor litter elements where compartments face upwards. The plants used in these planters are local species that are commonly known to attract birds. These plants are categorized based on which elements they are to be in and sorted based on sun requirements. To locate the plants, the tool performs a sun study on the relevant compartments, before placing the plants according to where they can thrive.

[evaluation]
By using these parametric tools, the assemblies benefit from the vast amount of data made accessible in Part I to accommodate specific local birds



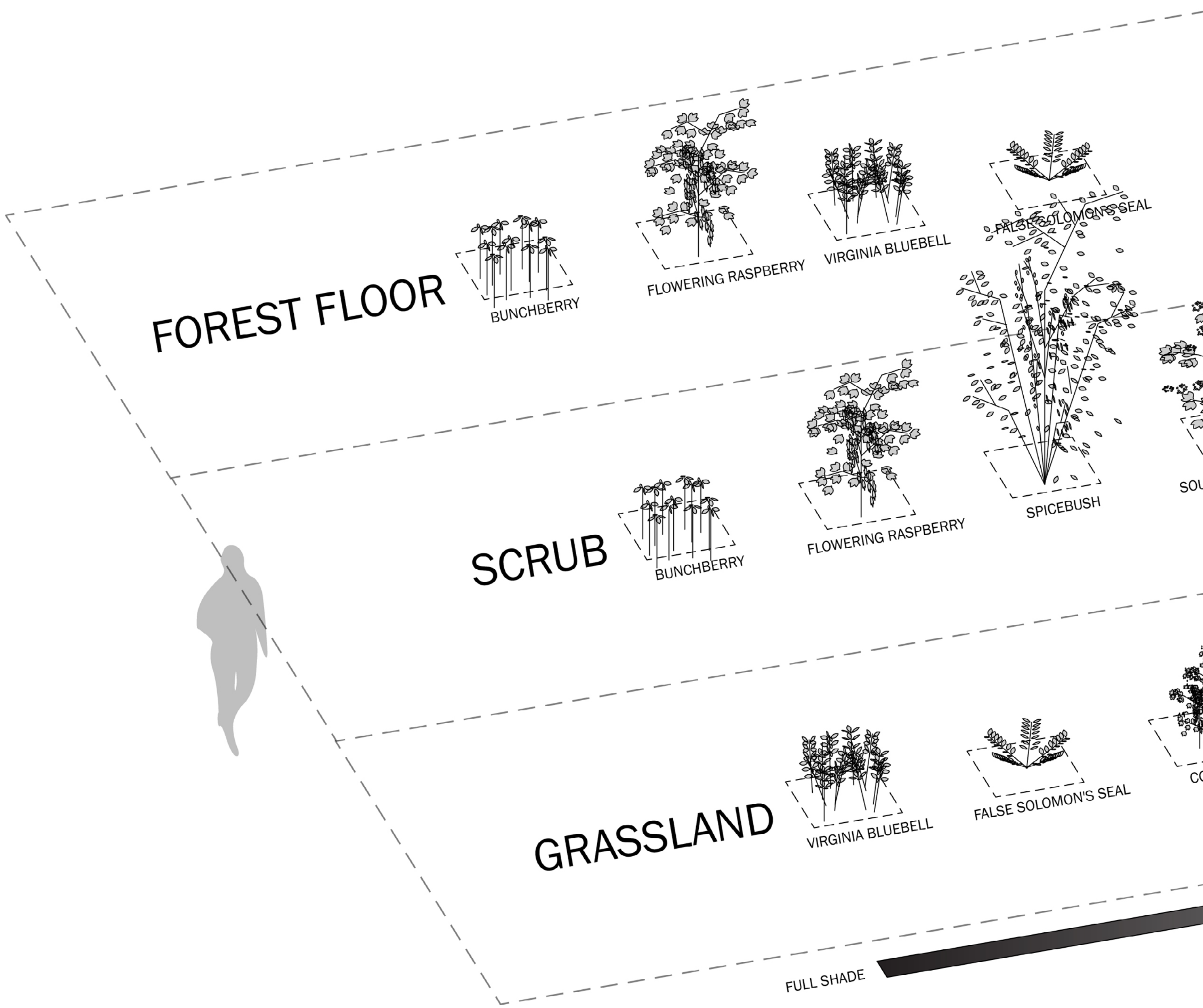
Perching mesh infill



Nesting cavity infill

Planter infill

Fig 3.10. Assembly compartment types


FOREST FLOOR
BUNCHBERRY
FLOWERING RASPBERRY
VIRGINIA BLUEBELL
FALSE SOLOMON'S SEAL
SCRUB
BUNCHBERRY
FLOWERING RASPBERRY
SPICEBUSH
GRASSLAND
VIRGINIA BLUEBELL
FALSE SOLOMON'S SEAL
FULL SHADE

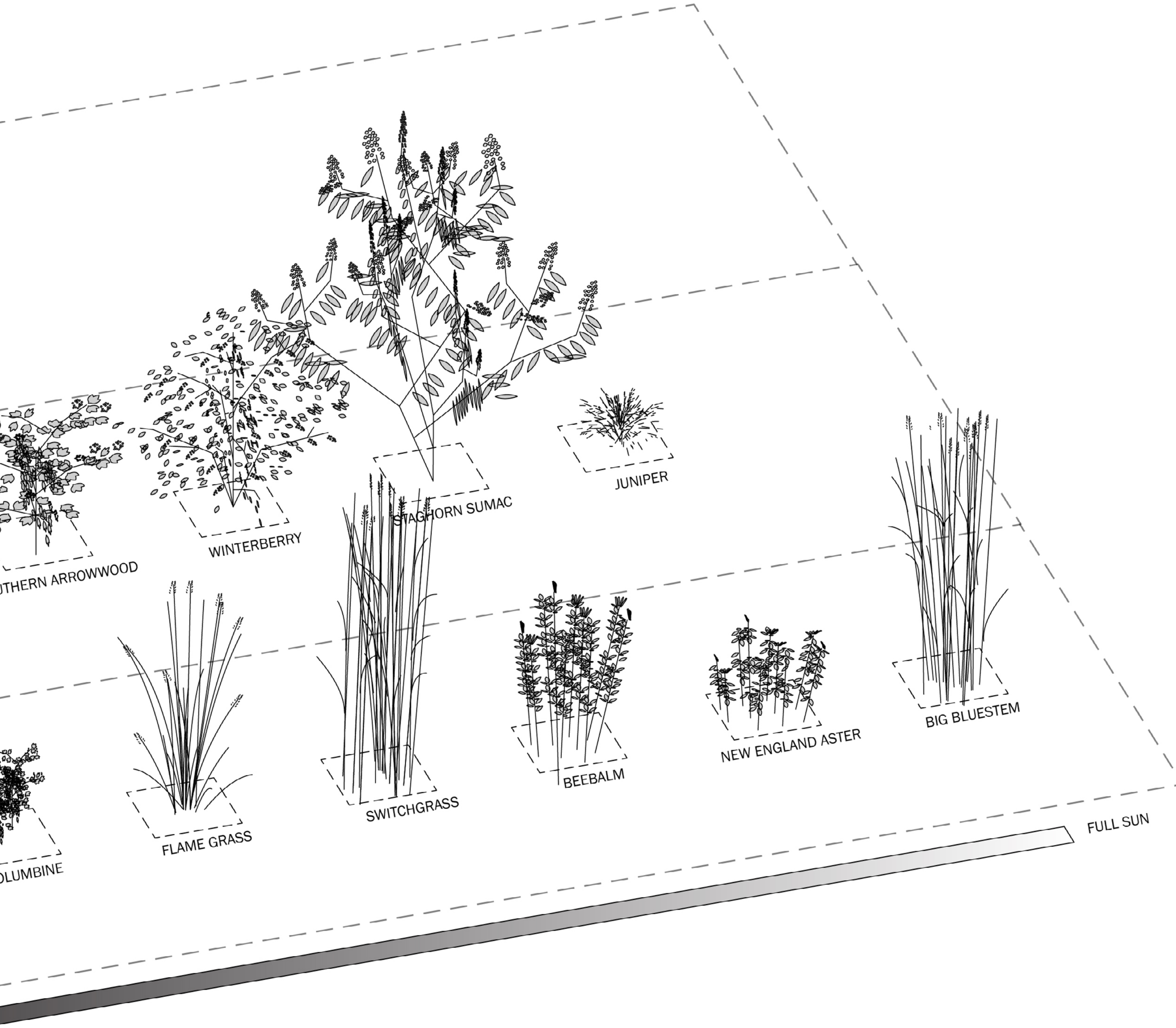
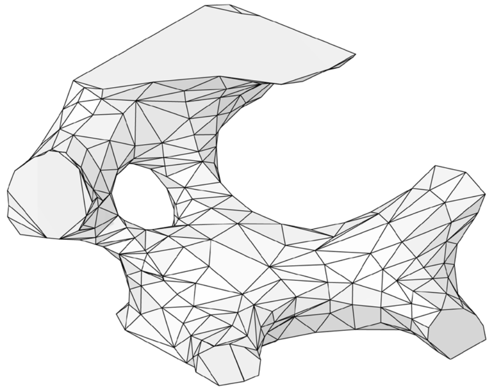
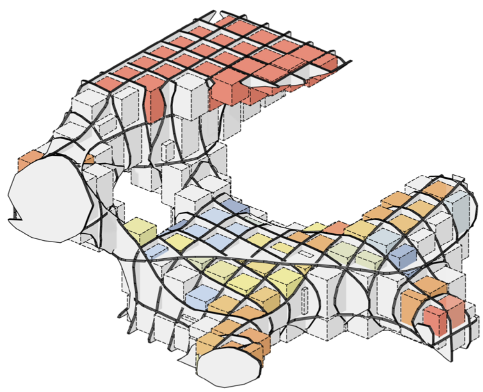


