Landscape Connectivity Analysis for Conservation Planning in Southern Ontario

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the 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.

Statement of Contributions

Section 4.4 of this thesis borrows heavily from two reports produced for Geography 668: Indigenous Environmental Management Perspectives, taught by Dr. Miguel Sioui. The intent of the reports is to consider how Indigenous environmental management perspectives apply to our graduate research, and as such the students of this class are encouraged to adapt the work that they have produced for Geography 668 within our final theses.

Abstract

The strategic planning of land conservation is a critical undertaking in urban/peri-urban areas. Natural areas in cities and their surroundings exist in an environment of competitive land use pressures, where the allocation of available land may be complex and politically charged. Organizations pursuing land conservation in these areas must balance biodiversity aims with fiscal and resource limitations, a competitive market, and the need for decision-making accountability.

To support the prioritization of conservation lands for protection, analysts may incorporate landscape connectivity analysis. By quantifying how the configuration of habitat facilitates species movement, connectivity analysis provides a rationale for conservation planning that supports the dispersal of species across the urban/peri-urban matrix.

While connectivity analysis is useful for conservation planners, several factors have created a confusing environment for those interested in employing it. These include the rapid proliferation of connectivity research, the inconsistent use of methods and terminology, and an absence of updated selection guidelines for practitioners. Thus, my research evaluates how conservation organizations may best use landscape connectivity analysis to support conservation planning in urban/peri-urban areas.

In this thesis, a systematic review of urban/peri-urban connectivity literature is followed by application of review results to a conservation planning case study in Southern Ontario. Reflections on these two research phases support a proposed framework that outlines the pivotal decisions, organizational limitations, and best practices for using landscape connectivity analysis for conservation planning. This provides tangible benefit for organizations protecting and stewarding natural lands, particularly in areas like the urban/peri-urban matrix of Southern Ontario.

Acknowledgements

In my daily life, I’ve cultivated a gratitude practice which has three parts. I am grateful for my spirit, and the determination I’ve brought to each day. I am grateful for the world as it exists, and the gifts that it provides. Finally, I’m grateful for the privileges granted to me, including a network of phenomenal people. While I am the sole author of this work, several individuals have contributed greatly to supporting my growth through this degree and making my research possible.

My supervisor Dr. Jeremy Pittman’s enduring positivity has continued to spur me on as I work through this project. No matter my nerves going into a thesis meeting, I’ve always come out thinking “I can do this”, which I am immensely grateful for. Thank you to my committee member Dr. Rob Feick, who has been a steadfast source of expertise, support, and detailed feedback. Thank you also to my external reviewer, Dr. Stephen Murphy, for providing your valuable time to read and comment on my work, and to Tracey Beirness, whose administrative work has facilitated my progress along each step of this degree.

I have been very lucky to work with Dr. Tom Woodcock (**rare** Planning Ecologist) for the duration of this project. His knowledgeable input, in concert with the voices of the **raresites** committee and Executive Director Dr. Stephanie Sobek-Swant, has allowed for my research interests to be applied in a meaningful way to on-the-ground conservation work in Southern Ontario. I can’t emphasize enough my appreciation for the research opportunity, the funding I’ve received, and the personal connections I have made through this project.

The Indigenous perspectives produced within this thesis are included with deep appreciation for Dr. Miguel Sioui at Laurier University. His guidance and mentorship have been invaluable to my personal growth, my understanding of Indigenous worldviews, and the quality of my research. Thank you.

My friends and family deserve mention for their patience and good humour throughout this program. Thank you for accepting the late responses, vent sessions, and long periods of radio silence as I worked my way through these last two years.

Finally, I could not have completed this thesis without the unwavering support of my partner, Eric. Thank you for the last-minute grammar edits, for late night dinners, for reminders to breathe and take walks, and for truly being here through it all.

Positionality & Land Rights

As an academically trained environmental scientist of white European descent, my view of the world has been shaped by my heritage and education. Through the process of researching this thesis, I have had opportunities to broaden my understanding to include other worldviews, especially Indigenous environmental perspectives. This process has been deeply valuable to me, and I recognize that I have more to learn.

This report considers the value of natural landscapes across Waterloo Region and Wellington County. My campus, personal residence, and most of my study site are within the Haldimand Tract. This land, six miles deep on either side of the Grand River, was promised to the Six Nations of the Grand River in 1784 (Six Nations of the Grand River, n.d.). The lands currently owned by Six Nations encompass less than 5% of that originally granted, and it is important to acknowledge this unjust loss of land rights. I wish to express gratitude for the original stewards of this land, including the Haudenosaunee Peoples of the Six Nations of the Grand River and the Anishinaabe Peoples of the Mississaugas of the New Credit. I also direct readers to the reference above to learn more about Six Nations and their valuable work in the Haldimand Tract.

Table of Contents

List of Figures

List of Tables

Additional Note

This document regularly refers to the **rare** Charitable Research Reserve and the **raresites** committee. The use of bolded and lower-case text reflects the style guidelines for the organization's name. While use of these terms is typically also italicized within the organization, I have chosen to forego this part of the formatting for accessibility reasons.

Chapter 1: Introduction

This chapter serves to break down the general concepts contained within my thesis, emphasize the importance of further research in conservation planning and connectivity analysis, consider the wider community that this research may benefit, and to establish my research paradigms, aims, and overall design.

1.1 What is Systematic Conservation Planning?

Despite its critical importance for the promotion of biodiversity and mitigation of climate change, the conservation of natural landscapes is a complex and often tumultuous affair. The protection and stewardship of ecologically sensitive lands can be hamstrung by fiscal limitations, competitive land uses, and the complexity of enmeshed human and natural systems – challenges which require flexibility, integrity, and scientific grounding to be successful. Indeed, Margules & Pressey (2000) have proposed that the quality of conservation planning can be evaluated by its ability to: (1) efficiently use limited resources, (2) work effectively in an environment of competing land uses, and (3) demonstrate an accountable, systematic, and critically-reviewed decision making processes. The authors describe this process as “systematic conservation planning”, and highlight six stages that it should follow:

1. Biodiversity data compilation,
2. Conservation goal identification,
3. Existing conservation area review,
4. Additional conservation area selection,
5. Conservation action implementation, and
6. Conservation area maintenance (Margules & Pressey, 2000; p. 245).

Throughout their paper, the importance of consistent, quantitative decision-making is emphasized. For example, quantitative conservation targets for species and habitats are recommended, and clear criteria should be set which identify how well conservation lands work to achieve said conservation targets. Further, the conservation planning process itself may be aided by site selection algorithms or spatial decision support systems (SDSS), which combine spatial analysis and visualization capabilities of geographic information systems (GIS) with decision models to help planners systematically analyze problems, evaluate alternatives, and quantitatively assess trade-offs (Margules & Pressey, 2000; Keenan & Jankowski, 2018).

The systematic conservation planning process may be used in several different contexts, the details of which will affect the conservation goals and evaluation criteria chosen. For example, the goals and evaluation criteria used to protect habitat for a critically endangered species within its small range may be very different from those used by a municipality choosing where to locate naturalized parkland. Conservation goals and criteria may stem from practical considerations (e.g., relative financial cost of parcels, regulatory requirements), species considerations (e.g., occurrence data, habitat needs for considered species), and habitat/landscape level considerations (e.g., habitat rarity, size, quality, disturbance, and/or connectivity) (Margules & Pressey, 2000). Together, these aspects of ecology and planning can form a framework by which land use planners may systematically prioritize conservation lands for protection.

1.2 Landscape Connectivity Analysis: A Primer

The individual criteria that contribute to a robust conservation planning strategy differ in their complexity and scale. The vast majority of the items listed in the previous section require the evaluation of a potential conservation area in isolation. To elaborate, an individual conservation area’s cost, zoning, species composition, and size can all be evaluated without consideration of its surroundings. However, failing to account for the larger landscape when evaluating and prioritizing areas for conservation omits a vital part of the natural processes occurring on landscapes (Saunders et al., 1991).

In their 1991 review paper, Saunders et al. recount the process of habitat degradation, fragmentation, and loss that has taken place throughout human history. The legacy of this nearly global phenomenon, they argue, is a natural world that exists as a scattered collection of remnant habitat “patches”, which exist within a “matrix” of non-habitat land uses (p. 19-20). Taken together, these habitat patches and matrix are what ecologists consider a “landscape”, the arrangement of which is dictated by geology, soils, topography, climate, and human intervention (Saunders et al., 1991; Smith & Smith, 2001). Landscape ecology has been studied and debated in some form for several decades before 1991, producing concepts such as island biogeography (MacArthur & Wilson, 1967) and the SLOSS (“single large or several small”) reserve pattern debates (Gilpin & Diamond, 1980). However, Saunders et al.’s (1991) review called for more comprehensive research that would lead to a better understanding of habitat patch isolation and its effects on species populations.

Shortly thereafter, a widely-used formal definition of “landscape connectivity” (sometimes called “ecological” or “habitat” connectivity) emerged in the literature. Taylor et al. (1993) defined landscape connectivity as “the degree to which the landscape facilitates or impedes movement among resource patches” (p. 571). The authors elaborate that the measurement of connectivity is vital to landscape ecology, remarking that “an animal’s ability to utilize a resource patch will also be dependent upon its ability to get there”, the difficulty of which can vary (Taylor et al., 1993, p. 571).

The resulting field of “landscape connectivity analysis”, which quantitatively studies the degree of interconnection between patches and how that interconnection facilitates/impedes movement, has continued to grow and diversify since the early 1990s. Tischendorf & Fahrig published a foundational review in 2000 which documented this early growth in the field. Their review considers all existing papers on landscape connectivity (which, at the time, was only 33), and is instrumental for distinguishing two main types of connectivity - structural (the physical connectedness of habitat patches as seen on a map) and functional (the evaluation of predicted species movement between patches). The article further studies existing connectivity literature, documenting methodological details (e.g., how species movement is quantified) and analytic approaches (e.g., which connectivity models, theories, and metrics are used). The Tischendorf & Fahrig (2000) study functions as a “time capsule” of this early connectivity research, which has since rapidly accelerated in its development.

Today, literature using landscape connectivity analysis for conservation is widespread and diverse. Later review papers on the topic have emphasized the notable acceleration of landscape connectivity publications and the diversity of approaches used in the field (Rayfield et al., 2011; LaPoint et al., 2015; Correa Ayram et al., 2016; Lookingbill et al., 2022). Critical innovations have propelled this acceleration, such as:

- The application of graph theory to quantify and visualize ecological connectivity (Urban & Keitt, 2001),
- The use of ‘least-cost’ analysis to model wildlife movement and functional connectivity (Adriaensen et al., 2003),
- The creation of graph-based ‘habitat availability indices’ to quantify patch importance (Pascual-Hortal & Saura, 2006; Saura & Pascual-Hortal, 2007b),
- The evolution of graph theory and least-cost analysis into circuit theory, using electricity-based models to add randomization to wildlife movement models (McRae et al., 2008), and
- The novel use of airborne LiDAR to conduct connectivity analysis in three dimensions (Casalegno et al., 2017).

Through the rapid innovation and growth within the connectivity analysis field, the spectrum of approaches, metrics, tools, and outputs has become multifarious. Even a decade ago, Rayfield et al. (2011) noted over 60 possible connectivity measures for conservationists to select from. Even if the inclusion of connectivity is intended to be only part of a systematic conservation planning strategy, the choice of connectivity analysis approach must be considered at length. Tools and approaches are often tailored to specific contexts (e.g., spatial scale, management objective, object of study, technical ability), and use of approaches in the wrong context may provide difficult to interpret or misleading results, leading to negative management consequences (Pascual-Hortal & Saura, 2006; Rayfield et al., 2011).

Landscape connectivity analysis may provide a powerful addition to a systematic conservation planning framework, due to its ability to consider habitat patches through their function within a diverse landscape, rather than in isolation (Saunders et al., 1991; Taylor et al., 1993). However, a strong understanding of the theories and applications that are possible in the connectivity analysis field should be developed prior to its use as a conservation planning tool.

1.3 Topic Relevance & Research Question

As discussed in the previous sections, landscape connectivity analysis can add value to the systematic conservation planning process by allowing for consideration of inter-patch dynamics that transcend the valuation of patches in isolation. This perspective can help planners to prioritize conservation lands more effectively in an environment of competing land uses, fiscal limitations, and political disagreement.

Because of the rapid innovation in the landscape connectivity field (LaPoint et al., 2015; Correa Ayram et al., 2016; Lookingbill et al., 2022), an updated theoretical understanding of how connectivity analysis may be conducted and incorporated into a conservation planning framework would be useful for land use planners. However, a review of all connectivity approaches currently existing, including recommendations for the spatial contexts they may be suited for, would be a mammoth undertaking within the bounds of a master’s thesis. Instead, a thorough and targeted review of connectivity approaches applied to a single spatial context could produce meaningful benefit in the form of pragmatic advice for real world, practice-oriented conservation planning problems. In my view, there is perhaps nowhere in Canada that is in more need of high quality systematic conservation planning than the peri-urban regions of Southern Ontario in 2023.

The pressure on Southern Ontario’s ecoregions (Manitoulin-Lake Simcoe & Lake Erie Lowlands) has been demonstrated by Kraus & Hebb (2020), who assessed conservation metrics across all of Canada’s ecoregions. Metrics such as species richness, species-at-risk prevalence, human footprint, habitat fragmentation, conversion of natural cover, and rate of climate change were used to assign ecoregions with “biodiversity” and “threat” scores. For both scores, the two Southern Ontario ecoregions scored among the highest in Canada. Despite this, the authors found that these same ecoregions scored among the lowest for habitat protection, prompting the label of “crisis ecoregions” (Kraus & Hebb, 2020, p. 3583). Since the publication of the aforementioned article in 2020, the situation has become even more critical. In a political climate that defunds conservation programs, eliminates environmental oversight committees, prioritizes car-centric development, and weakens protection for wetlands and species-at-risk (McIntosh & Syed, 2022; 2023), conservation in Southern Ontario has become a seemingly Sisyphean task.

In the face of these challenges, there is a clear need in Southern Ontario to develop systematic conservation planning frameworks which support thoughtful conservation planning. These frameworks must maximize conservation benefits while minimizing use of limited resources. They must account for the multi-faceted nature of competing land uses and public goods. Finally, these frameworks must be transparent and open to critical review, fostering accountability to influenced communities. In particular, it is of great importance to support environmental NGOs and land trusts in their pursuit of land protections. These organizations, while typically limited in their resources, prioritize consistent fulfillment of their conservation mandates in the face of shifting political priorities. Systematic conservation frameworks which benefit land trusts can therefore provide tangible benefit for the state of biodiversity in urban and peri-urban areas, including Southern Ontario.

With this in mind, the research question I am posing in this thesis is:

What are the best methods for conservation organizations in urban/peri-urban areas to advance conservation planning through the use of landscape connectivity analysis?

1.4 Research Design

In Farthing’s “Research Design in Urban Planning”, the author defines research design as “the provisional decisions taken about research at the initial stages of developing the project” (2016, p. 4). For example, it is recommended that researchers consider their research question, its justification, the logical approach for answering it, and the methods that may be used to go about the research itself (Farthing, 2016). My research question and its justification have already been discussed in the previous section. In the following paragraphs I consider the logical paradigms that inform my investigation approach and outline the methods that I have chosen to form the phases of my thesis research.

1.4.1 Logical Approach

Research design requires one to consider how their broad assumptions about the natural and social world impact the design of the research itself (Creswell & Creswell, 2018; Farthing, 2016). For this thesis, I have chosen to use Moon & Blackman’s (2014) research design framework, which aims to guide natural scientists working within unfamiliar social philosophies. Moon & Blackman define three fundamental elements of research: Ontology, Epistemology, and Philosophical Perspective.

Ontology, which is concerned with the nature of reality, is broadly defined as existing on a spectrum of realism to relativism (Moon & Blackman, 2014). Put simply, a realist ontology sees reality as a single and universal truth unaffected by human experience, whereas the relativist considers reality as constructed by the individual. Epistemology focuses on how one can produce knowledge about the reality defined by one’s ontology (Moon & Blackman, 2014; Farthing, 2016). Philosophical perspectives, meanwhile, relate to the researcher’s philosophical orientations that may guide knowledge acquisition. These may be shaped by individual culture, scientific discipline, previous education, and past experiences; they are also pluralistic, frequently overlap, and are likely to change over time (Moses & Knutsen, 2012; Moon & Blackman, 2014; Creswell & Creswell, 2018).