Fig 3.11. Plant selection by habitat and required sun



Base mesh



Structural ribs, pixel division & allocation, sun study

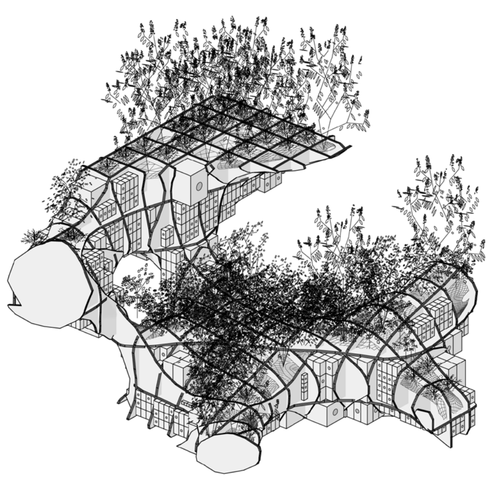
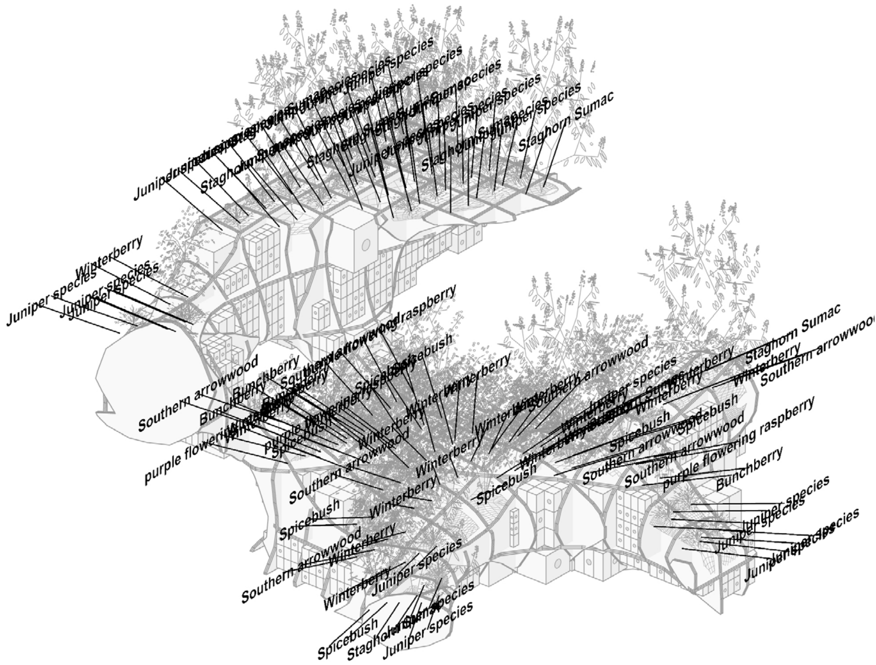
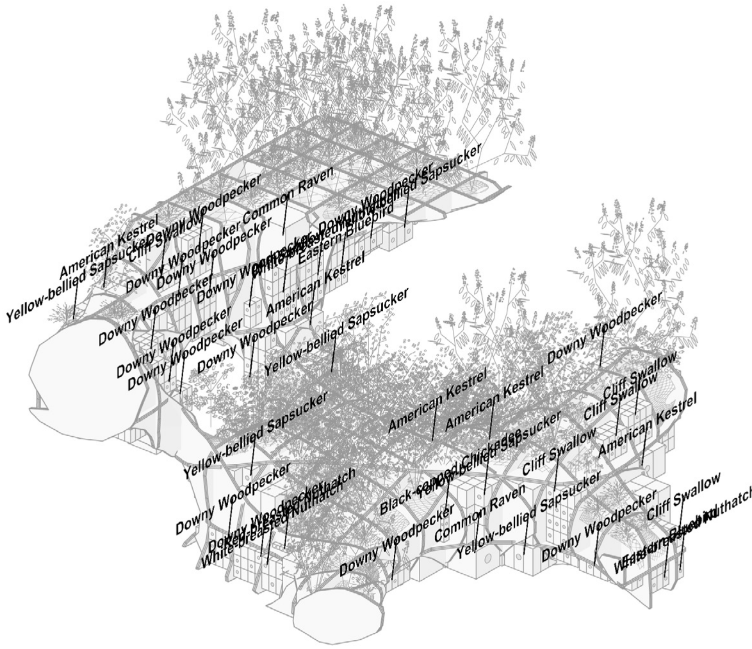


Fig 3.12. Assembly generation process

Assigned plants + Nesting boxes

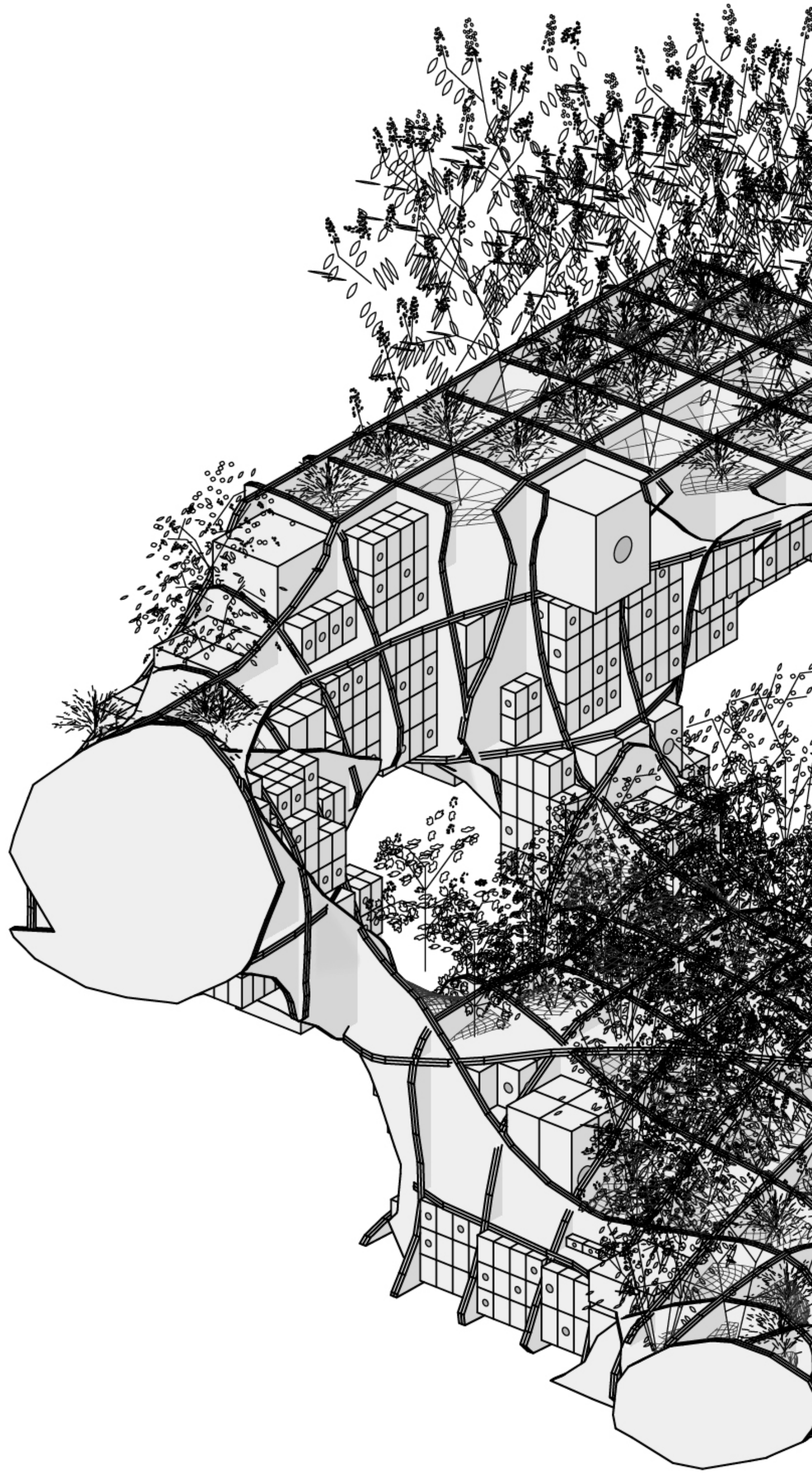


Plant species locations



Sample of bird species accommodated

Fig3.13. Selection of plants and birds accommodated in assembly fragment



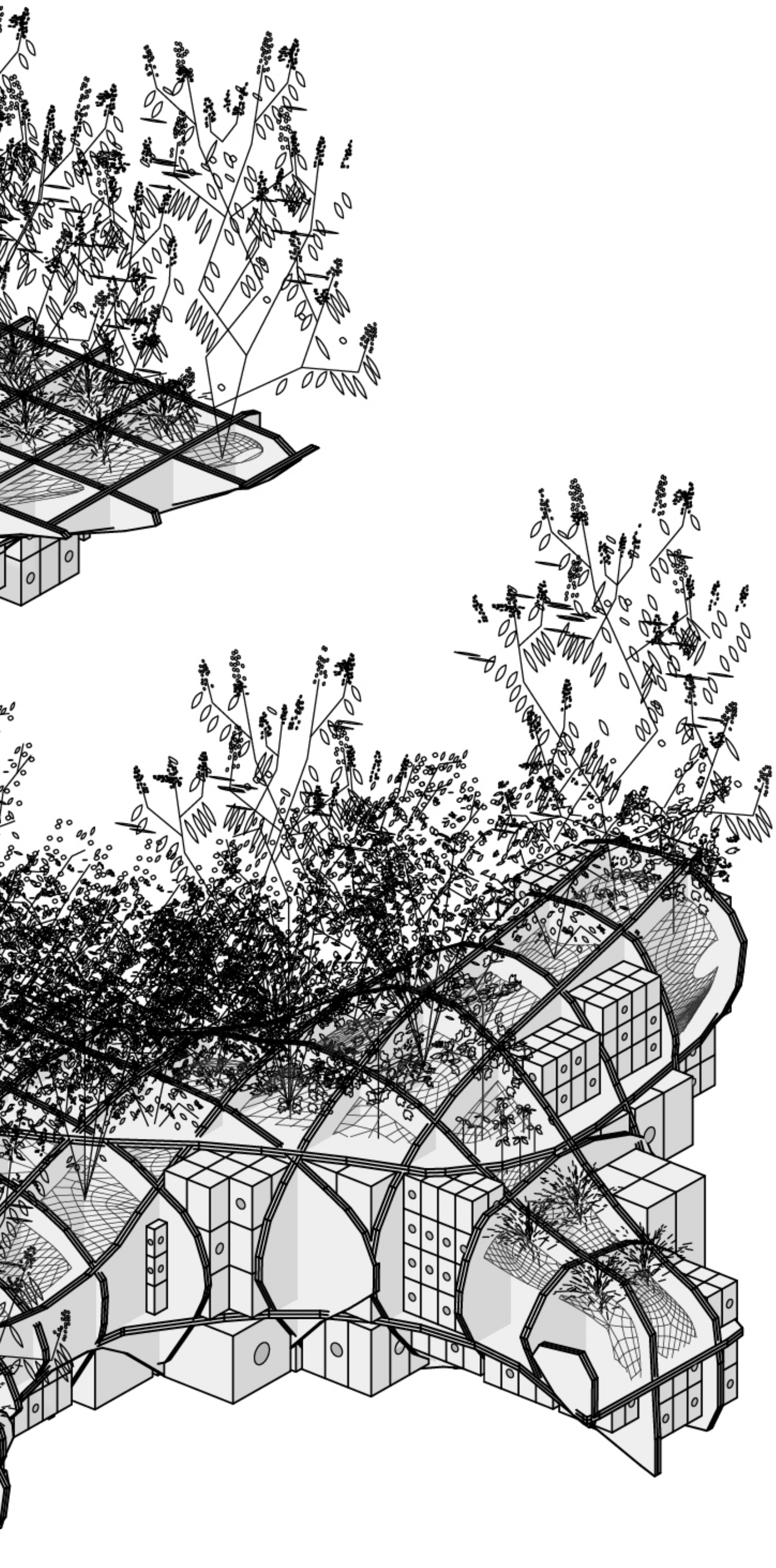
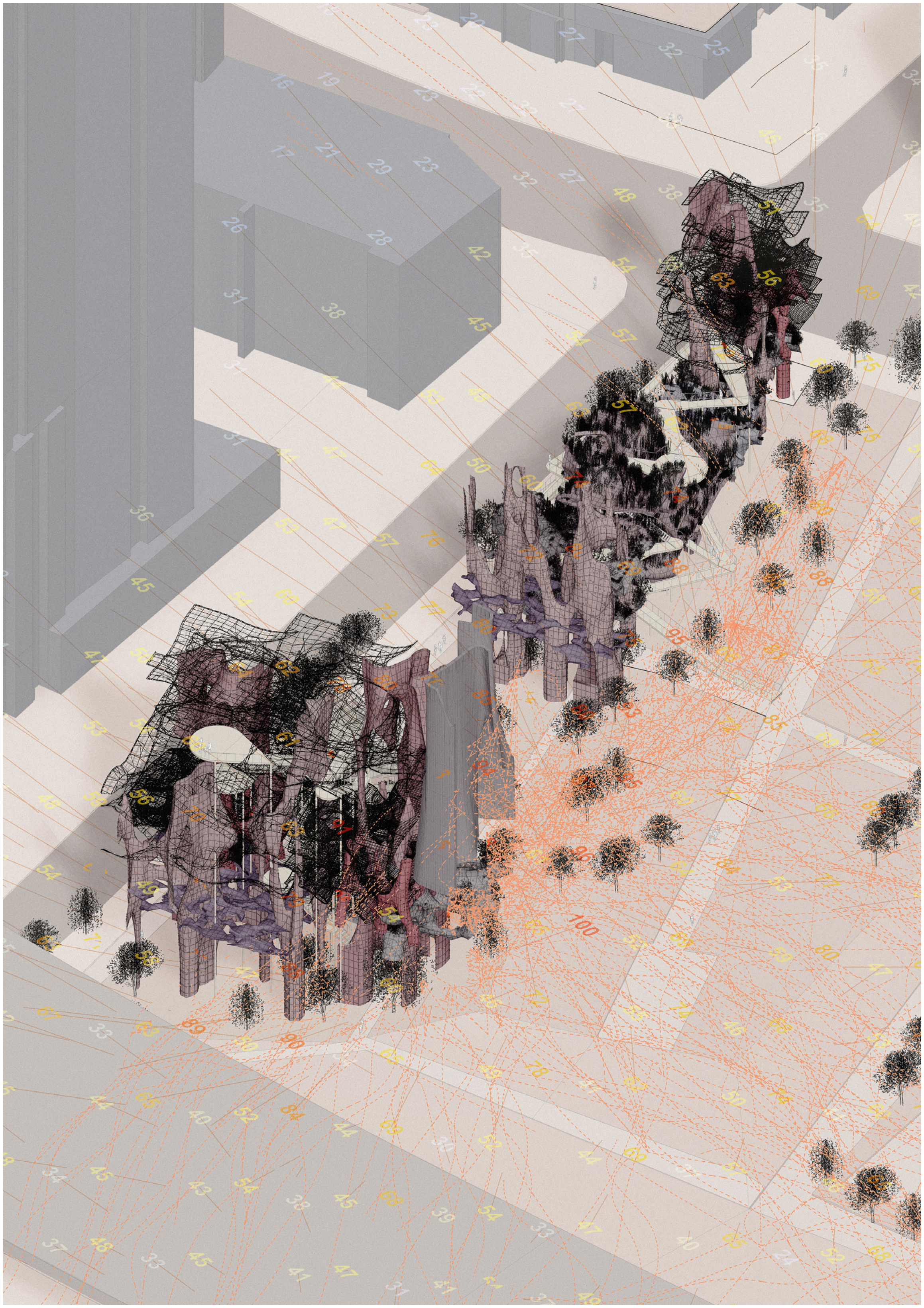