Moon & Blackman's (2014) framework also borrows Crotty's (1998) division of epistemological positions into three main categories based on the assumed relationship between subjects and objects: "Objectivism", "Constructionism", and "Subjectivism". Objectivism separates the nature of reality from the perception of individuals, and assumes that "objective truths" can be discovered about the world, provided that research methods are rooted in rationality, empiricism, and independence from research objects. Constructionism rejects this single "objective truth" that exists and must be discovered - rather, it posits that knowledge must be constructed by humans through engagement and interpretation, often with separate sets of meaningful knowledge created by different individuals with their own cultural and historical perspectives. Even further down this line of thought, subjectivism proposes that purely objective knowledge is impossible – research's focus should instead be on the perspectives and values of individuals (Crotty, 1998; Moon & Blackman, 2014).

Of the various philosophical perspectives discussed by Moon & Blackman (2014), the one that is most critical for my research is "Pragmatism". Pragmatism values knowledge generation based on its resulting application and use value in solving real-world problems (Crotty, 1998; Moon & Blackman, 2014; Cresswell & Cresswell, 2018). Pragmatists tend to be flexible in their ontology and epistemology, choosing whichever understanding of reality and knowledge is best suited to the problem at hand (Moon & Blackman, 2014; Cresswell & Cresswell, 2018). This pragmatic worldview has been the driving force behind the design of my research project, which aims to provide tangible solutions to real-world problems faced by land use planners.

In this thesis, I have paired my pragmatic worldview with a "Bounded Relativist" ontology and "Constructionist" epistemology. This view of reality and knowledge is moderate between objective reality/truth and entirely subjective perception (Moon & Blackman, 2014). Bounded relativism recognizes that a consistent reality may be shared across a bounded group (e.g., cultures, species, geographies), but that different realities exist outside of these groups. A constructivist epistemology supports this ontology, in that

I must acknowledge that my research likely cannot produce an objectively “best” connectivity analysis method or conservation planning strategy independent of human perception. Ultimately a mixed research design that relies on gathered empirical knowledge, stakeholder consultation, and individual experience may “[give] rise to meaning and knowledge within a defined social context” (Moon & Blackman, 2014, p. 1172). In my case, the defined social context is that of urban/peri-urban land use planners with priorities centred on conservation amid competition, fiscal pressure, and a need for accountability.

1.5 Thesis Structure & Research Methods

To answer my research question and deliver recommendations to conservation planners, I have gathered information from both the academic literature and practical experience.

In Chapter 2, I present a systematic literature review which evaluates landscape connectivity approaches in an urban/peri-urban context. This systematic literature review provides strong theoretical roots for further research by documenting the use of connectivity analysis tools, theories, metrics/indices, and the data requirements for these various facets of the connectivity analysis process. It also considers the research objectives, the local spatial and organizational context, and how connectivity tools may be integrated into larger conservation planning processes.

Chapter 3 complements this literature review with a stakeholder-informed case study within the spatial context of Southern Ontario. The case study demonstrates the importance of stakeholder engagement and an understanding of local context when choosing connectivity tools, and fosters growth of applied knowledge through the actual creation of connectivity data for use in a land conservation strategy. Beyond provision of results, this chapter includes detailed reflections on choices made throughout the study.

Finally, Chapter 4 synthesizes the data gathered within the literature review and case study into a set of broad discussion points and best practices learned over the course of this project. This culminates in a framework of decisions required for a landscape connectivity analysis project, including recommendations and best practices for conservation planners. These recommendations focus on the application of connectivity analysis to systematic conservation planning both for the local context of the case study and the broader conservation community.

Finally, Chapter 5 outlines the main contributions of the thesis and identifies areas for future research. Appendices at the end of this thesis provide additional data about case study methods and further information about specific terminology.

Chapter 2: Literature Review

To better provide informed recommendations on landscape connectivity analysis for conservation planning, I have conducted an in-depth systematic literature review. This review investigates the various methodologies of connectivity analysis that have been developed, tested, and distributed through peer-reviewed channels. My intent is to create a solid foundation of understanding from which I can compare analytic approaches, tools, and promising methods which may be applicable to the context of systematic conservation planning in an urban/peri-urban environment. I have tailored my analysis to evaluate the methodological advantages of landscape connectivity analysis techniques in practice. In the following sections, I detail the steps taken throughout the literature review process, the findings across the literature, and my initial takeaways.

2.1 Review Methods

2.1.1 Database Search, Imports, & Duplicates

I conducted a “Title/Abstract/Keyword” search on the databases “Web of Science” and “Scopus”. The specific search conducted was:

(“habitat connectivity” OR “landscape connectivity”) AND (urban OR city)

This search returned 470 results from Scopus and 473 results from Web of Science. The citation and abstracts of these were downloaded as Excel Workbooks and then uploaded to Covidence Literature Review software (Covidence, n.d.). Upon a cursory review of various databases to ensure consistency, I noted that several papers had been missed in my initial search, due to a third commonly used connectivity phrase: “ecological connectivity”. I first manually imported three papers that I deemed important to include, and then chose to increase my sample size by conducting another search in Web of Science and Scopus, this time with the search input:

(“ecological connectivity”) AND (urban OR city)

These additional results (122 from Scopus and 143 from Web of Science) were processed identically to the previous search and uploaded to Covidence. Between all data imports, the final count of studies for consideration in my literature review was 1,211. Through both manual and automatic duplicate detection processes, 489 duplicates were removed from the sample, and the remaining 722 studies were moved forward to the Title & Abstract Screening stage.

2.1.2 Title & Abstract Screening

To eliminate studies that were irrelevant to my research question, the 722 studies were run through a title and abstract screening process in Covidence. In order to be deemed "relevant" and advance to the next phase of the review, title and abstract information were evaluated against the following five criteria:

1. The study explicitly refers to urban or peri-urban areas.
2. The study considers biotic connectivity in a natural setting.
3. The study seems to be applying connectivity analysis, introducing a new tool, or conducting a literature review.
4. The abstract must comment on landscape connectivity methodology (i.e., there must be some reflection on connectivity methods or proposal of new methods).
5. Exclude studies that only consider marine ecosystems.

Through the use of the criteria above, 495 studies were deemed irrelevant to this research. The remaining 227 papers were moved forward to the Full Text Review phase.

2.1.3 Full Text Review

The full text review is a more detailed screening phase to ensure that all literature included in the final data extraction will contain information that is relevant to the review (Covidence, n.d.). This process requires first acquiring and uploading all papers as PDF files to view them within the Covidence software. Next, each paper is read in its entirety and categorized "Include" or "Exclude". At this phase, study exclusion depends on a set of pre-defined and ranked exclusion criteria, allowing the researcher to track reasons for exclusion and report on them as needed (Covidence, n.d.).

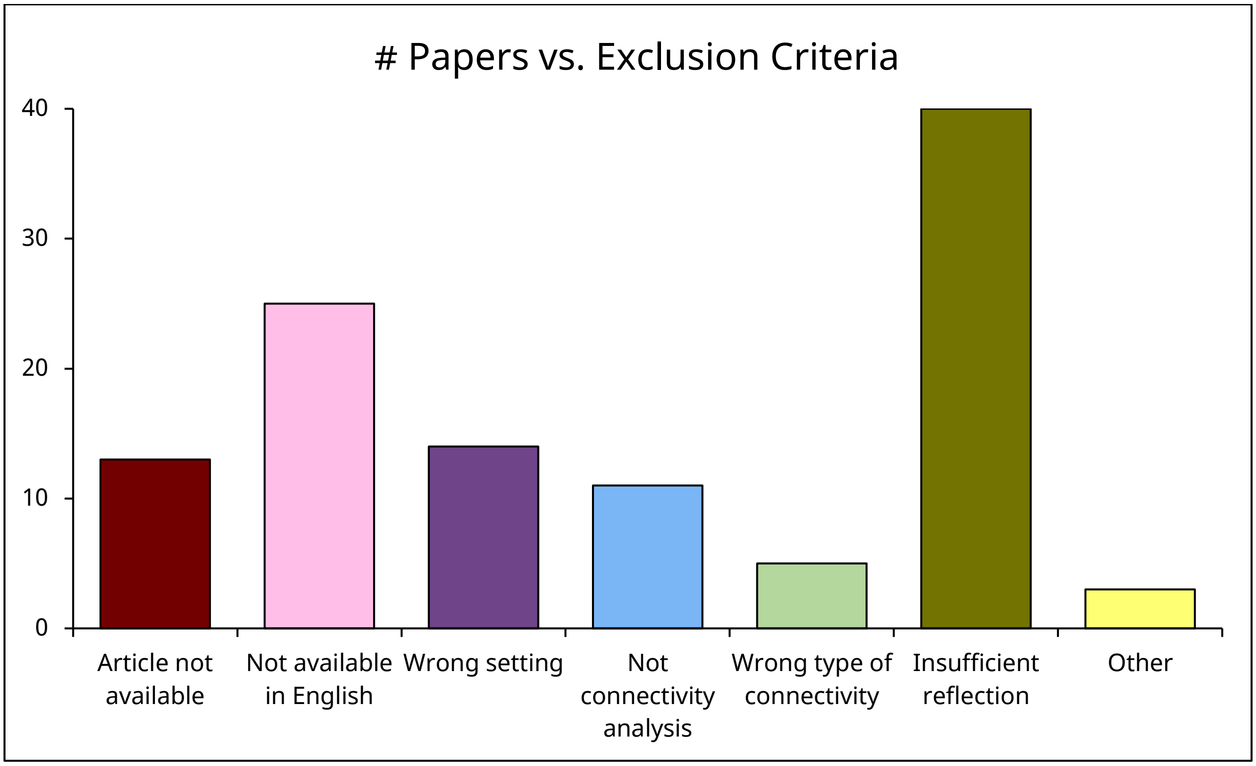
Full PDF copies of all 227 papers were searched for online. Papers were searched for using the University of Waterloo Library database, Web of Science, Scopus, Google Scholar, and ResearchGate. For 13 papers, no full-text version was found, or the full-text version was not accessible. An additional 25 papers had a full version, but there was no version available in English. These were also excluded from consideration. The remaining papers were downloaded as PDFs and then uploaded to Covidence. These papers were reviewed in their entirety and screened via the following seven exclusion criteria:

1. Article not available.
2. Not available in English.
3. Wrong setting (i.e., marine, not urban/peri-urban).
4. Not landscape connectivity analysis.
5. Wrong type of connectivity (i.e., abiotic, hydrologic, pathogen).
6. Insufficient reflection on methodology.
7. Other (see notes).

Through this process, a total of 111 papers were excluded from consideration. Exclusion reasons varied across the seven criteria, as demonstrated in Figure 1 below.

Figure 1

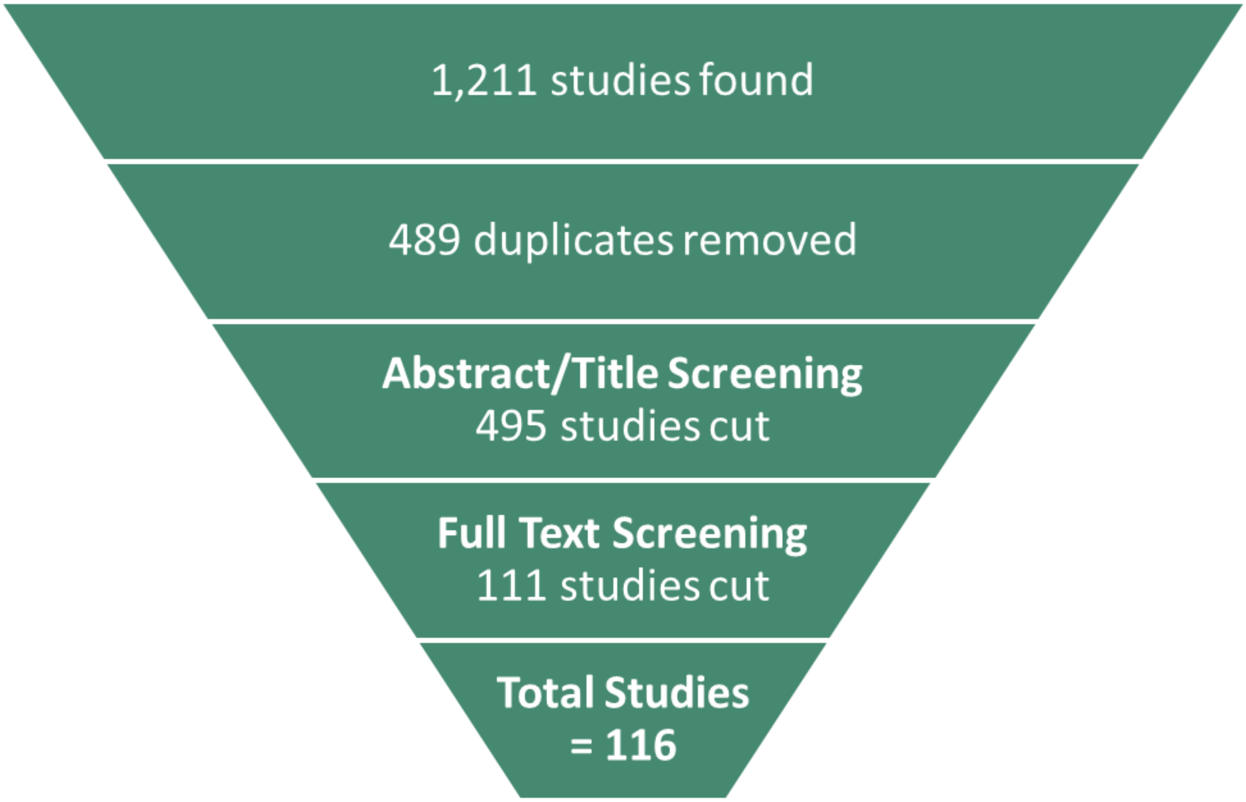
Number of Papers Discarded During Full Text Review per Exclusion Criteria.



As shown in the chart above, the most common reason for exclusion was “insufficient reflection on methodology”. Generally, this took the form of studies which used connectivity analysis to better understand another phenomenon (such as the behaviour of a focal wildlife species), but didn’t further discuss connectivity analysis itself. Of the three papers listed as “Other”, one was excluded because it was a research proposal that was unable to report on any results (Quinn & Tyler, 2007), and the other two were excluded due to poor quality of work and/or an unacceptably small number of references (Selim & Demir, 2019; Schwarz-v. Raumer, 2021). Upon conclusion of the full text review screening, the papers remaining for in-depth data extraction totalled 116. The overall screening process can be visualized in Figure 2 below.

Figure 2

Graphic of the systematic filtering process used for the literature review.



2.1.4 Data Extraction

The final 116 papers considered in this review were run through the Covidence data extraction process. In order to extract data in a systematic and organized way, Covidence allows the user to create and customize a data extraction form which is then displayed next to the research paper being analyzed to be filled out, one paper at a time. Upon conclusion of the data extraction process, the filled out data extraction forms for each paper are compiled by the software and available for export as a single Excel spreadsheet, allowing for efficient analysis (Covidence, n.d.).

In the customization of my data extraction form, I drew from several other landscape connectivity reviews articles (Tischendorf & Fahrig, 2000; Calabrese & Fagan, 2004; Rayfield et al., 2011; Zeller et al., 2012; LaPoint et al., 2015; Correa-Ayram et al., 2016; Lynch, 2019;

Karlsson & Bodin, 2022; Lookingbill et al., 2022). These reviews use a diversity of methods to collect and evaluate literature surrounding connectivity methodology, and provide the foundation for my form, which I then modified to better represent my own research context.

In addition to landscape connectivity reviews, I drew significantly from the textbook "Spatial Decision Support Systems" by Sugumaran & DeGroote (2011) to create a set of data extraction questions about how connectivity analysis may have been integrated into SDSS for systematic conservation planning. The final data extraction form includes five thematic sections, each with several multiple choice or short-form questions. The thematic sections and their content are listed in Table 1 below:

Table 1

List of Thematic Sections and the Review Variables Contained Within Them.

Thematic Section	Content
Basic info	Study ID, lead author, year of publication, study title, journal / source, institutional affiliation
Spatial context	Continent, country, province/state/region, urban area(s), spatial scale, level of urbanization
Methodology	Object(s) of study, type of connectivity measured, analytic approach, validation strategy
Methods	Field data collected, raw spatial data used, measures calculated, analysis software used, connectivity output
Spatial decision support systems	SDSS included (yes/no), goal of SDSS, SDSS approach used, SDSS software used

It should be noted that, of the 116 studies examined in this review, three of them are literature reviews that do not conduct any connectivity analysis themselves. These were kept due to their in-depth reflections about urban connectivity analysis methodology. Because of this, several of the numbers reported in the following sections will add up to 113, as the three literature reviews often had values of "n/a". In section 2.2, I provide a detailed breakdown of the review results.

2.2 Basic Info & Spatial Context

2.2.1 Temporal & Geographic Trends

In my sample of urban/peri-urban connectivity literature, I noted a rapid increase in the rates of publication over time, a phenomenon also remarked on by LaPoint et al. (2015) and Lookingbill et al. (2022). Of the 116 papers in my review, 9% were published prior to 2010, while over 40% were published since January of 2020 (see Figure 3). Beyond overall temporal trends, the geography of urban/peri-urban connectivity research seems to have shifted over time. Figure 4 shows the percentage of reviewed papers across time and study continent (excluding the single paper from 2001). The overall share of papers from Europe stays relatively stable at one-third, while the proportion of research from North America decreases (56% to 4%) and the reverse occurs for Asia (0% to 55%).

Figure 3

Column Graph Showing an Increase in Connectivity Papers over Time.

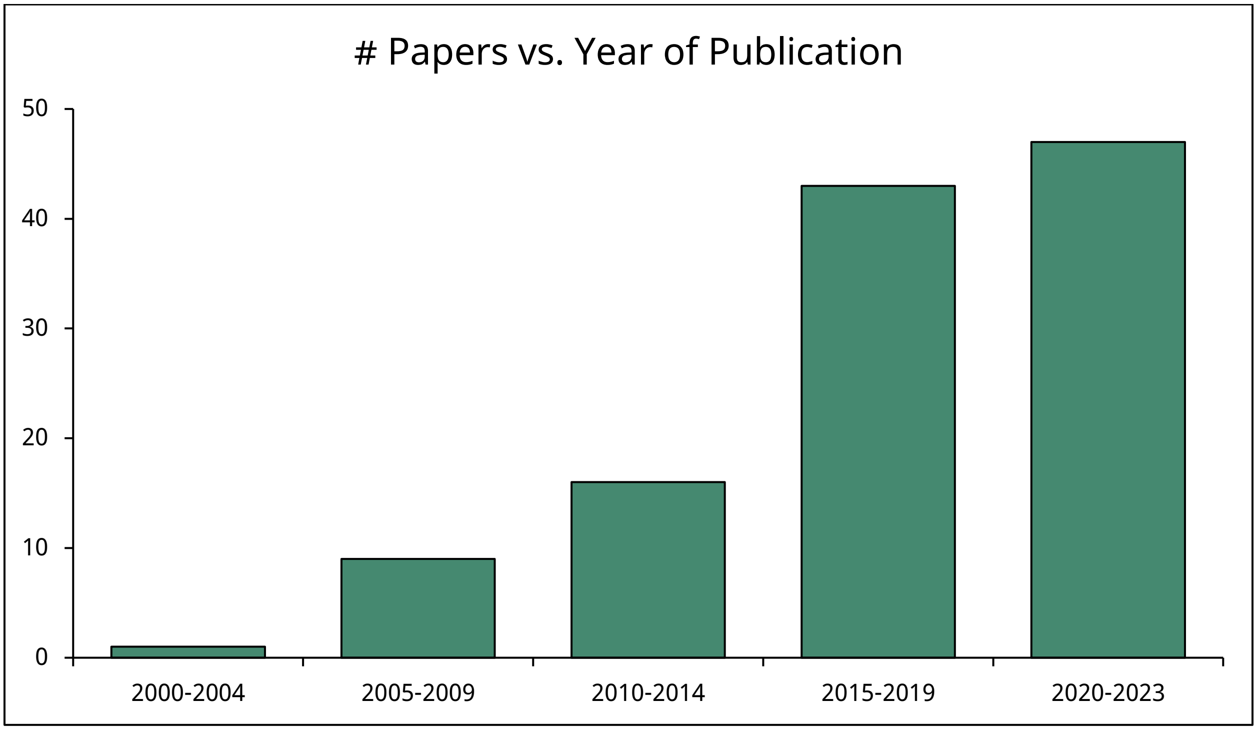
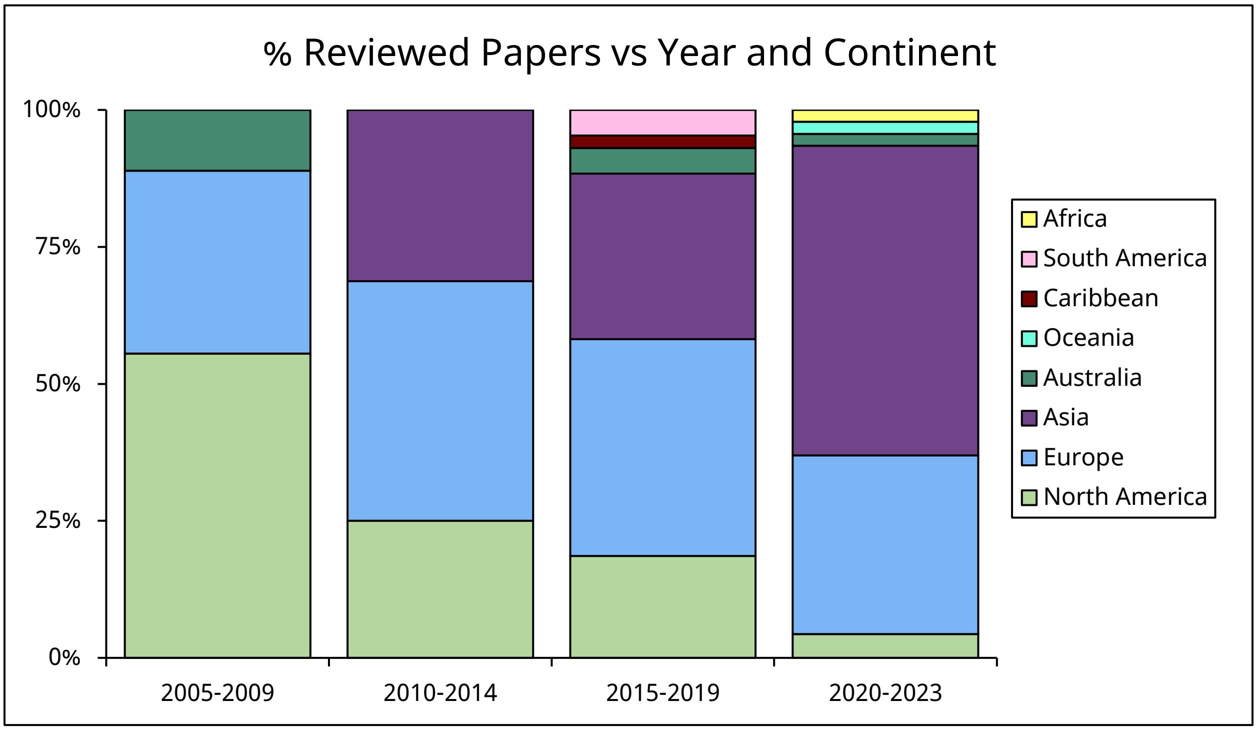


Figure 4

Proportion of Reviewed Papers by Continent over Time.



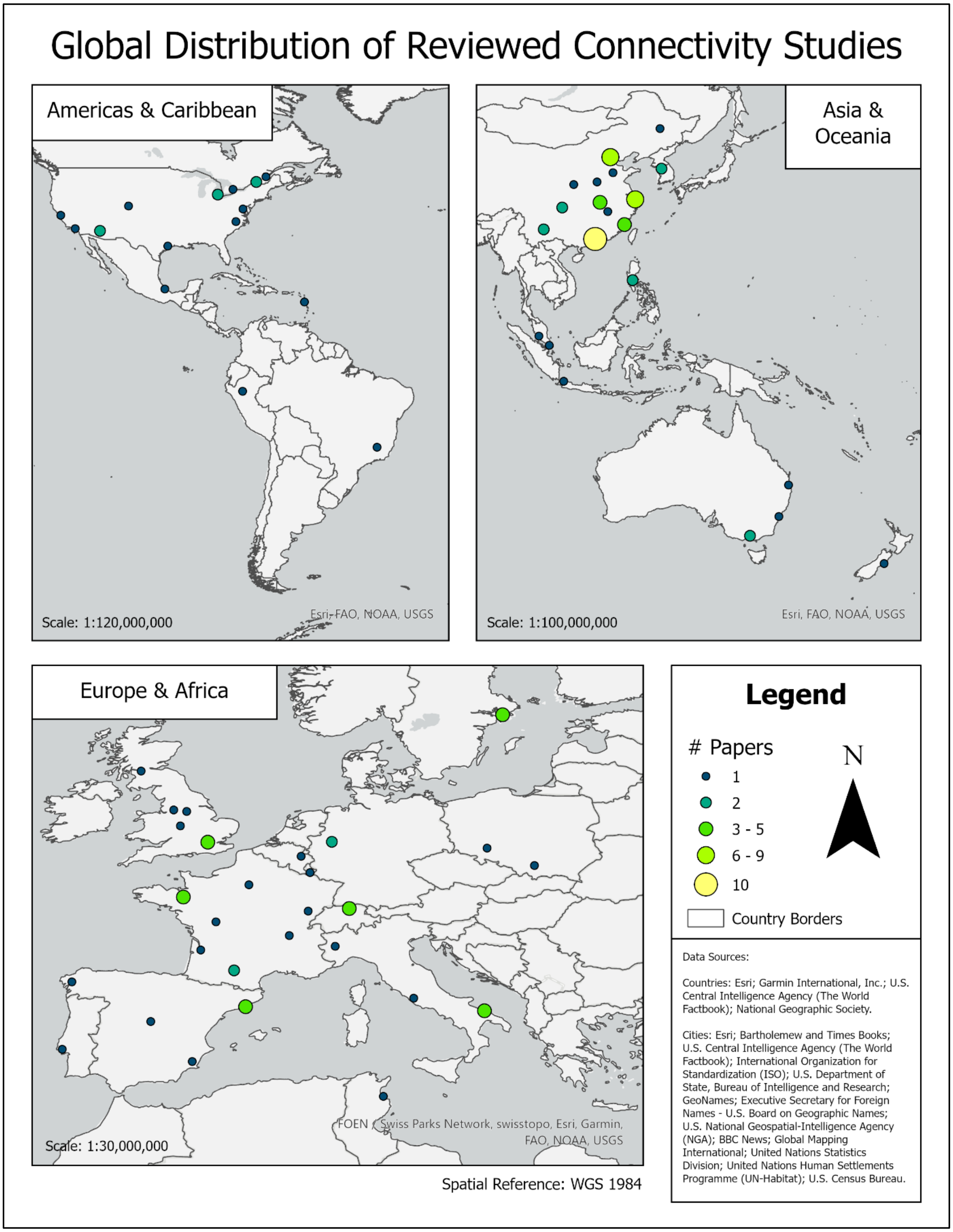
This geographic trend is consistent with Lookingbill et al.'s (2022) review of urban/peri-urban connectivity papers from 2015-2020. They compare their literature sample with the earlier review of LaPoint et al. (2015) and find similar trends for Europe (stable at 30%), North America (50% to 16%), and Australasia (19% to 48%). In my consideration of these geographic trends, possible biases and drivers were evaluated. There have been recent shifts in the culture of academic publications, including an increased pressure on researchers to publish, and the proliferation of so-called "predatory" journals with less reputable standards (Camargo et al., 2023). To address the possibility that these geographic shifts in my sample of connectivity literature could be driven by this phenomenon, I cross-referenced my reviewed articles with both the Norwegian Register for Scientific Journals, Series, and Publishers (n.d.) and Beall's List (n.d.) of Potential Predatory Journals and Publishers. Of the 116 articles, seventeen were flagged by one or both of these sources as having potentially problematic journals and/or publishers. Ten of these are from China, two are from Italy, and one each are from Canada, New Zealand, Poland, Sweden, and Tunisia. Even with these articles removed, the trends of stable publication from Europe, an increase from Asia, and a decrease from North America remain.

To ensure that my exclusion criteria do not bias the literature sample against non-English countries, I checked the origin of the 38 papers that I had excluded due to lack of availability or lack of an English version. Of these, 32 are from Asia (all China), three from Europe (France, Poland, and Spain), and one each from Brazil, Colombia, and Iran. Even with these considered, there is notably low representation of urban/peri-urban research outside of China, Western Europe, and North America.

Overall, the individual countries most represented within the 116 reviewed papers are China (34%), the United States (11%), and France (9%). Canada is relatively well represented as well, with five total studies included in the analysis. Of the Canadian studies, two focus on Montreal (Albert et al., 2017; Deslauriers et al., 2018), one on Quebec City (St-Louis et al., 2014), one on Windsor (Choquette et al., 2020), and one on the Greater Toronto Area (Stille et al., 2018). A global map showing the distribution of reviewed studies can be found in Figure 5 below.

Figure 5

Composite Map With Weighted Circles Showing Distribution of the 116 Reviewed Studies.



Global Distribution of Reviewed Connectivity Studies

Americas & Caribbean

Asia & Oceania

Europe & Africa

Data Sources:

Countries: Esri; Garmin International, Inc.; U.S. Central Intelligence Agency (The World Factbook); National Geographic Society.

Cities: Esri; Bartholemew and Times Books; U.S. Central Intelligence Agency (The World Factbook); International Organization for Standardization (ISO); U.S. Department of State, Bureau of Intelligence and Research; GeoNames; Executive Secretary for Foreign Names - U.S. Board on Geographic Names; U.S. National Geospatial-Intelligence Agency (NGA); BBC News; Global Mapping International; United Nations Statistics Division; United Nations Human Settlements Programme (UN-Habitat); U.S. Census Bureau.

2.2.2 Fields of Study & Thematic Areas

The vast majority of lead authors for the reviewed connectivity studies are affiliated with universities (86%). The rest are divided between research institutes (7%), governmental organizations (3%), consulting companies (3%), and a single non-profit. Within each of these institutional affiliations, I recorded the department that the lead author is associated with. I then divided these departments into seven main fields of study. Similarly, I divided the academic journals which published each article into thematic areas. The spread of these is detailed in Tables 2 and 3 below. As shown below, environmental science and ecology are highly represented across both journals and departmental fields of study in this sample of literature. This may suggest connectivity analysis as a tool used more frequently by natural scientists than urban or regional planners.

Table 2

Lead Authors' Field of Study Recorded Across Reviewed Literature.

Fields of Study	# Papers
Biology, Ecology, & Conservation	25
Environmental Science, Sustainability, & Pollution	23
Engineering & Landscape Architecture	16
Geography & Geomatics	15
Multidiscipline	14
Land Use, Urban Planning, & Policy	12
Forestry, Agriculture, & Resource Management	11

Table 3

Themes of Journals to Which Reviewed Articles Were Submitted.

Journal Themes	# Papers
Biology, Ecology & Conservation	52
Land Use, Urban Planning, & Policy	28
Environmental Science, Sustainability, & Pollution	27
General Science	4
Geography & Geomatics	3
Engineering & Landscape Architecture	2

2.2.3 Spatial Scale & Level of Urbanization

Spatial scale has been demonstrated to have a strong effect on the outcomes of landscape connectivity analysis (Pascual-Hortal & Saura, 2007). In their study of this topic, Pascual-Hortal & Saura (2007) show that some connectivity metrics are highly sensitive to changes in spatial scale, while others are designed to be robust across multiple scales. In their study, the use of the wrong metric for a given spatial context leads to different land prioritization decisions, making this topic important to consider in the choice of methodology for conservation planning.

Of the studies reviewed, the most common spatial scales of analysis are City (41%) and Region/County (33%). However, connectivity analysis is also conducted at very large and very small spatial scales. For example, a study of land snail genetics measures connectivity within 1.3km-diameter circles (Balbi et al., 2018), while a study of protected area networks in Spain considers the entire province of Almeria, measuring 8,774 square kilometres (Piquer-Rodriguez et al., 2012). In addition, several studies aim to measure connectivity at multiple spatial scales, such as that of Girvetz et al. (2008), which measures connectivity in the state of California, comparing analyses across two administrative scales and six watershed scales.

In addition to spatial scale, I tracked the level(s) of urbanization within each article's area of study. Because the screening process for this literature review operates to only include urban or peri-urban papers, there are no fully rural studies included in the sample. Possible options for urbanization include Urban Core, Urban Park, Suburban, and/or Peri-Urban. However, this assignment proved difficult to implement in practice for several reasons. First, most studies at a spatial scale larger than neighbourhood look at multiple scales of urbanization. Second, many studies lack an explicit definition of "urban" and how their study areas fit into such a term. This challenge is discussed at length by LaPoint et al. (2015), who presents a myriad of subjective and objective descriptions of "urban" across literature. They find that most studies use subjective terms like "peri-urban", "residential", and “industrial”, while some others use objective measures like building density or zoning-derived land use categories. Several papers in the LaPoint et al. study (and my analysis) do not provide any explanation of urbanization beyond generic descriptions like “city” or “town”.