Fig 3.14. Shrub assembly fragment - Axonometric

INTERVENTION ILLUSTRATIONS

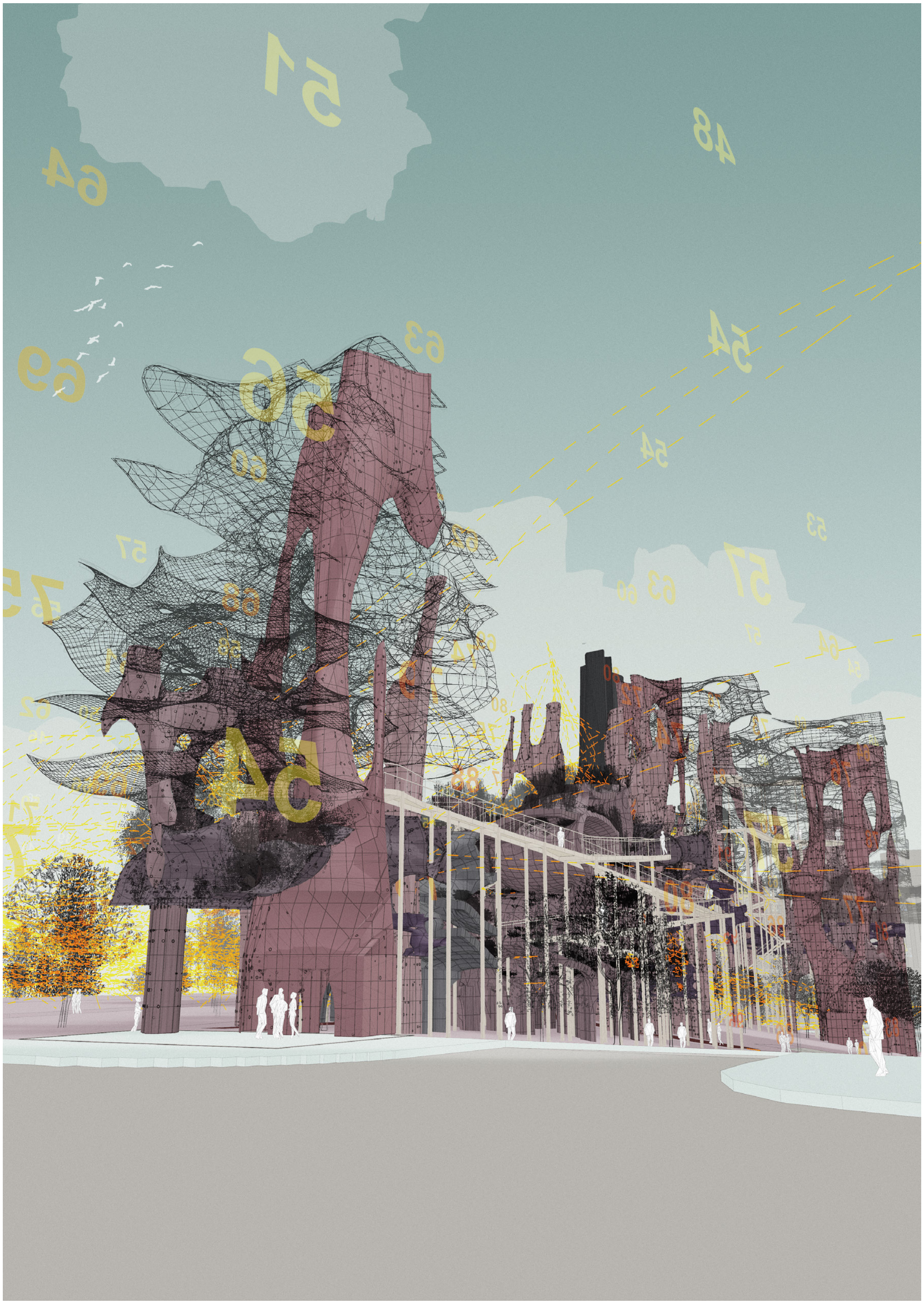
The following set of images illustrate the results of the habitat composition and assembly procedures in generating a *Patch Enhance* intervention located at Canoe Landing Park. As a flagship in a network of interventions, this habitat brings attention to non-human species that we share the city with. In addition to it performative roles, the language of the intervention subverts traditional forms of built environment and landscape and presents a new typology. This new typology represents a novel habitat for a novel urban ecosystem.