I ultimately chose to keep my initial urbanization categories as-is, but added an extra category of “mixed”, which includes any study that seemed to consider more than two levels of urbanization. Just over 66% of studies fell in the “mixed” category, while the rest are fairly evenly distributed across the other categories.

2.3 Approach to Connectivity Analysis

Beyond organizational and spatial context, there are several ways in which connectivity studies may be categorized. These include: (1) The object(s) of study, (2) the type of connectivity being measured, (3) the analytic approach being used, and (4) the validation strategies (if any) being used to ensure that connectivity outputs are robust and accurate.

2.3.1 Object(s) of Study

The object of a connectivity study dictates the specific entity (or entities) for which connectivity is being measured. For instance, many studies evaluate connectivity for a single wildlife species of concern (e.g., the great crested newt, Matos et al., 2019). Alternatively, some may use the data of several focal species to support conservation efforts that benefit a larger wildlife cohort (e.g., ten amphibian species, Donati et al., 2022). Other studies may not consider individual species at all, but instead use general connectivity measurements to track fragmentation of the overall landscape (e.g., Wanghe et al., 2019).

For the purpose of this review, there are six possible “object of study” categories (see Table 4 below). It is most common for studies in my sample to use only one category (66%), though some studies present hybrid models that consider two (26%) or even three (5%) study objects. Of the studies that evaluate only one object category, the most commonly considered is “multiple species” connectivity; of the hybrid studies, the most common combination is multiple species + blue-green infrastructure. These are generally studies that use focal species to represent connectivity on a larger scale and propose greenspace networks based on the results.

Table 4

Categories of Study Object Considered in this Review.

Object of Study	Description	Examples
Single Species	One focal species considered.	European Hedgehog
Multiple Species	List of species OR a multi-species group.	"Green Frog, Wood Frog, & Spring Peeper" OR "Birds"
Single Habitat Type	Type of natural feature grouped by composition or shape.	Forests, Corridors, Wetlands
Blue-Green Infrastructure	All "natural" features on the landscape.	Greenspace, Natural Heritage System, Parks
Cultural Ecosystem Services	Ecosystem services not covered by blue-green infrastructure.	Walkability, Recreation Value
General Landscape	Entire landscape focus.	n/a

2.3.2 Types of Connectivity

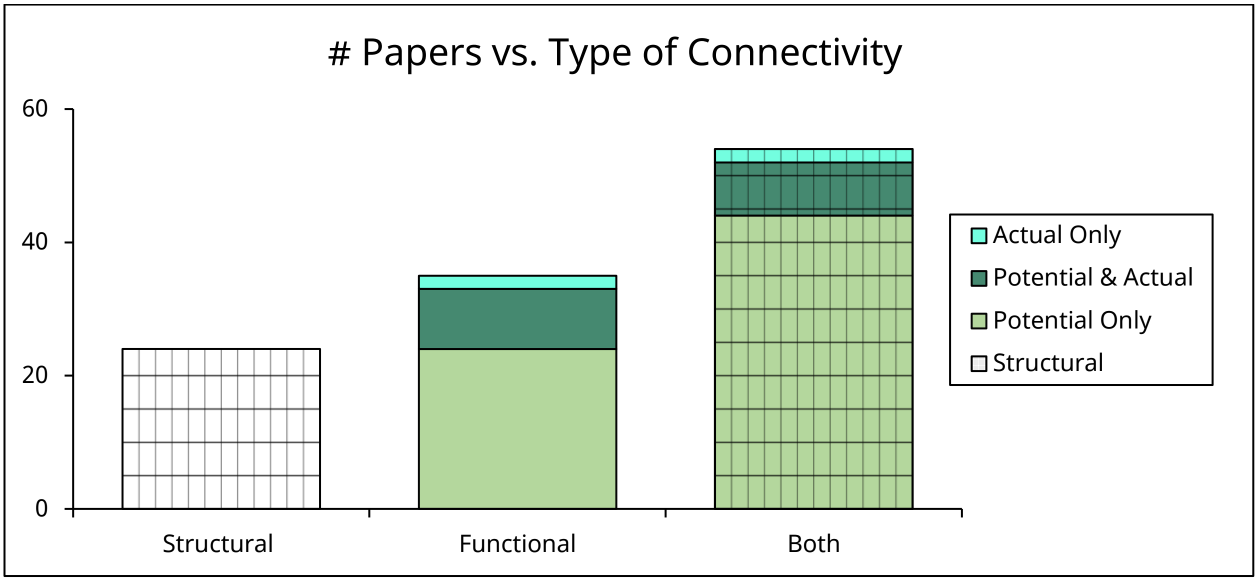
Tischendorf & Fahrig (2000) propose the most commonly used distinction between types of landscape connectivity. As discussed in Chapter 1, "structural connectivity" is a spatially driven measure of the physical connectedness of habitat patches (i.e., as seen on a map), whereas "functional connectivity" is the evaluation of predicted species movement between habitat patches. This distinction has helped to classify most later literature into studies that measure connectivity structurally, functionally, or both.

Beyond this distinction, Calabrese & Fagan (2004) recommend further division of functional connectivity into "potential" and "actual" connectivity. They argue that "potential connectivity" combines physical attributes of landscape pattern with available information about species' dispersal ability to predict connectivity on the landscape. This is distinct from measures of “actual connectivity”, which require field observation of species movement through a landscape to provide concrete and empirical connectivity values.

The categories of “structural”, “functional – potential”, and “functional – actual” connectivity have become commonplace in the field of landscape connectivity analysis, and provide a useful framework for the classification of methodologies that has been encouraged by reviewers (Correa-Ayram et al., 2016; LaPoint et al., 2015; Lookingbill et al., 2022). I also use this framework to classify studies, and additionally draw on a well-considered distinction by Almenar et al. (2019) to discern structural from functional connectivity – in short, that the use of cost distances and resistance surfaces denote a functional connectivity analysis, while connectivity based on Euclidean (or straight-line) distance can be considered structural. As demonstrated in Figure 6, the majority of studies in my sample use a combination of structural and functional connectivity measures. Studies that measure functional connectivity tend to prefer potential connectivity measurement, an anticipated result considering the fieldwork requirements to collect actual connectivity data.

Figure 6

Graph Showing Types of Connectivity Measured Across Literature Reviewed



2.3.3 Analytic Approach

In addition to the distinction between structural and functional connectivity, there are several analytic approaches that may be applied to process spatial and wildlife data into connectivity outputs. Using the various frameworks provided by previous literature reviews (Calabrese & Fagan, 2004; Correa-Ayram et al., 2016; LaPoint et al., 2015; Lookingbill et al., 2022), I divided these analytic approaches into four broad categories that I felt were able to represent all studies. They are briefly defined as follows:

- **Spatial Pattern Indices (SPI):** As defined by Calabrese & Fagan (2004), SPI are quantifications of landscape form, usually involving equations that incorporate measurements of quantity, area, distance, density, and/or complexity. There are many spatial pattern indices that are not direct measures of connectivity (e.g., patch area), but several have been developed to act as direct connectivity measures (e.g., effective mesh size). Because SPI do not incorporate species dispersal or landscape resistance, they are always structural connectivity measurements.
- **Graph/Network Theory (GNT):** Initially used for fields of geography and computer science, Urban & Keitt (2001) proposed graph theory as a reimagining of landscape connectivity analysis. GNT views the ecological landscape as a simplified network of nodes and links, which represent patches and corridors. GNT analysis may be used structurally, or may incorporate cost surfaces and effective distance to allow for functional measures (Almenar et al., 2019).
- **Circuit Theory (CT)**: Technically an off-shoot of GNT, McCrae et al. (2008) proposed incorporating the physics of electricity to introduce randomness and multi-path scenarios within connectivity measures. CT requires definition of nodes, links, and a resistance surface upon which modelled electric current will move to illustrate connectivity. Since its inception, the innovation and use of CT has expanded dramatically, and now warrants its own category of approach (Dickson et al., 2018).

- **Simulation Models (SM)**: Simulation models involve the digital simplification of a given system, definition of rules for how that system behaves, and a process of experimentation that models how that system behaves over time, ultimately for the purpose of better understanding or improving the system in the real world (Robinson, 2004). This may include modelling multiple scenarios for the same landscape and interpreting the results to choose an optimal solution, or allowing technology such as Artificial Intelligence (AI) to do this for the user (Sugumaran & DeGroote, 2011).

In the literature I reviewed, most papers (64%) tend to use more than one analytic approach in their connectivity analysis. The most commonly used approaches overall are Graph/Network Theory (79%) and Spatial Pattern Indices (49%), and the most common combination of approaches is these two put together (19%).

2.3.4 Validation Strategies

As discussed previously, functional connectivity measures can be divided into potential (modelled) and actual (empirically-derived) connectivity. In either case, the data about species movement must come from somewhere, whether that is an author's judgement, expert opinion, literature review, or collected field data. These strategies can serve to improve the validity and transparency of connectivity models and to ensure that planning recommendations are rooted in reality (Laliberté & St-Laurent, 2020; Lookingbill et al., 2022). Even structural connectivity measures can benefit from validation strategies, such as the practice of field ground-truthing to ensure that land-use maps are accurate prior to using them for analysis.

In my review, three possible validation strategies (expert opinion, literature review, and field data) were recorded. I chose to be fairly generous in my interpretation of "expert opinion", allowing authors' best judgement to count provided the authors were detailed in their rationale for chosen input values. Of the 113 papers that conducted connectivity analysis (i.e., not including the three literature reviews), very few fail to use some form of validation strategy (8%). It is most common to only use one strategy (54%), but several studies use two (30%) or even all three (8%). The most common choice by connectivity analysts is to turn to the literature and use already-published sources of wildlife dispersal data and habitat preferences to validate connectivity models.

2.4 Specific Methods in Connectivity Studies

Beyond the general ways that connectivity can be measured, there is a diversity of specific methods that may be chosen throughout connectivity analysis itself. I have divided this section into three parts, each encompassing a different phase of the connectivity analysis process. First I consider inputs required for connectivity models. The second section includes the technical software and tools required for analysis. Finally, the third section covers the ultimate connectivity outputs from each type of analysis.

2.4.1 Data Inputs & Measures

In this review, possible data inputs for connectivity analyses were first classified into “spatial data” and “field data”, in order to distinguish between information gathered from the field by the researchers, and information retrieved through other sources such as governmental mapping databases. A third category called “measures” was also created, encompassing inputs that are not generally available from databases and need to be calculated from spatial or field data. Each of these is considered below.

2.4.1.1 Field Data

Data gathered from the field falls into seven possible categories, and varies greatly in terms of the work and intervention required by the researchers. The majority of field data studies use simple observation, including land-use ground truthing and species observation. Examples of species observation data include visual species counts, frog and bird call monitoring, and road mortality counts. One study (Stille et al., 2018) also uses stream monitoring, which includes species observation (e.g., benthic invertebrates) as well as observation of other abiotic habitat features (e.g., water quality, stream temperature).

Beyond these relatively “hands-off” methods, nine more studies include field data that requires more interaction with the research objects. These are made up of three categories (defined by Zeller et al., 2012, and represented by three papers each):

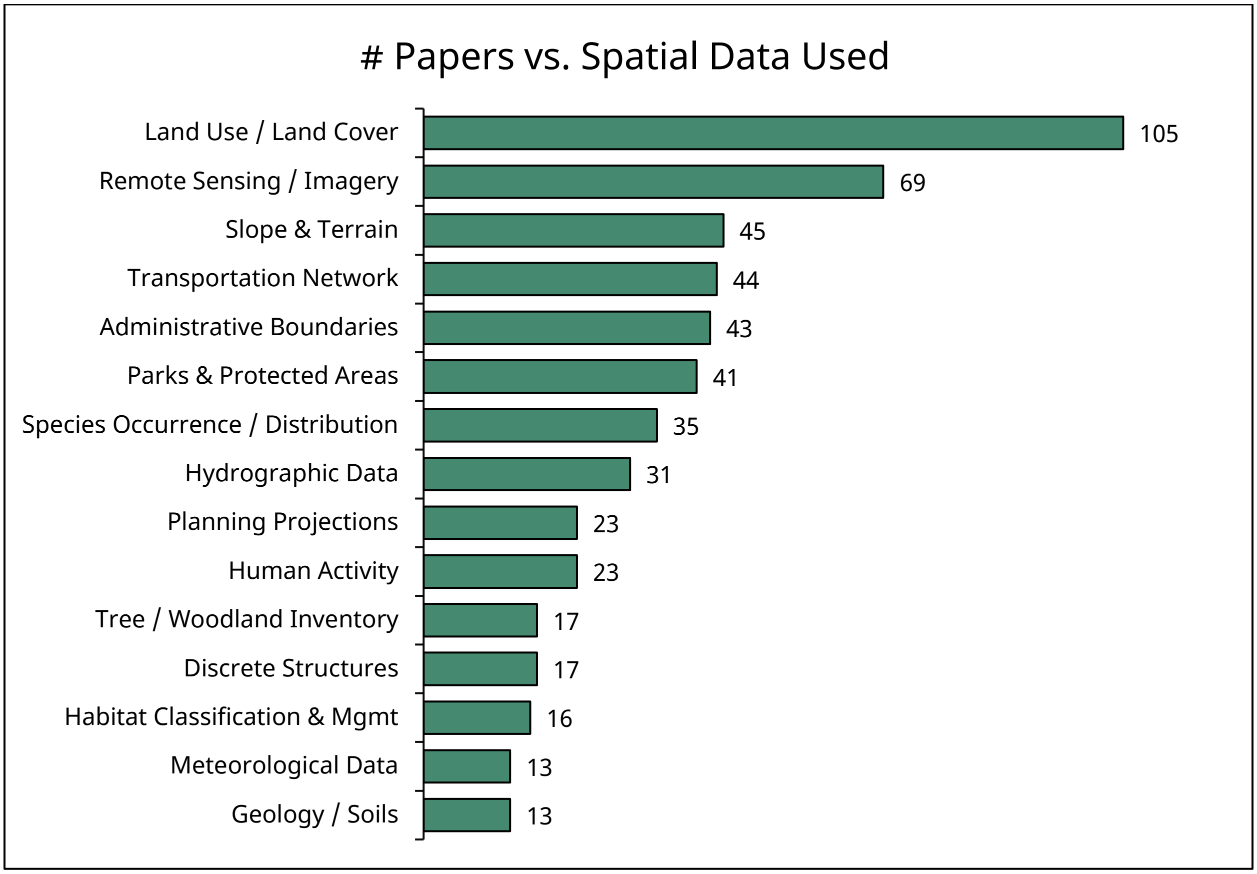
- **Capture-mark-recapture surveys**, in which marked species are caught multiple times to generate “two or more sequential locations of the same individual, but not at a sufficiently frequent interval to treat… as a movement pathway.” (p. 785),
- **Telemetry or radio-tracking**, which allows for full movement pathways to be estimated based on frequent-interval location data, and
- **Genetic data collection**, in which genetic samples are taken from the species of study and used to calculate measures such as genetic drift and gene flow.

2.4.1.2 Spatial Data

The diversity of spatial data used for connectivity analysis is striking, and required organization into 15 broad categories to allow for easier data processing. These are listed in Figure 7 below, along with their frequency of use. For a full list of spatial data definitions as they were applied in this review process, please refer to Appendix A.

Figure 7

Frequency of Use for Various Spatial Data in Reviewed Connectivity Research



By a fairly wide margin, Land Use / Land Cover and Remote Sensing / Imagery are the two most commonly used spatial data inputs across reviewed studies. These were observed to form the foundation of most connectivity analyses, with over 97% of studies including at least one. The next most common datasets (Slope & Terrain, Transportation Network, Administrative Boundaries, and Parks & Protected Areas) are frequently used to calibrate resistance surfaces by providing information about the ease or difficulty for wildlife attempting to navigate a given landscape.

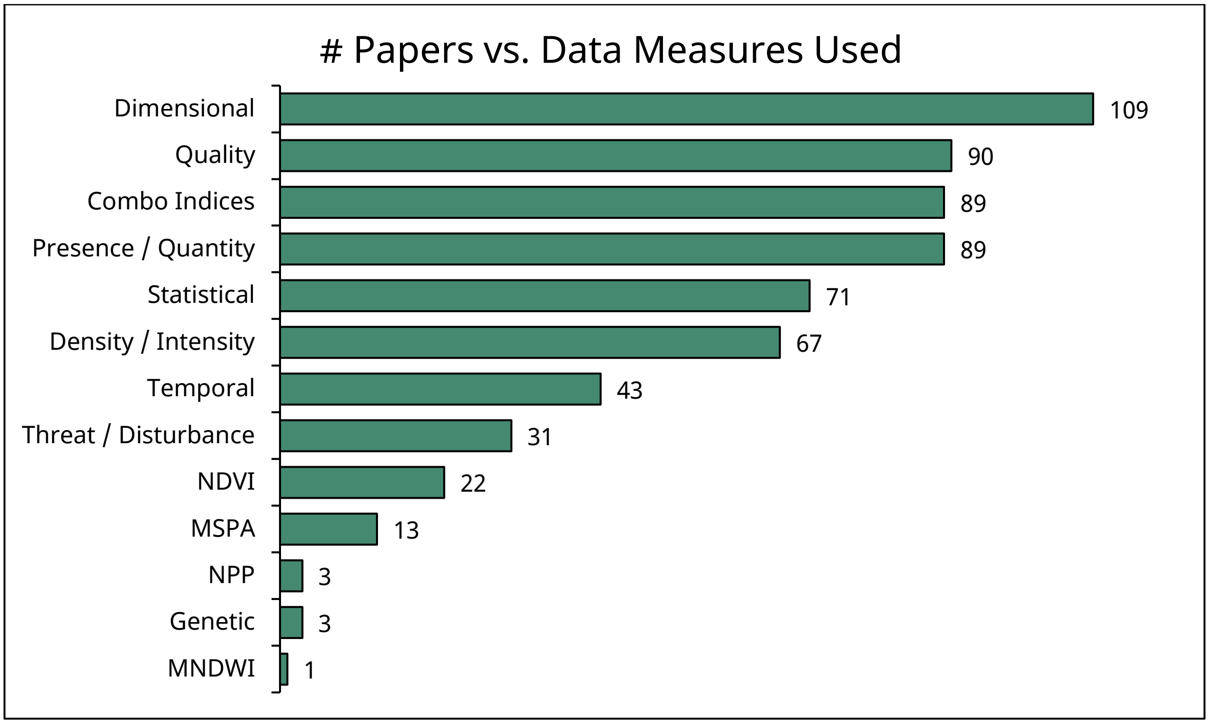
It should also be noted that "Species Occurrence / Distribution" data was limited to only include such data that was not collected by the authors themselves. This prevented double counting between this variable and the field data inputs discussed in Section 2.4.1.1.

2.4.1.3 Data Measures

Data measures are separated from input data as a "middle ground" between the data inputs and connectivity outputs. This category refers to the calculations that need to be performed during connectivity analysis that are not direct measures of connectivity, but are ultimately used to determine the final connectivity output. A total of 13 categories of measurement are used. Figure 8 below shows the frequency of different types of data measurement that occur throughout the reviewed connectivity analysis literature. The most common data measurement is "Dimensional Measures", such as "distance", "area", and "shape complexity". These measurements are generally expected in spatial analysis, and many of them can be done using simple mapping software, such as Google Earth. Similarly, "Presence / Quantity" measures that refer to values like "# of patches" are quite simple to measure and are frequently integrated with connectivity outputs.

Figure 8

Frequency of Use for Data Measurement Methods in Connectivity Research



Note: NDVI = Normalized Difference Vegetation Index; MSPA = Morphological Spatial Pattern Analysis; NPP = Net Primary Productivity; MNDWI = Modified Normalized Difference Water Index.

It should be noted that the category “Combo Indices” is artificially inflated, as this category was used as a sort of “wastebasket taxon”, into which any complex measurements that do not fit into another listed category were added. Additionally, there are occasions when complex “measures” (like NDVI and NPP) are reported as downloaded from government mapping sources. However, because not all articles specify whether the measurements were calculated by the authors or were retrieved from elsewhere, all use of these variables is treated as though they had been calculated by the authors and classified as “Measures”. Like the spatial data categories, definitions can be found in Appendix A.

2.4.2 Connectivity Analysis Software Tools

The use of software tools is fairly ubiquitous in landscape connectivity analysis due to the complexity of working with and quantifying spatial data. Other than the literature reviews, only five papers in my sample do not specify any form of software used.

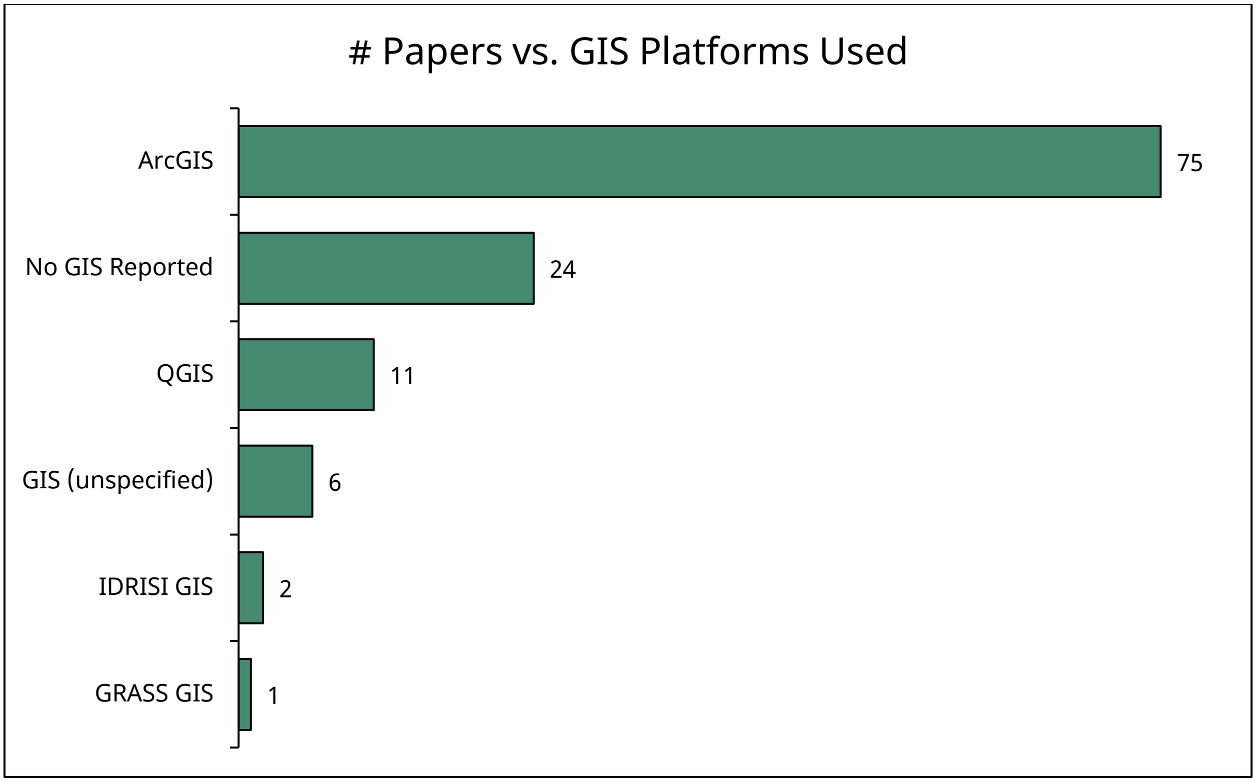
During the initial data extraction phase of my literature review, I recorded the use of software tools of any kind, from AI-fueled urban modelling software to aspatial programs like Microsoft Excel. However, due to the immense diversity of potential software used across these studies, it was necessary to separate out irrelevant data and focus my review on only software tools directly used to measure connectivity. These include analytical GIS tools (e.g., ArcGIS), connectivity-focused R packages, GIS toolboxes (e.g., Linkage Mapper), and standalone landscape analysis software tools (e.g., Fragstats). Classification was complicated by the fact that some software tools exist as both a standalone tool and as a toolbox that can be integrated into a GIS software. In cases like these, any tools bearing the same name and general methodology are lumped under the same name, regardless of whether they are standalone or a toolbox.

The most common GIS platform used is ESRI’s ArcGIS and its various versions (i.e., ArcMap, ArcView, ArcGIS Pro). Although ArcGIS can be financially exclusive software, it is still widely regarded as the industry standard, and is often a provided resource within academic institutions (ESRI, n.d.-a). Because the majority of papers in my review are affiliated with academic institutions, it follows that they would make use of the capabilities of ArcGIS where available. However, there are several uses of alternative GIS software reported, as well as some studies that use GIS but do not specify which one (see Figure 9).

Beyond general GIS platforms, there were 28 connectivity software tools reported in my review, demonstrating the diversity of analysis methods in this field. However, several of these tools are either: (1) only reported being used once, (2) no longer available, (3) required an emailed request to the researchers to acquire, (4) outdated, and/or (5) work only with outdated GIS technology. The five most commonly reported connectivity tools (in order of prevalence across reviewed papers) are: Conefor (27%), Circuitscape (17%), Linkage Mapper (16%), Fragstats (11%), and Graphab (10%).

Figure 9

Frequency of Use for General GIS Platforms in Connectivity Research



2.4.3 Connectivity Outputs

In this review, the “output” of a landscape connectivity analysis refers to the final map, metric, index, or other product that quantitatively represents connectivity on the landscape. Across the literature reviewed, a total of 33 different connectivity outputs are represented, ranging from single-numeric scores assigned to individual patches (e.g., Betweenness Centrality) to maps of the least-cost paths (LCP) or least-cost corridors (LCC) between patches. I have listed the ten most frequently used connectivity outputs in Table 5 below, including the analytic approach used to produce the output.

Table 5

Ten Most Frequently Used Connectivity Outputs Across Reviewed Literature.

Connectivity Output	Analytic Approach	# Papers
Least Cost Analysis (e.g., LCP, LCC)	GNT	59
Probability of Connectivity (PC)	GNT	36
Integral Index of Connectivity (IIC)	GNT	19
Cumulative Current	CT	12
Effective Resistance (ER)*	CT	11
Equivalent Connected Area (ECA)	GNT	10
Current Density	CT	9
Current Flow Centrality	GNT + CT	9
Betweenness Centrality (BC)	GNT	9
Node Gravitation (G)	GNT + SM	7

*Also called “resistance distance”

There is a noticeable lack of Spatial Pattern Indices among these frequently used connectivity outputs. This seems odd initially, considering that SPI is an analytic approach used in around half of studies overall. However, there is a factor that I think explains this inconsistency. In connectivity analysis, the SPI analytic approach may be used in the “measurement” phase (see Section 3.3.1) to provide quantifications of landscape morphology, but these indices may not actually measure connectivity directly (Calabrese & Fagan, 2004). While there are some direct connectivity SPI measurements as well (e.g., Effective Mesh Size, Landscape Division Index, Cohesion Index), there are several SPIs within the software Fragstats that I classified as “measurements” rather than connectivity outputs, such as “# of patches”, “patch area”, and “patch perimeter”. While these calculations may later get plugged into an equation that does represent connectivity (for example, the Conefor indices), they were not in themselves counted as connectivity outputs. While SPI is certainly an important analytic approach for connectivity analysis, it is underrepresented in the “final output” category.

2.5 Spatial Decision Support Systems

Thus far in my literature review chapter, I have considered the organizational context, spatial context, general connectivity approach, and specific methods considered when designing and conducting a landscape connectivity study. This exercise has captured a reasonably clear picture of the nuances of landscape connectivity analysis itself. However, my intent for this thesis is to link connectivity analysis methods to systematic conservation planning in urban/peri-urban contexts. With this in mind, the final section of my literature review deals with spatial decision support systems (SDSS), and how they have been implemented in the literature to apply connectivity data to systematic conservation planning.

As discussed briefly in Chapter 1, SDSS are systems that use spatial data, GIS, and decision models to systematically solve problems by evaluating solution alternatives and trade-offs (Keenan & Jankowski, 2018). The use of such systems’ clearly-defined problem-solving methods is highly valuable to a variety of fields, such as planning service coverage for mobile phones, expanding transit systems, or selecting optimal sites for new buildings (Keenan & Jankowski, 2018).

The field of SDSS is highly diverse, and the definition of what counts as SDSS has been a highly debated topic (Sugumaran & DeGroote, 2011; Keenan & Jankowski, 2018). Because the primary focus of my thesis is on landscape connectivity analysis, a full account of the debates within the SDSS field is beyond the scope of this research. Instead, I have drawn from Sugumaran & DeGroote’s “Spatial Decision Support Systems” (2011) textbook to define the list of possible SDSS approaches used in my data extraction form. This also assisted me in my definition of possible SDSS goals, and software tools used within connectivity papers. In the following sections, I define and explain SDSS approaches and tools used within the reviewed connectivity analysis literature, then discuss how SDSS may be used to apply connectivity data to conservation planning.

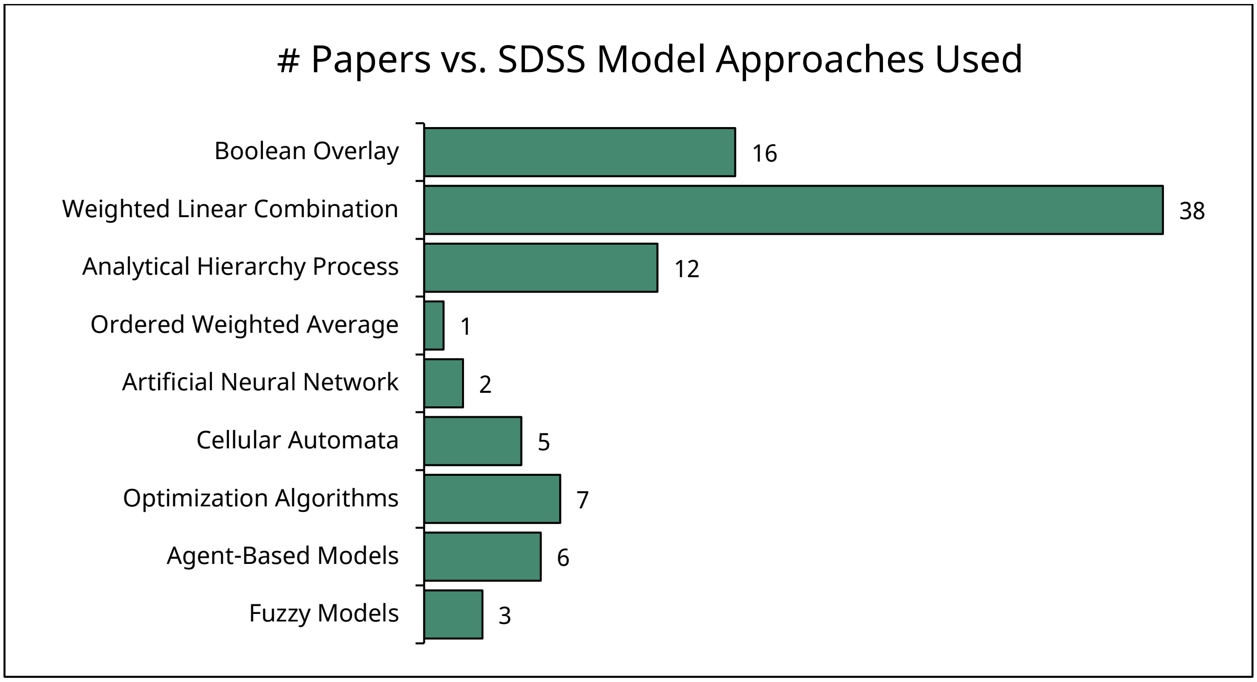
2.5.1 Organization of SDSS

Overall, SDSS was used in 54% of the 116 reviewed papers. To organize and report on the categorization of SDSS in my literature review, I refer regularly to Chapter 4.3 of Sugumaran & DeGroote (2011), titled “Modeling Techniques in SDSS” (p. 146-166). The “modeling technique” portion of an SDSS provides the framework for the analysis itself, which is combined with input data and GIS to provide spatially-relevant solutions (Sugumaran & DeGroote, 2011). These modelling techniques may be grouped in a variety of ways – Sugumaran & DeGroote choose to separate them into “generic” and “application-specific” approaches, based on how tailored they are to solving a specific problem. However, the application-specific models presented in the chapter are industry examples, none of which are representative of the literature that I reviewed. Therefore, I structured my review around the nine “generic” SDSS modeling techniques, calling them “SDSS Approaches”, and modified them slightly to better fit my data. These nine approaches are: (1) Boolean Overlay, (2) Weighted Linear Combination, (3) Analytical Hierarchy Process, (4) Ordered Weighted Average, (5) Artificial Neural Networks, (6) Cellular Automata, (7) Optimization Algorithms, (8) Agent-Based Models, and (9) Fuzzy Models. The proportional use of these nine approaches are included in Figure 10 below.