50 Avian accommodation value

---- Potential flight path

Fig 3.15. *Patch Enhance* intervention – Axonometric



50 Avian accommodation value

---- Potential flight path

Fig 3.16. *Patch Enhance* intervention – Perspective from street

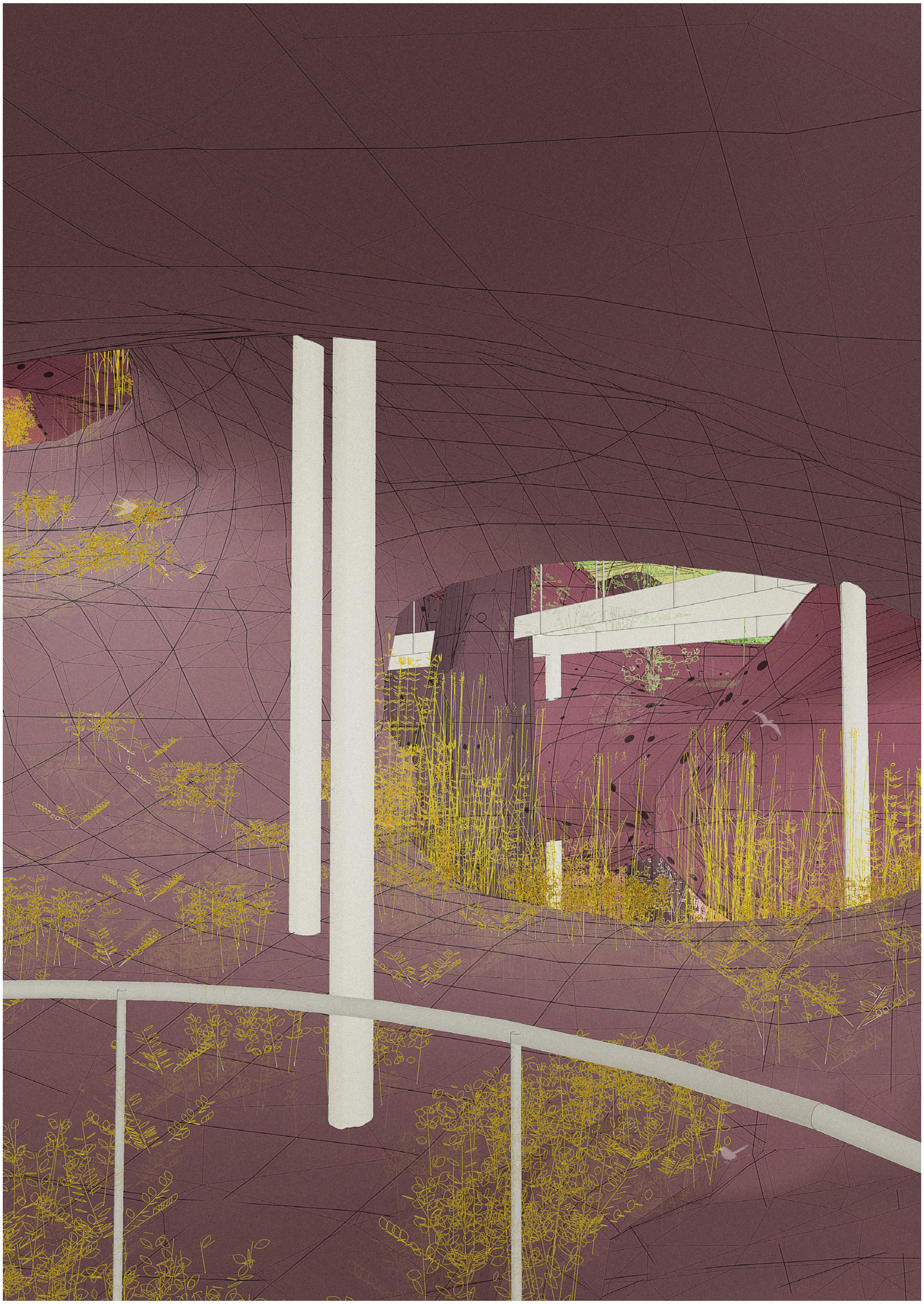
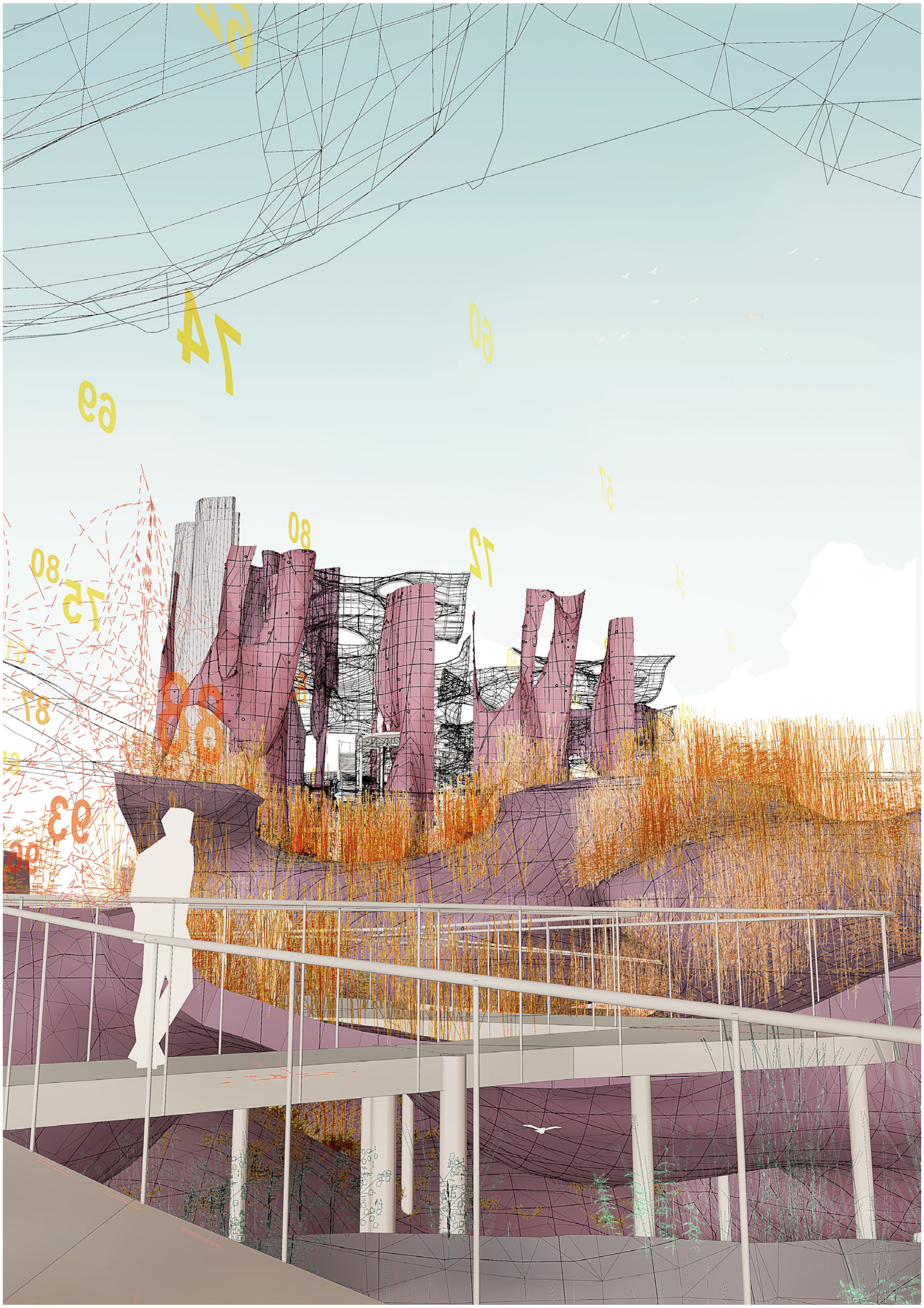
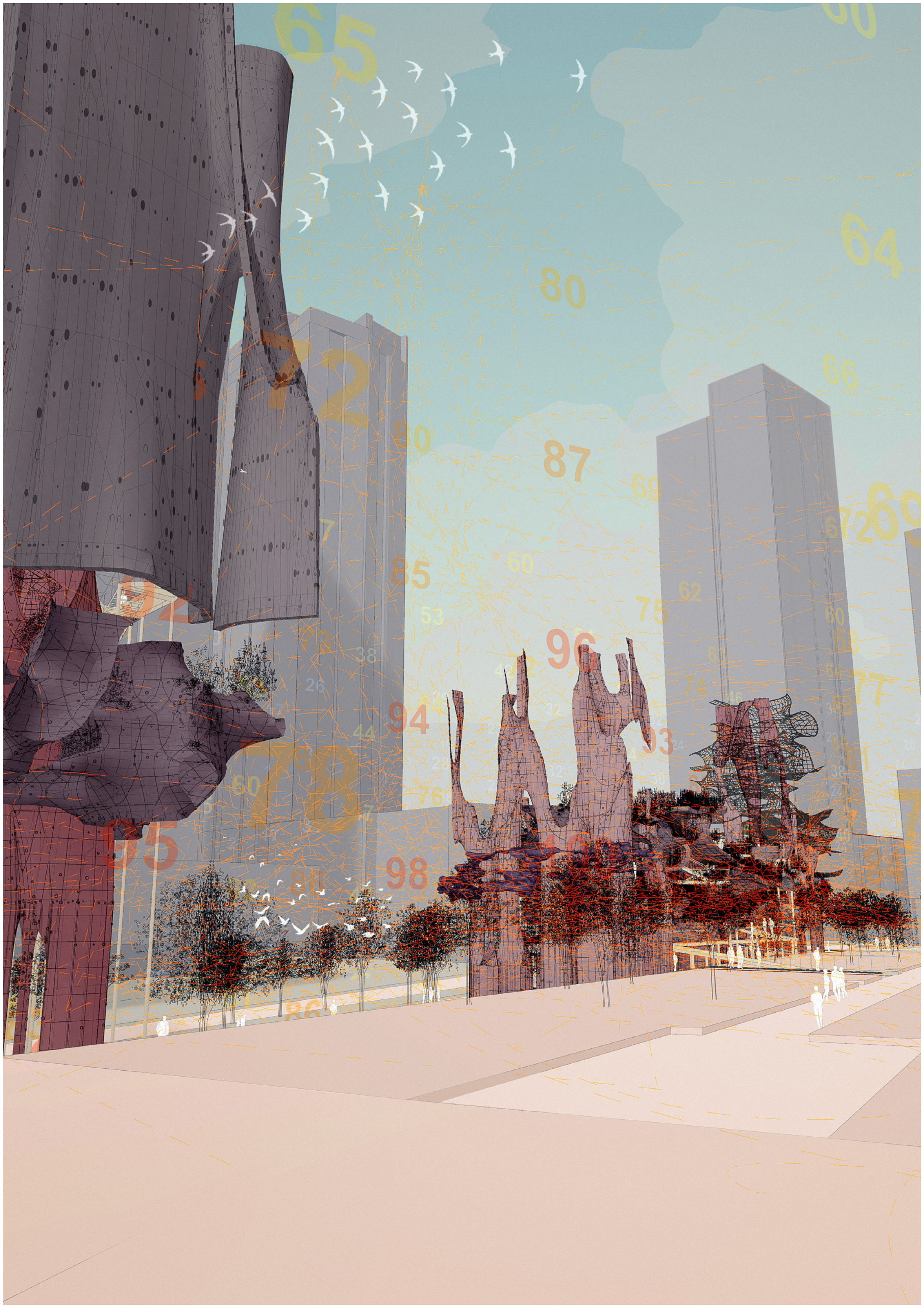


Fig 3.17. *Patch Enhance* intervention – Interior of grassland



50 Avian accommodation value
---- Potential flight path

Fig 3.18. *Patch Enhance* intervention – View of grassland



50 Avian accommodation value
---- Potential flight path

Fig 3.19. *Patch Enhance* intervention – Perspective from park

Fig 3.20. *Patch Enhance* intervention – Interior perspective from open woodland

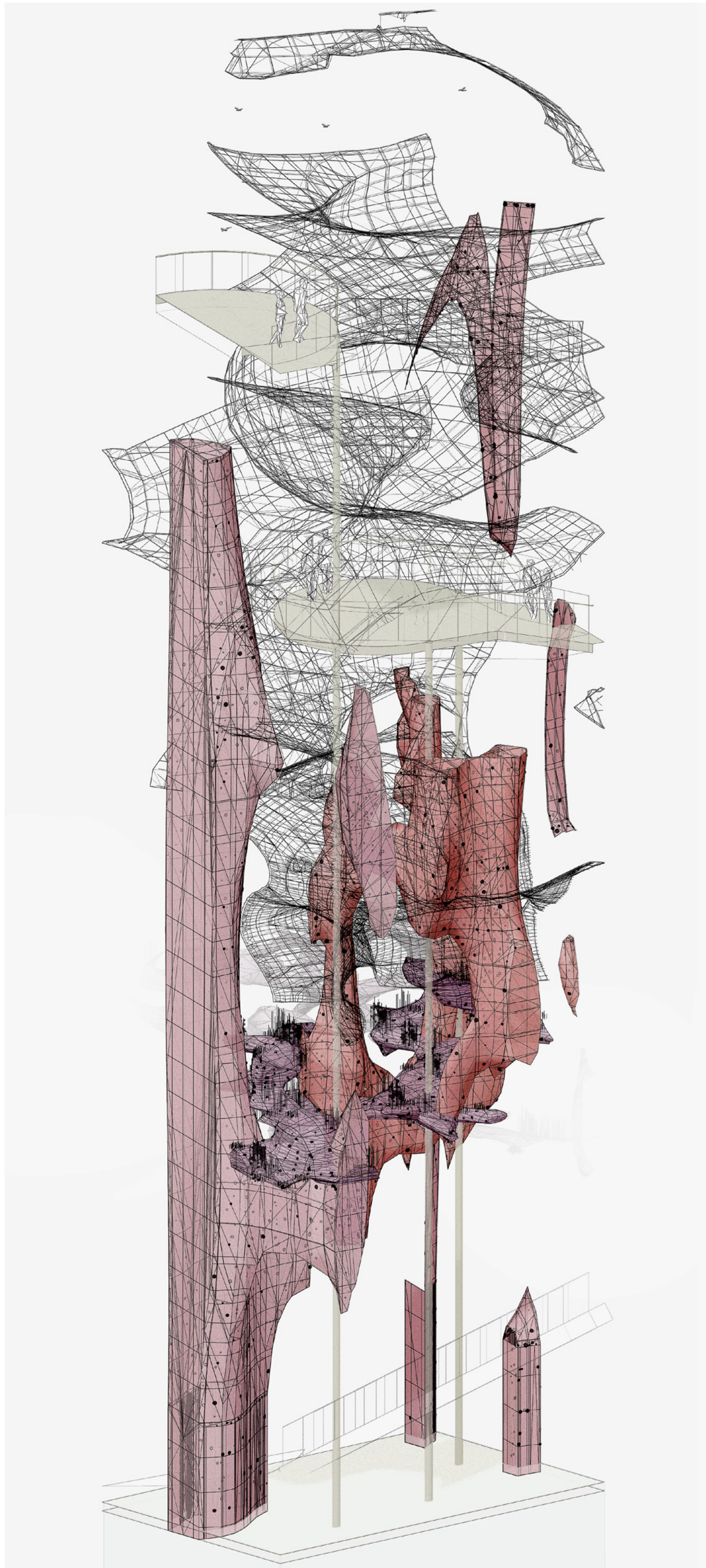


Fig 3.21. Forest fragment - Axonometric

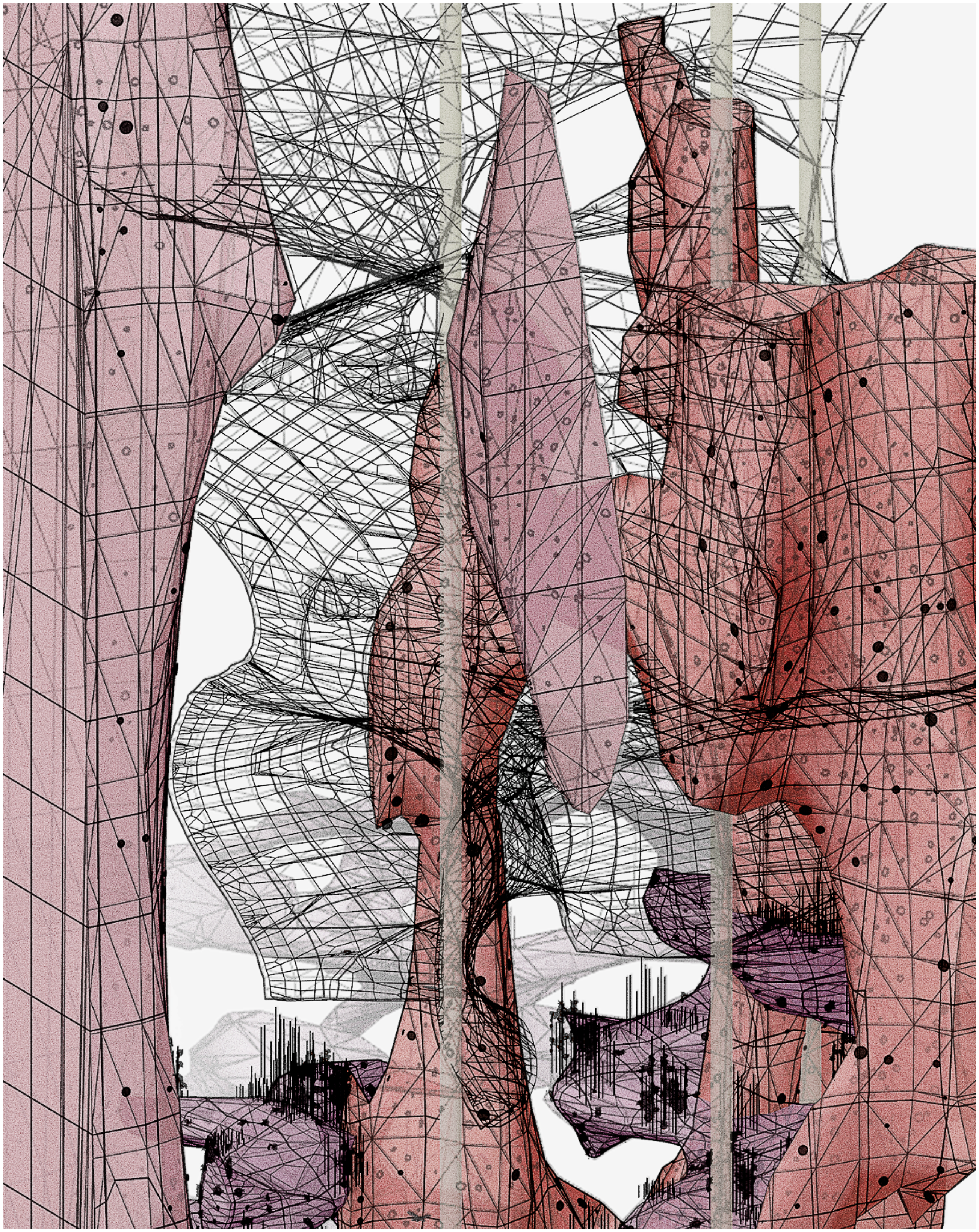


Fig 3.22. Forest fragment – Detail

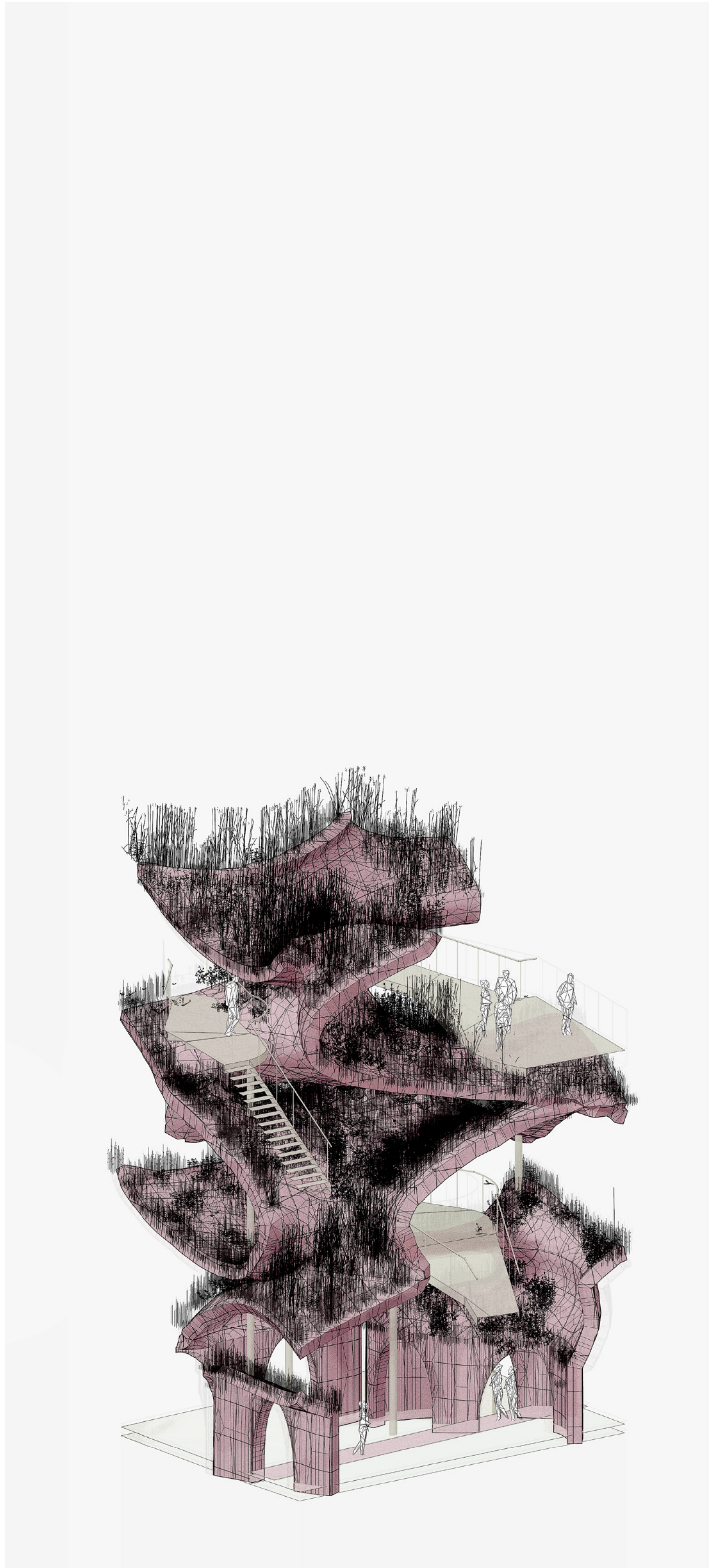


Fig 3.23. Grassland fragment - Axonometric

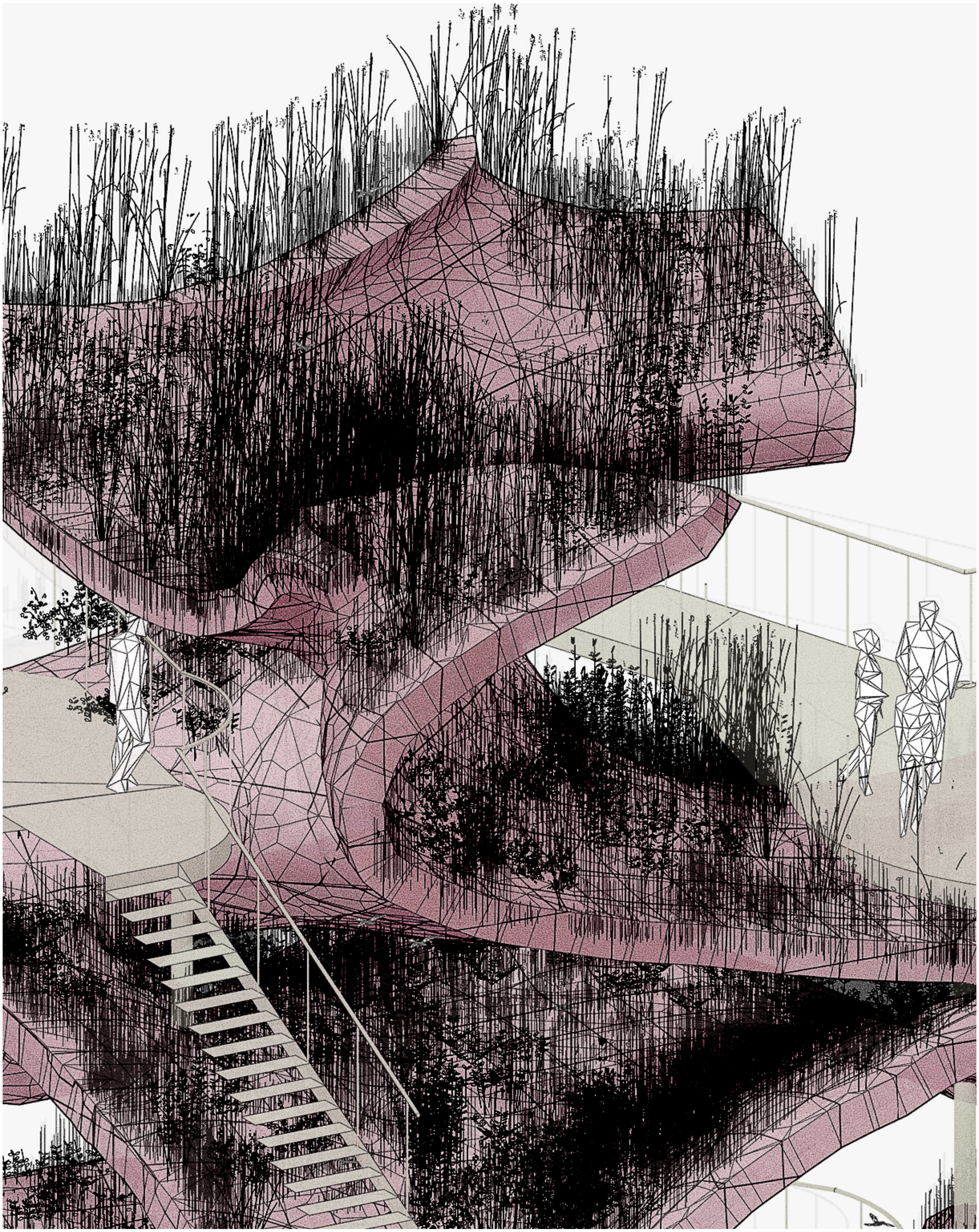


Fig 3.24. Grassland fragment – Detail

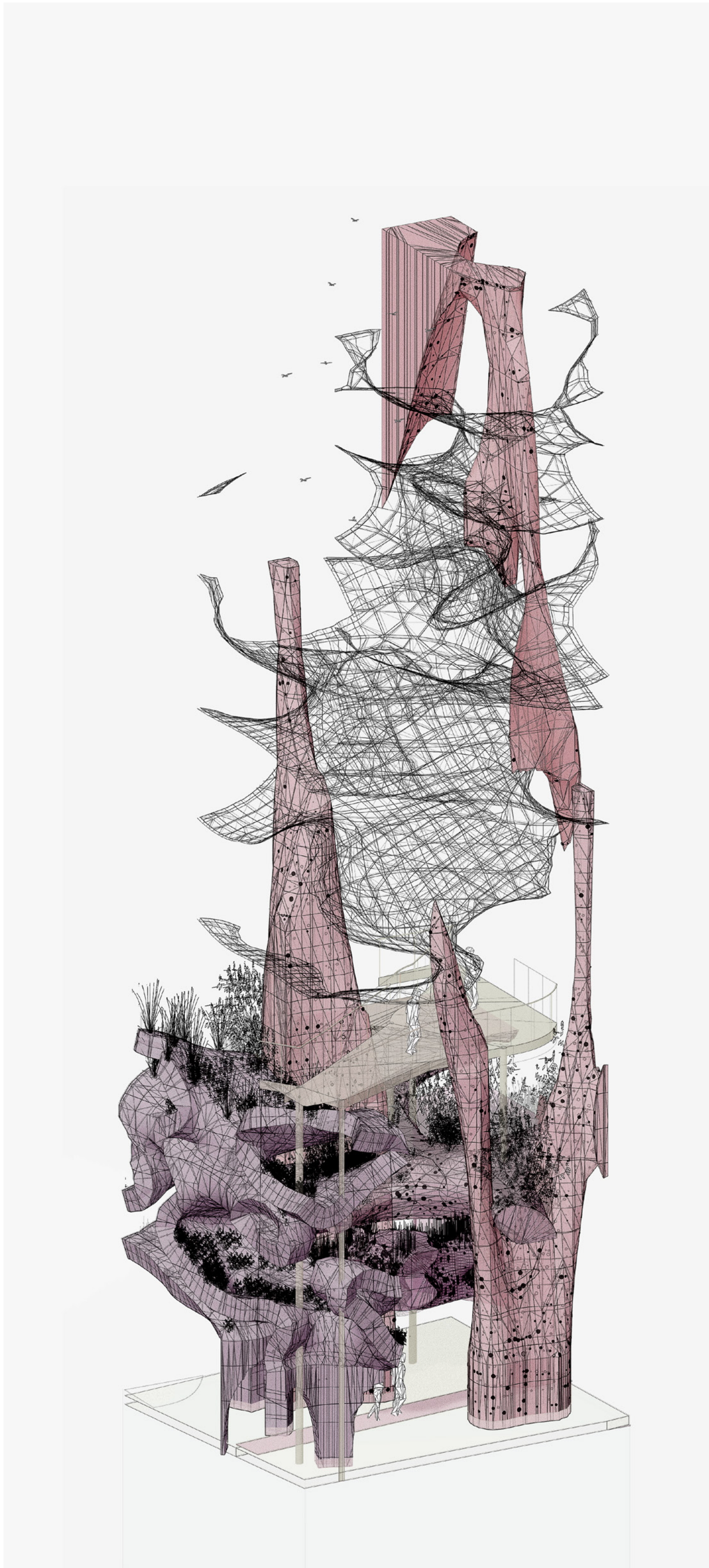


Fig 3.25. Open woodland fragment - Axonometric

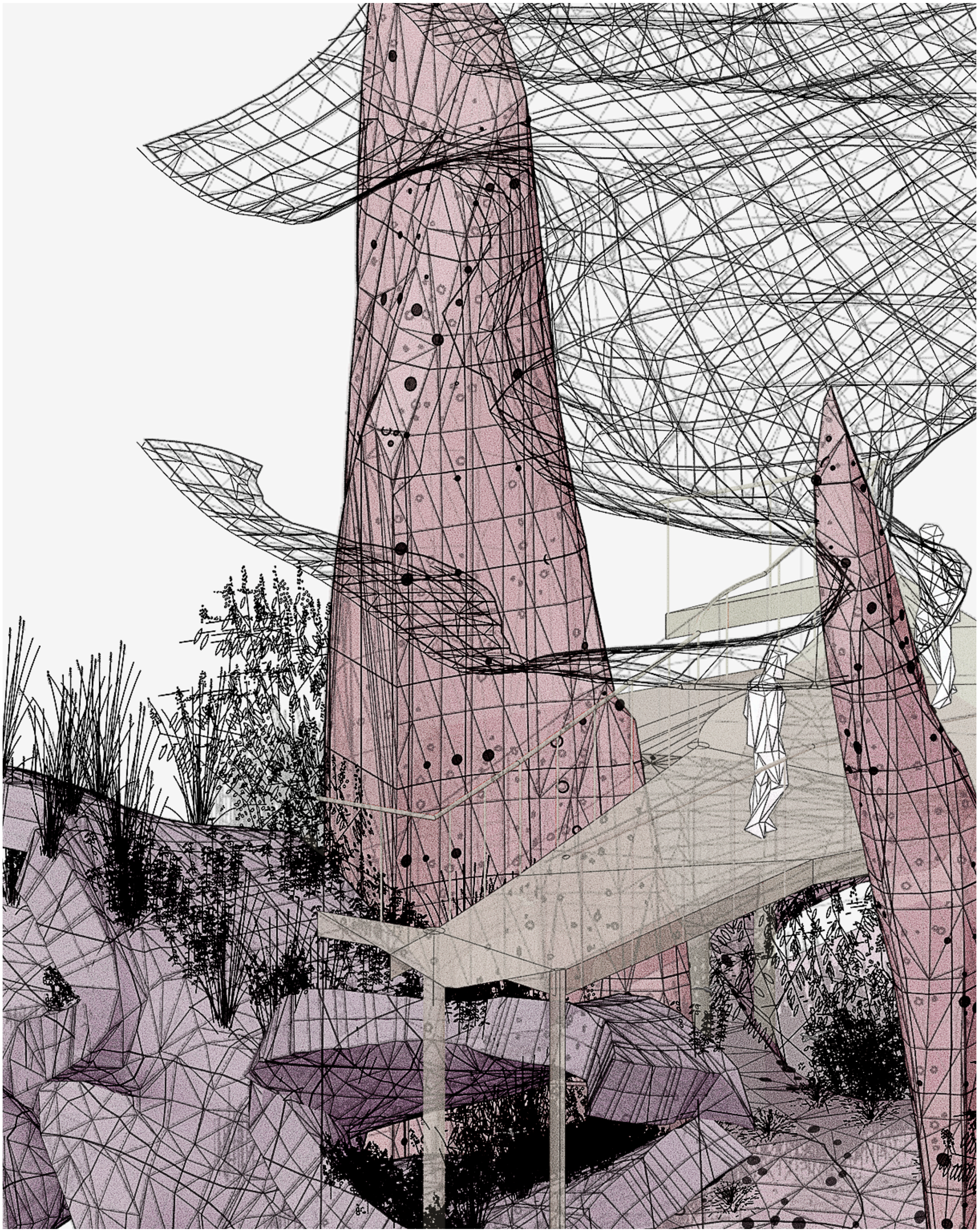


Fig 3.26. Open woodland fragment - Detail

CONCLUSION

While the majority of the concepts and methods used in these studies already exist in the field of landscape ecology, the application of these processes in the field of urban design, as well as the addition of agent-based path networks, 3D networks, and data populated networks, has potential to be very effective in helping architects, landscape architects, and planners work amidst the interactions between urban fabric and regional ecologies.