In the following sections, I briefly describe each SDSS approach and provide occasional examples of how these may be used for connectivity analysis studies within the literature review, including examples of SDSS software tailored toward supporting connectivity-related decision-making.

Figure 10

Breakdown of Spatial Decision Support (SDSS) Models Used Across Reviewed Literature.



2.5.2 Boolean & Weighted Overlay Analyses

Perhaps one of the simplest and most common forms of SDSS is the use of overlay logic within GIS software. These techniques typically use multiple data rasters and a systematic overlay procedure to produce a composite raster that answers a question or shows locations which meet multiple criteria (Sugumaran & DeGroote, 2011). The overlay techniques considered for this review include Boolean overlay, Weighted Linear Combination, and Ordered Weighted Average.

Boolean overlays, in the simplest terms, apply Boolean logic to multiple sets of raster data. For example, three rasters, one containing road data, another containing species occurrence data, and a precipitation model, may be overlaid following the Boolean logic “ideal patch must be >200m from road AND have frogs present AND receive >900mm rain per year”. This method is fairly easy to execute and interpret, but the binary boundaries that it creates may not reflect on-the-ground reality (Sugumaran & DeGroote, 2011).

The Weighted Linear Combination (WLC) method attempts to solve this problem by allowing for continuous scoring instead of binary. As described by Sugumaran & DeGroote (2011), the steps include "(1) define evaluation criteria / map layers, (2) standardize criterion map layers, (3) define criterion weights, (4) construct the weighted standardized map layers, (5) generate an overall score by adding the weighted standardized map layers, and (6) rank the alternatives based on the scores" (p. 149-150). This is, by far, the most commonly used spatial decision support method across reviewed literature, with 41% of papers that use SDSS choosing WLC. A Canadian example of this method being used for connectivity analysis and site selection is Choquette et al. (2020), wherein the WLC method is combined with the functional connectivity tool "Corridor Designer" to develop a multi-criteria site selection method for the Massasauga Rattlesnake. The authors assess habitat size, distance from roads, and land cover types in combination with expert opinion and literature review to apply suitability scores across a landscape raster. This suitability is inverted to create a cost surface, which is then input to Corridor Designer to prioritize functional corridors that may benefit the at-risk reptile (Choquette et al., 2020).

The Ordered Weighted Average (OWA) approach takes the concept of weighted importance even further, and applies two different types of weights – general, all-encompassing importance weights identical to the WLC method, and "order weights" which specify the importance of weight criteria in relation to each other. For example, if the importance of creeks changes based on the creek's proximity to slopes, this can be accounted for by the OWA (Sugumaran & DeGroote, 2011; Ferretti & Pomarico, 2013).

The WLC and OWA options contain more subtlety than the Boolean overlay because they create continuous rasters of suitability rather than discrete areas for analysis. However, weighted overlays have been criticized for their lack of standardization and oversight in the assignment of weights (Sugumaran & DeGroote, 2011).

2.5.3 Analytical Hierarchy Process

In order to standardize the assignment of weights to decision-support systems, analytical hierarchy process (AHP) systems may be utilized. AHP is a specific methodology developed in the 1980s, which systematically determines relative importance of each criterion through pairwise comparison (Saaty, 1987). Rather than a researcher performing WLC and judging appropriate weighting based on their own research, the AHP method necessitates iterative pairwise comparison to determine relative weights between each criterion (Department for Communities and Local Government, 2009). Ideally, this should be done by multiple decision-makers independently, and then consistency between the comparison matrices is checked before the relative weights are aggregated (Sugumaran & DeGroote, 2011). For example, in a recent Chinese study identifying sites for a green infrastructure network, Liu et al. (2022) defined the resistance surface for their connectivity model using an AHP approach applied to 30 experts' questionnaire responses regarding the relative weight coefficient for land use type, topography, and human activity. This ensured objectivity in the allocation of resistance weights.

2.5.4 Geo-computation & Artificial Intelligence

In addition to the approaches considered above, there are several SDSS approaches which make use of either the geo-computation abilities of modern geospatial software or the novel rise of artificial intelligence to support decisions in land use planning.

Artificial Neural Networks (ANN) model complex relationships through an adaptive learning process meant to simulate the human brain and identify relationships between individual datasets (Sugumaran & DeGroote, 2011). While powerful, the logic leading to conclusions in ANN is not necessarily clear (functioning as a "black box"), and prevents full accountability for the decisions being made (Sugumaran & DeGroote, 2011). This may explain its relative lack of use in connectivity research (as shown previously in Figure 10).

Cellular Automata (CA) are dynamic system models. They operate on a grid of cells whose discrete values change over time based on neighbourhood cell relationships (i.e., a cell may change from “no forest” to “forest” over time based on neighbouring forest cells) (Sugumaran & DeGroote, 2011). In literature reviewed, CA are generally used for predicting changes in land use and the effects on connectivity. For example, a study by Perkl et al. (2018) uses CA to examine how urban growth predictions threaten different scenarios of habitat connectivity protection.

The term “Optimization Algorithm” is used in this review to denote modeling techniques that harness algorithms and AI to create an optimal scenario for some purpose. Examples of these include the “low-degree-first” algorithm, genetic algorithms, and the PEST model. A full discussion of these methods is beyond the scope of my thesis.

Agent-based Models are also an AI-based approach, in which agents (i.e., simulated research objects with pre-defined behaviour rules) act autonomously within a digital environment possibly containing other agents (Sugumaran & DeGroote, 2011). Agent-based models are particularly useful for collaborative land use planning, such as a study by Sahraoui et al. (2021) which utilizes multi-agent Companion Modelling to involve stakeholders in a participatory resource planning exercise. While relatively work-intensive, this process allows for predictive insights from local policy makers to influence different scenarios within the models, improving communication and governance outcomes (Sahraoui et al., 2021).

2.5.5 Fuzzy Modeling

Finally, fuzzy models attempt to account for the complexity and “fuzziness” of the real world by allowing for objects to partially fall into one or multiple categories (represented on a scale of 0 to 1), rather than being classified in a discrete way (Sugumaran & DeGroote, 2011). For example, a transition from grassland to forest is not necessarily a discrete line as may be seen on a map – rather, there may be transition vegetation on the boundary, which falls partially into both categories. Fuzzy models can be applied to various SDSS approaches (such as WLC, AHP, or geo-computation / AI models) to represent spatial values more accurately. For example, Pyke (2005) uses fuzzy logic to prioritize lands for conservation based on their suitability as habitat for the California Tiger Salamander. The ranking framework effectively integrates complex and often disparate considerations in a transparent way, allowing for later comparison or repetition of this research.

2.5.6 Overall Application of SDSS & Connectivity Analysis

Across the landscape connectivity literature reviewed, 63 articles (or 54%) use SDSS of some kind. Of these, there are several problems that the SDSS was applied to solve. I categorized these possible problems into five general categories:

- **Biological Investigation:** Study uses connectivity data to implement spatial decision-making that optimizes for the preferences or characteristics of a biological object of study (e.g., wildlife, seed dispersal).
- **Method Comparison:** Study aims to systematically compare multiple methods of connectivity analysis to determine which is more effective for a particular context.
- **Land Use Cover Change (LUCC) Evaluation:** Study uses connectivity data to evaluate a temporal change in land use / land cover (sometimes with predictive modelling), which is used to recommend strategies that achieve positive outcomes.
- **Site Selection:** Study provides recommendations for the location of a landscape feature based on the use of connectivity data and SDSS (e.g., conservation land acquisition).
- **Network Creation:** Study combines SDSS and connectivity analysis to produce a fully-designed network of greenspace or protected habitat, such as ecological security patterns in China (Li et al., 2022a).

Figure 11

Five Major Applications of Connectivity to SDSS Across Reviewed Literature.

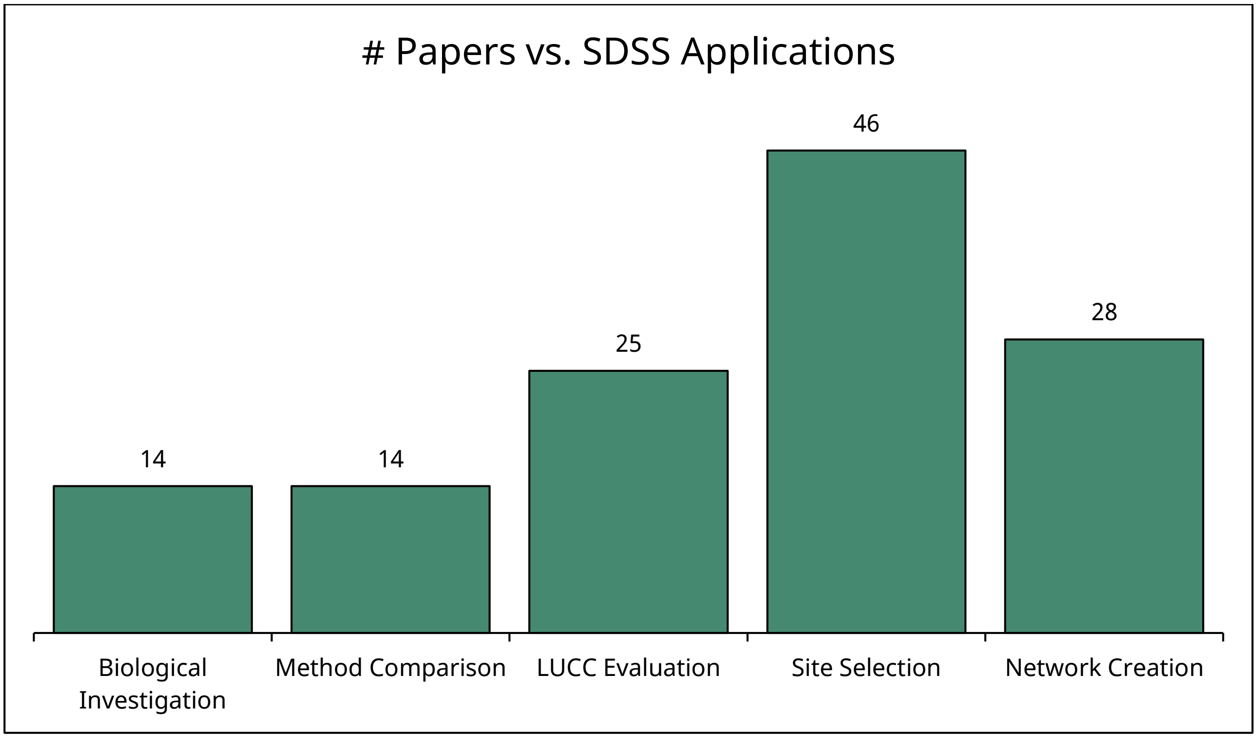


Figure 11 illustrates the spread of analysis problems considered across the 63 SDSS papers. Site Selection is the most common problem type that SDSS is applied to solve, but the five analysis problems frequently co-occur. Only 27% of the SDSS papers approach a singular problem above, whereas 51% of the papers tackle two and the remaining 22% consider three or more.

As demonstrated in the sub-sections above, SDSS is as diverse as connectivity analysis, in both its breadth of possible approaches and its applications in solving real-world problems. These sections are intended to serve as an educational platform from which the reader may further inform themselves on the strengths, weaknesses, and applications of various spatial decision support tools. However, they do not provide specific recommendations as to the optimal choice for the user, as such choices will depend on a variety of considerations.

2.6 Literature Review Takeaways

The objective of this systematic literature review is to produce a comprehensive and organized account of what connectivity analysis methods are being used within urban/peri-urban environments. As demonstrated in the previous sections, the field of landscape connectivity analysis is incredibly diverse, with seemingly infinite possible combinations of theories, approaches, software tools, and output metrics. This observation reflects previous authors' sentiments on the subject – four key challenges have been outlined by other connectivity reviews which bear discussion here:

1. Overwhelming diversity of approaches (Rayfield et al., 2011; Correa Ayram et al., 2016),
2. Lack of clarity in definition and application of terms (Tischendorf & Fahrig, 2000; Rayfield et al., 2011; LaPoint et al., 2015),
3. Inconsistent application of methods (Tischendorf & Fahrig, 2000; Rayfield et al., 2011; LaPoint et al., 2015), and
4. Absence of selection guidelines for practitioners (Rayfield et al., 2011).

In the following sections, I connect these challenges to the literature I reviewed, first discussing the tug-of-war between diversity and clarity/consistency, then reflecting on the need for selection guidelines that assist organizations assessing landscape connectivity.

2.6.1 Diversity vs. Clarity & Consistency

The rapidly increasing publication of connectivity studies has been consistently reported across reviews (Rayfield et al., 2011; LaPoint et al., 2015; Correa Ayram et al., 2016), and is further reflected in my own research (as previously shown in Figure 3). Alongside this general increase in connectivity articles has been what Rayfield et al. call an "explosive proliferation" of connectivity measures (2011, p. 847). With so many emerging ways to conduct connectivity analysis, inconsistencies around the definition of key terms and the application of key methods have become a nearly inseparable part of this field (Tischendorf & Fahrig, 2000; Rayfield et al., 2011; LaPoint et al., 2015).

To combat this, there are several examples of reviewers and researchers attempting to create clear definitions, frameworks, and divisions between concepts within published journal articles, including Calabrese & Fagan's "A Comparison-Shopper's Guide to Connectivity Metrics" (2004) and Rayfield et al.'s "Connectivity for Conservation: A framework to classify network measures" (2011). However, the rapid development and diversification of the landscape connectivity field leads to these previous frameworks of classification quickly becoming outdated. As an example, Calabrese & Fagan's six-category guide separates "Nearest Neighbour" from "Spatial Pattern Indices", but lumps all graph-theoretic approaches under a single category (2004, p. 532). This may have been useful at the time, but graph theory has since exploded in its diversity. In my own review of urban/peri-urban connectivity literature, "Nearest Neighbour" is used in 3% of the papers, "Spatial Pattern Indices" (including nearest neighbour, which is grouped within SPI for my review) are observed in 20%, and graph-theoretic approaches (including circuit theory) are used in 86% of the literature (or 100 of the 116 papers). Based on the evolution and relative use of graph theory in recent literature, Calabrese & Fagan's system of classification has become unbalanced and less helpful.

Rather than relying on the scattered publication of academic journal articles to provide clarity and consistency to the application of landscape connectivity concepts, a more centralized authority on the subject with a public-facing platform and flexibility to update regularly would be incredibly useful for further development of the field.

An excellent resource in this regard is the Conservation Corridor website, developed by the Connectivity Conservation Specialist Group (CCSG) under the International Union for the Conservation of Nature (IUCN) (CCSG, n.d.-a). Beyond providing a digital hub for partners with various academic, non-profit, government, and business institutions to improve connectivity on the natural landscape, the website features a "Connectivity Toolbox" page which functions as a guide, explaining common connectivity tools, approaches, and practices in relatively plain language (CCSG, n.d.-b). This is a phenomenal step in the right direction. Support for this organizations' dissemination of ideas as a centralized authority and expansion to consider urban/peri-urban contexts specifically would likely improve connectivity understanding across the field.

2.6.2 Selection Guidelines

Beyond calling for improved definition and application of concepts, Rayfield et al. (2011) points out the lack of method selection guidelines for practitioners conducting landscape connectivity analysis on the ground. Whether it is for landscape connectivity analysis, systematic conservation planning frameworks, or the SDSS that may link the two, the methodological choices made by analysts will depend on the unique context of the project at hand. With so many options to choose from, understanding the most optimal connectivity analysis approach for a given context and situation is a difficult task.

In section 2.2.2, I note five main organization types that contributed to my sample of urban/peri-urban connectivity analysis literature: universities (86%), research institutes (7%), government (3%), private sector (3%), and a single non-profit article. To determine if selection guidelines could be gleaned from the available literature, I filtered my review results by organization and searched for trends, goals, and preferred methods (see Table 6 for a summary of information gathered).

It should be noted that the low number of papers from non-university sources may skew these observations. Within university articles, all recorded analysis problems, types of connectivity, analytic approaches, validation strategies, field data collection methods, GIS platforms, connectivity outputs, and SDSS methods are represented. Since the relative number of articles separates the "university" perspective from the other four organization types, this general diversity and broad utilization of goals, methods, and approaches across university articles has been treated as the "standard" against which all other organizational contexts could be compared.

Table 6

Notable trends in connectivity analysis approaches across organization types.