While the upfront investment in acquisition of data and development of digital tools is substantial , the focus on computation has been successful as both an illustrative and analytical tool and has made it possible to reveal and utilize complex and dynamic patch networks.

As discussed earlier, these computational tools are divided into two categories: the network tools and the habitat composition/assembly tools. The habitat and assembly tools developed in Part III make the most direct use of the data accessed through the network, while pushing boundaries related to the perception on urban green space and nature. While the case study design is very resource-intensive, the work-flows and tools developed could be applied more at different scales and intensities at other locations throughout the network. In addition, the network tools developed can help inform any designer or policy maker operating in the realm of urban ecology to make decisions that strengthen this urban habitat network.

In conclusion, this work, through its network studies and biophilic habitat design, acts as both a tool and a catalyst for pushing our ability to design for the species that bring life to our cities.

NEXT STEPS

Testing
Testing the results of these design activities would offer direction for next steps and improvements. At the network scale, different interventions could be rapidly tested using the network simulation tools. Each intervention's effect on the connectivity of the network can be measured, giving a hierarchy to the intervention suggestions. At the habitat scale, the assemblies proposed could be paired down to something that could be easily fabricated and tested in the field to see how well it accommodates birds.

Interdisciplinary collaboration
While this work was heavily informed by studies in biophilia and landscape ecology, collaboration would be key in bringing these tools to real world use. It would be advantageous to have the network illustrations evaluated by experts in landscape ecology to ensure their accuracy, and keep them up to date with current research. In addition, collaboration with city planners could help identify additional key areas of research and bring to light urban forces not yet addressed in this work.

Within the design realm, sharing this framework with designers in architecture and landscape architecture has potential to produce a wide variety of interventions. Documenting how and whether their designs benefit from the network and data tools could further inform this work.

Additional Investigation
Now that these tools are developed, they could to deployed to test habitat networks of different cities, allowing many comparative evaluations. In addition to evaluating different locations, these network these tools have potential to focus on specific avian and other vagile species. A series of maps could be generated that illustrate how differently specific species are able to move through urban fabric, which would add sophistication to the designer's understanding of urban habitat networks.

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