	University	Research Institute	Government	Private Sector	Non-Profit
Priorities & Analysis Problems	Generally balanced/diverse.	Generation of data about wildlife and ecosystems.	Site selection & LUCC evaluation.	Site selection & LUCC evaluation.	n/a
	All priorities and problems considered.	Method comparison, network creation, LUCC evaluation.	High concern about planning impacts & conservation for biota.	Similar to government in planning & conservation concerns.	Single study focused on site selection for wildlife preservation.
	n/a	Low interest in site selection problems.	Low interest in wildlife data & method comparison.	No interest in wildlife data & method comparison.	n/a
Use of Validation Strategies	Mostly literature review, some use of expert opinion & field data.	*	*	No field data or expert opinion, only literature review.	Study uses all three validation strategies.
Field Data Collection	Mostly land use and species observation, low levels of intensive field work.	Much higher levels of intensive field work (i.e., radio telemetry & genetic data).	*	No field work.	Study uses species observation.
Software Used	All GIS (primarily ArcGIS) and nearly all connectivity tools represented.	Use ArcGIS and QGIS; Circuitscape used in half of studies, several other tools represented.	Use either ArcGIS (¾) or R software (¼); one study uses Circuitscape, no other connectivity tools reported.	ArcGIS used across studies; R Software, Corridor Designer, Graphab, and MaxEnt also utilized.	Study used ArcGIS and Corridor Designer.
Outputs Produced	All possible outputs (>30) represented.	11 outputs represented; mostly popular GNT metrics, a few SPI & CT.	1 study uses Current Density (CT), 1 uses CONNECT index (SPI), 2 use GNT metrics.	Only popular GNT metrics used.	Study used Least Cost Analysis (most popular GNT metric).
SDSS?	~50%	*	*	100%	100%
SDSS Models Applied	All models applied, WLC most common.	Boolean Overlay, WLC, and AHP.	Only WLC.	WLC, Optimization Algorithm, & Cellular Automata.	Only WLC.

(green = top priority; yellow = notable considerations; pink = low/no priority); *denotes similar to university.

Based on the information in the table above, some trends can be gleaned. First, it seems that, while universities have a fairly even distribution of goals and problems to focus on, research institutes skew toward the collection of biological data. Conversely, government and the private sector tend to focus on planning impacts and site selection. The single non-profit study connects biology and planning, pairing wildlife data with a site selection strategy for corridor creation (Choquette et al., 2020). These different sets of priorities are reflective of what Ann Forsyth calls “cultures of planning”. While research institutes aim for a culture of “scientific frontiers” (aiming to generate new theories and add to the body of knowledge), private companies and governments seem more focused on “practical applications” (considering the usefulness of knowledge for practice, and evaluating on-the-ground effects of decisions already made). The single non-profit study seems to pair these two cultures, while the university studies demonstrate a broad diversity, expanding beyond these to include other planning cultures as well (2012, p. 163-164).

The methods applied by each organization can produce some insights as well. Universities and research institutes seem to have the most resources and technical expertise, with a high relative diversity of validation strategies, field work techniques, software used, outputs produced, and SDSS models utilized. Based on the literature reviewed, research institutes seem to rely more on intensive field work (i.e., radio tracking, genetic data collection) than other organizations. Outside of these research-focused institutions, the profile of connectivity methodology shows limitations.

The government studies of connectivity demonstrate similar validation and fieldwork preferences to universities, including use of expert opinion, literature review, land use ground-truthing and species observation. Use of ArcGIS is common in the government studies, and there seems to be a preference for connectivity analyses and SDSS models based entirely in ArcGIS (or R Software), rather than standalone connectivity and SDSS tools. This may indicate a reluctance to train staff on the use of new software when methods can be found within existing tools. In contrast, the reviewed connectivity studies from the private sector demonstrate a proportionally broad use of software tools, including ArcGIS, R, Corridor Designer, Graphab, and MaxEnt. These studies also use more technical SDSS models such as optimization algorithms and cellular automata. This may indicate an embrace of technical solutions for connectivity modelling to avoid the need for field work (which was not reported by the private sector studies).

There is only a single study reported by a non-profit within my literature review (Choquette et al., 2020), whose methods reflect similar validation strategies to universities. The choice of software (ArcGIS & Corridor Designer), output (Least Cost Analysis), and SDSS model (WLC) for this study generally indicate a preference for well-established methods which are relatively simple in their execution. Of the connectivity software tools reviewed in this chapter, Corridor Designer stood out for its use of simple lay-person language and a highly supportive, educational website (CorridorDesign, n.d.).

Ultimately, these reflections on organizational preferences across the academic literature must be interpreted with caution due to the comparatively small number of non-university articles. The sample size of <10 papers by research institutes, governments, private companies, and non-profits may obscure urban/peri-urban connectivity trends in these organizations.

One possibly misleading assumption is the ubiquitous use of ArcGIS. While ESRI products lead the market and are reportedly used widely by all organization types (ESRI, n.d.-a), the marketing database “Enlyft” reports that QGIS is often preferred by small companies, especially by those with <50 employees and <$10 million in revenue (Enlyft, n.d.). Assuming that ArcGIS is optimal for all contexts risks limiting guidelines to only companies that can either afford it or qualify for fee exemptions, which would exclude companies that must rely on open-source technologies like QGIS.

This exercise shows that connectivity analysis selection guidelines based purely on published academic literature (while valuable) have limits. While organizations may be actively analyzing connectivity, record of these endeavours may not be published in an exclusive peer-reviewed context, and reliance on academy-based observations risks obscuring the on-the-ground needs of governments, private companies, and non-profits.

With this in mind, my thesis aims to pair the theoretic conclusions gathered from the literature with practice-based observations and stakeholder consultation gathered in a case study.

In Chapter 3, I demonstrate the consideration and selection of connectivity analysis methodology within the context of a non-profit land trust. This includes reflections on the organizational needs that surface throughout the case study, the efficacy of the methods chosen, and the usefulness of the final output created for the benefit of the non-profit organization. Then, in Chapter 4, I reflect on both this literature review and case study to provide more targeted guidelines for the selection of urban/peri-urban connectivity analysis methods across organizational contexts.

Chapter 3: Case Study

As has been discussed in the previous chapters, landscape connectivity analysis for systematic conservation planning is a diverse field with several possible approaches and tools available. The choice of methods will depend significantly on the local context, the conservation objectives, and the organizations’ technical capacity. Because of this, it is difficult to provide broad recommendations for conservation planners interested in conducting connectivity analysis.

To demonstrate the use of connectivity analysis for systematic conservation planning in a tangible and instructive way, I have supplemented my thesis with a case study based in the urban/peri-urban regions of Southern Ontario. While Chapter 2 provides a strong theoretical foundation, this case study allows for the practical application of this knowledge. Over the course of this thesis, I have been fortunate to work with the **rare** Charitable Research Reserve as a case study partner.

In the following sections of Chapter 3, I first provide background on **rare**, their mission, and their study area of Waterloo Region and Wellington County. Next, I specify my case study objectives, detail my materials and methods, and report on the results of my connectivity analysis. Finally, I discuss the relevance of my results, both to **rare**, and to urban/peri-urban conservation planners in general.

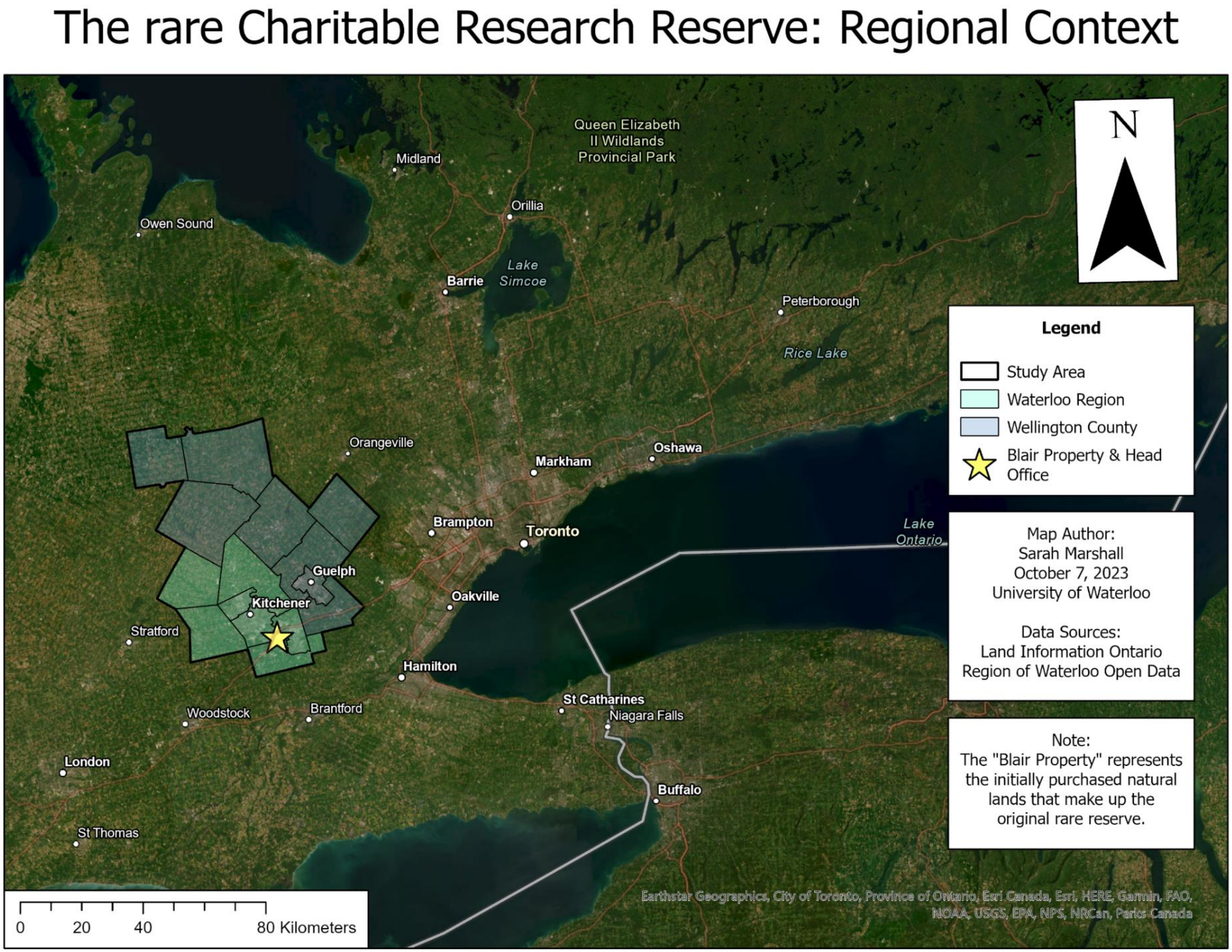
3.1 Background

3.1.1 The rare Charitable Research Reserve

The **rare** Charitable Research Reserve is an urban land trust and environmental institute which stewards over 1,200 acres of land across eight properties in Waterloo Region and Wellington County (see Figure 12). These two geographic areas fall within Southern Ontario’s “crisis ecoregions” mentioned in Chapter 1. This organization works with community members to protect sensitive lands, manage over 14 kilometers of public nature trails, and act as a pillar of environmental research and education (**rare**, 2023).

Figure 12

Map Providing the Geographic Location and Regional Context for the rare Charitable Research Reserve.



Map Author:
Sarah Marshall
October 7, 2023
University of Waterloo

Data Sources:
Land Information Ontario
Region of Waterloo Open Data

Note:
The "Blair Property" represents the initially purchased natural lands that make up the original rare reserve.

Earthstar Geographics, City of Toronto, Province of Ontario, Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, NRCan, Parks Canada

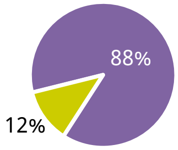
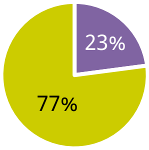
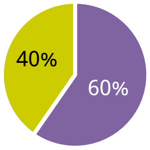
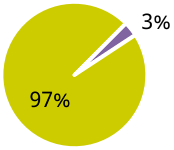
The diversity of species and habitats that **rare** stewards is remarkable and provides an exceptional backdrop for the recreation, conservation, research, and education work that the institute supports.

3.1.2 The rare Study Area

The official study area of the **rare** Charitable Research Reserve is made up of Waterloo Region and Wellington County, including the City of Guelph (which is technically a separate single-tier municipality, but is treated as part of Wellington County for this case study). Together, these two jurisdictions encompass just over 4,000 square kilometres. Some general demographic and land use information for Waterloo Region and Wellington County are included in Table 7 below.

Table 7

General Demographic Data for Waterloo Region and Wellington County.

Demographics (2021)	Total Pop.	Land Area (km^2)	Pop. Density	Urban/Rural Pop.*	Urban/Rural Land Area*
Waterloo Region	587,165	1,370	428.6 / km^2		
Wellington County	241,026	2,665	90.4 / km^2		

*Urban = purple, Rural = yellow. (Statistics Canada, 2023)

The **rare** study area straddles two ecoregions: Lake Simcoe-Rideau (6E) and Lake Erie-Lake Ontario (7E) (Crins et al., 2009). A guide produced by the Ontario Ministry of Natural Resources and Forestry (OMNRF) describes 6E as mild, moist, and over 57% agricultural with diverse natural areas, including hardwood forests, wetlands, and alvars. Similarly, 7E boasts one of the mildest climates in Canada, which is taken advantage of by its approximately 78% agricultural land (Crins et al., 2009); It is also the most urbanized ecoregion in Ontario, with urban areas and roads encompassing another 7%. Though 7E is highly biodiverse, supporting rare Carolinian forest ecosystems, oak savannahs, and tallgrass prairies, the amount of habitat loss and fragmentation has led this ecoregion to be characterized as the “most imperiled in Canada” (Crins et al., 2009).

3.1.3 The raresites Committee & Land Securement Strategy

In October 2016, the **raresites** Land Securement Committee was formed. This committee brings together the diverse voices of approximately 10-15 naturalists, researchers, Indigenous leaders, and representatives of local/regional government interested in expanding the scale of conservation by **rare** (**rare**, n.d.). The **raresites** committee works together to identify appropriate conservation lands for protection, and then facilitate land securement. This may be done by **rare’s** purchase of a property, property donation or transfer to **rare,** and/or creation of a conservation easement agreement (**rare**, 2018).

The committee published the 2018 Land Securement Strategy (LSS) to serve as a “guideline as to where, why, and how **rare** secures land” (p. 8). In the 2018 LSS, potential conservation lands are graded using the “**rare** score” multi-criteria analysis system. Individual property parcels are remotely evaluated based on geospatial data and air photo interpretation, and provided with points for fulfilling a set of desirable criteria (**rare**, 2018). Property parcels are considered desirable if:

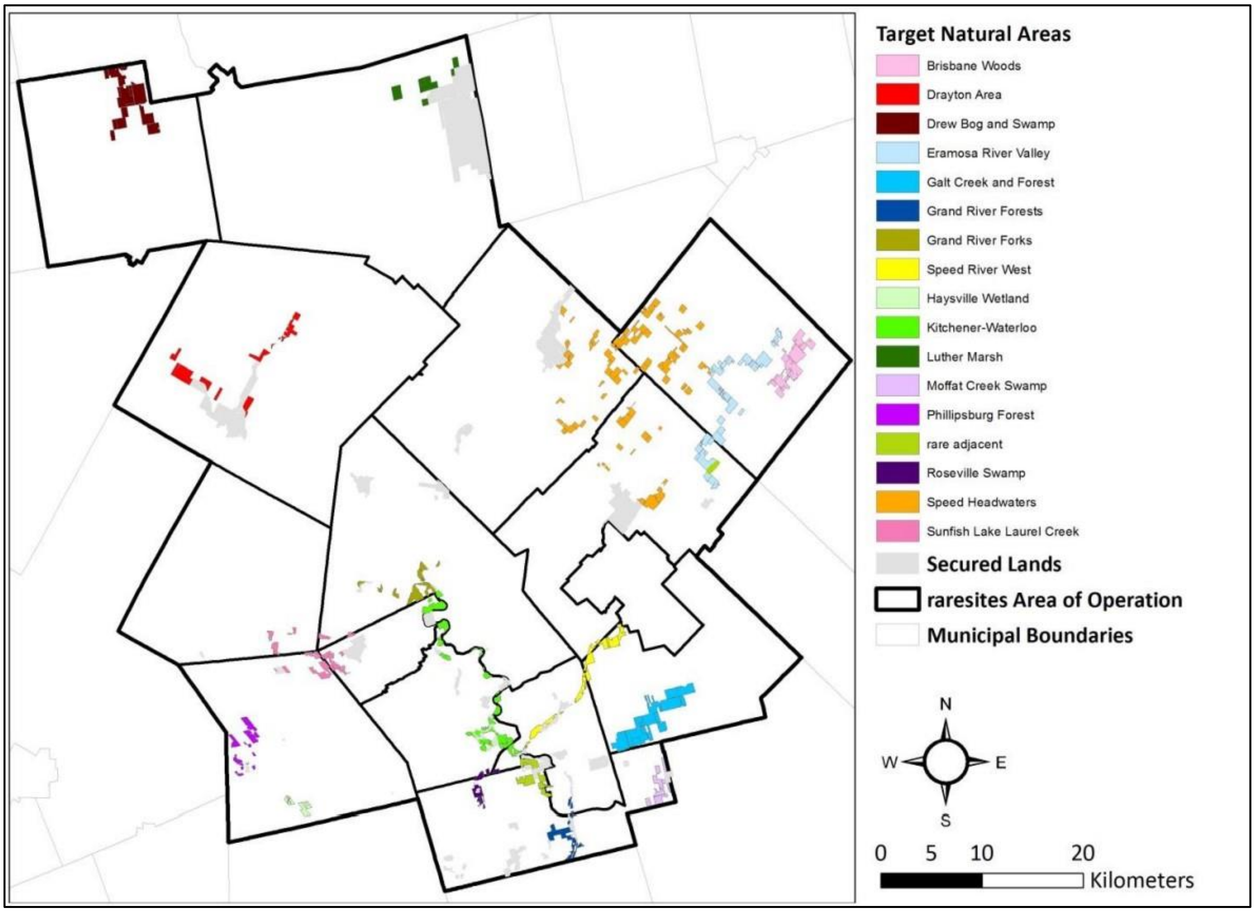
1. They are adjacent to currently owned or soon-to-be-secured **rare** properties.
2. They are adjacent to and/or contain features of protected areas and desirable conservation lands, such as:
    a. Parks,
    b. Conservation Areas,
    c. Provincially Significant Wetlands (PSWs),
    d. Areas of Natural & Scientific Interest (ANSIs), and
    e. the Region of Waterloo Greenlands Network.
3. They provide opportunities for restoration/rehabilitation research.

4. Their protection or restoration could mitigate stress to existing **rare** landscape features (e.g., through buffer mechanisms) (p. 79).

To reduce the list of properties that meet these initial criteria and permit landowner outreach, additional filtering criteria are used (**rare**, 2018). Properties are prioritized based on their likelihood of acquisition by other conservation organizations, their threatened status concerning areas likely to be developed, and their proximity or adjacency to other desirable properties. Finally, to ensure equal geographic dispersion across the study area, the LSS establishes 17 “target areas”, within which 365 properties are delineated as top priority for securement. The strategy of organizing priorities within “target areas” aims to ensure that there are priority conservation targets in every regional municipality. The conservation target areas and properties initially selected for the 2018 LSS are shown in Figure 13 below.

Figure 13

Map of 17 Target Areas Used in ***rare****'s 2018 Land Securement Strategy (****rare,*** *2018).*



The **rare** LSS is currently approaching five years of use and is due for major revisions, with a new document expected to be released in 2024. After five years in practice, this policy document has been tested thoroughly and strengths and weaknesses have emerged. For example, **raresites** members have suggested that prioritizing by municipal dispersion could risk ignoring key habitat patches for connectivity if they do not fit within the “correct” administrative area.

To improve the ecological grounding of their scoring system, the **raresites** committee is looking for a way to incorporate landscape connectivity analysis into their 2024 LSS revisions. In particular, the committee has expressed an interest in the measurement of multi-species connectivity, through a model that can account for the habitat preferences, movement, and dispersal patterns of a diversity of species in the study area.

As discussed in Chapter 1, the context of Southern Ontario in 2023 emphasizes the need to plan conservation as transparently and efficiently as possible. Therefore, this revision is an excellent opportunity to incorporate novel perspectives from the literature and present thoughtful recommendations for conservation prioritization in Waterloo Region and Wellington County.

3.2 Study Objective

Without a local context and a practical application of landscape connectivity, the knowledge created through my literature review remains theoretical. My vision for this case study is to use the knowledge collected in Chapter 2 to inform the selection of connectivity analysis methods which will support systematic conservation planning. The particular practical context I have chosen is that of a non-profit regional land trust interested in using connectivity analysis to support site selection in their conservation planning process. By applying theoretical knowledge to a specific and local context, this endeavour should generate both pragmatic benefit for my organizational partner and experience-based advice for conservation planners in general.

With the input of the **raresites** committee, I have tailored this case study toward the perceived needs of the revised LSS. My objective is to produce quantitative landscape connectivity scores for natural habitats in Waterloo Region and Wellington County, which can be used in concert with the existing criteria of the “**rare** scores” system. In addition to this objective, I have established two guiding principles for the methodological decisions made throughout this study:

1. As much as possible, methodological choices should draw from the wealth of study data already collected and analyzed during the systematic literature review.

2. Methodological choices must prioritize the feasibility of continued use of chosen models by the **raresites** team upon the conclusion of this research. Considerations include technical complexity, data availability, and software requirements.

Using this framework, the connectivity data produced by this case study should both validate the usefulness of the work conducted for my literature review, and help to support **rare's** future conservation efforts. This research may also benefit other conservation planners working in a regional, urban/peri-urban context.

3.3 Methodology

In Chapter 2, I represent the choices made throughout a connectivity study as a clear process broken into ordered sections. First local context is considered (institutional, spatial, etc.), then general approach, specific methods, and finally the optional use of SDSS. While this is a helpful hierarchy for the extraction of data from a large bulk of literature, in reality my choice of methods required more iteration and flexibility. Based on the need to prioritize feasibility for use by practitioners, I began by establishing the connectivity software tool, which could function as a bottleneck for replicability if not accessible to conservation practitioners in various contexts.

3.3.1 Software Tool & Index Selection

In the literature reviewed in Chapter 2, there are a total of 28 connectivity-focused software tools. To reduce the number of tools for consideration in this case study, I formed a set of informal filtering criteria. These criteria were based partially on consultation with **rare**, with an understanding that this connectivity analysis procedure will need to be explained to the committee and passed on to the **rare** Planning Ecologist for later use and adaptation. I also referred to the organizational considerations detailed in section 2.6, aiming for a tool that could maximize compatibility with all sorts of scenarios, software, and resource limitations. These criteria are detailed in Table 8 below.

Table 8

Elimination Process to Choose Case Study Software Tool

Reason for Removal	# Tools Removed	# Tools Remaining	Specific Tools Removed
Unable to find or access tool	3	25	CHLOE; FunConn; GeogDetector
Tool is outdated, or only works with outdated GIS	2	23	PathMatrix; Q-Rule
Tool is based in R software and requires command-line analysis	5	18	R-Studio; gdistance; grainscape; landscapemetrics; resistanceGA
Tool is only used 1x in literature review (limiting examples to draw from)	8	10	BEETLE; CAT; GeoHAT; LSCorridors; MatrixGreen; Omniscape; Pajek; UNICOR
Technical complexity is too high	4	6	Depthmap; Guidos; MaxEnt; PANDORA
No flexibility between using ArcGIS or an open source alternative	2	4	Corridor Designer; Linkage Mapper
Reliant on Java, which has new licensing requirements that may limit usability*	1	3	Graphab
Incapable of multi-species connectivity measurement and importance ranking	1	2	Fragstats
Tools Remaining = Conefor & Circuitscape			

*(Oracle, 2019)

Between the two options produced by the filtering process above, the graph-based tool Conefor (Saura & Torné, 2009) was deemed the most appropriate for the needs of **rare.** Conefor is the most widely used connectivity tool across my literature review, and frequently features studies that included site selection strategies. In addition, the tool is capable of measuring either structural or functional connectivity (see section 3.4.4), has flexible data requirements, and its “habitat availability indices” (Saura & Pascual-Hortal, 2007a; p. 7) are relatively simple to explain compared to tools rooted in circuit theory, like Circuitscape. Because Conefor’s indices received positive feedback from **rare** staff during evaluation meetings, this tool was determined to be the best choice. The delta of the Probability of Connectivity index (dPC) was noted as Conefor's best-performing index for establishing patch importance to connectivity (Saura & Pascual-Hortal, 2007a; 2007b), and was thus chosen as the study output.

The PC index is a probability-based habitat availability index rooted in graph theory, which ranges from 0 to 1 (higher scores representing improved connectivity). This is a landscape-level index, measuring connectivity for an entire study area. It is defined as "the probability that two animals randomly placed within the landscape fall into habitat areas that are reachable from each other" (Saura & Pascual-Hortal, 2007b, p.93), and is calculated as follows:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j p_{ij}^{*}}{A_L^2} \tag{1}$$

Where n represents the total number of habitat patches (or nodes, as described in section 2.3.3), a_i *and* a_j represent the areas of habitat patches *i* and *j,* A_L is the total landscape area (i.e., the region being studied, including both habitat and non-habitat), and $p*_{ij}$ is the maximum product probability of all possible paths between patches *i* and *j*, including direct paths and multiple-step paths through other patches (Saura & Pascual-Hortal, 2007b, p.93). The $p*_{ij}$ value is a negative exponential function of interpatch distance, defined by the distance between patches and the median dispersal distance (set to 0.5 probability) which is input to the model. The PC index can be calculated multiple times, varying the dispersal distance, to produce a range of connectivity scores based on different species' mobility.

To measure the importance of individual habitat patches within a landscape, Conefor calculates the delta PC index (dPC), which is a ranking of connectivity importance based on the change in overall landscape connectivity caused by the removal or addition of a given patch. The dPC value is given by:

$$dPC(\%) = \frac{PC - PC\prime}{PC} * 100 \tag{2}$$

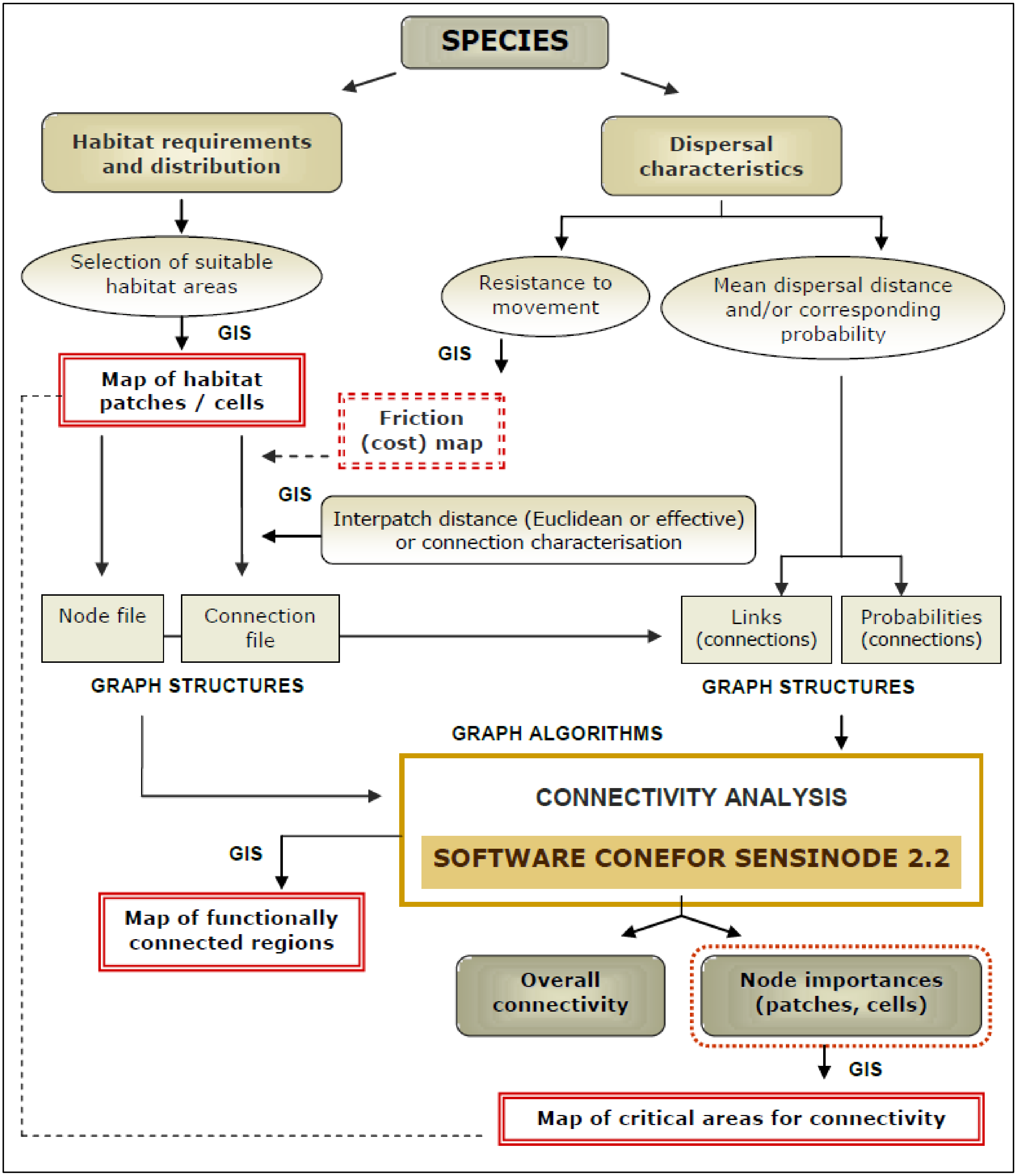
Where PC’ is the overall PC index value after removal of the patch in question (Saura & Pascual-Hortal, 2007b, p. 92). The framework to calculate the PC and dPC indices within Conefor is illustrated in the Conefor 2.2 manual (Saura & Pascual-Hortal, 2007a), and has been included in Figure 14 on the following page.

As shown below, the production of connectivity scores through Conefor requires (1) the selection of species, (2) selection of suitable habitat areas, (3) the calculation of interpatch distance (structural/Euclidean or functional/effective) between habitat patches, and (4) input of a dispersal distance associated with a probability of dispersal for the given species (Saura & Pascual-Hortal, 2007a). Together, these four inputs produce data on the overall connectivity of the landscape (PC), as well as data on the relative importance of each patch to landscape connectivity (dPC).

Thus far, I have established my case study objective, the local context (Waterloo Region and Wellington County), the type of study object (multiple species), and my choice of software tool (Conefor) and connectivity output (dPC). These decisions have also defined my analytic approach (graph theory). In Section 3.4, I detail the specific methods of the study, following the order of the Conefor framework in Figure 14. This includes focal species selection, habitat delineation, interpatch distance calculation, and tool configuration, including dispersal distance choices.

Figure 14

General methodology used by Conefor software. Source: Saura & Pascual-Hortal, 2007a (p.8).



3.4 Methods

3.4.1 Focal Species Selection

As discussed in Section 3.1.3, **rare** has indicated their interest in a connectivity output that reflects the habitat preferences and dispersal characteristics of multiple species found within the study area. To select specific focal species, I drew from the data already collected during the literature review process. First, I filtered the 116 articles from my review to show graph-theory based studies which conduct research into species habitat preferences and dispersal, and are based in North America. I then searched these studies for criteria specific to core habitat delineation, and investigated whether the species of study are known to occur in the **rare** study area. Through this procedure, I found three suitable articles, within which 15 species were deemed suitable and present in the **rare** study area. The focal species used, including information from their reviewed studies, are included in Table 9 below. Detailed information about all fifteen species' habitat preferences, dispersal, and sources of this information can be found in Appendix B.

Table 9

Focal Wildlife Species Chosen for the Case Study

Citation	Study Area	Common Name
Stille et al., 2018	Toronto, ON	Spring peeper
Albert et al., 2017	Montreal, QC	American toad Wood frog Red-back salamander Red-breasted nuthatch American woodcock Pileated woodpecker Barred owl White-tailed deer Snowshoe hare White-footed mouse Northern short-tailed shrew
Lookingbill et al., 2010	D.C., Maryland, Virginia, & West Virginia	Little brown bat Northern long-eared bat Tricolored bat

3.4.2 Land Cover Mapping

To begin, I established a buffer around the Waterloo Region and Wellington County to ensure that edge-effects did not affect the connectivity scores of patches near the outskirts. Based on observation of buffer sizes in other connectivity studies (Beier et al., 2011; Tarabon et al., 2020; Wei et al., 2022), I initially chose to buffer the study area by 20km, resulting in an area of analysis totalling 11,467 km^2.

To produce the land cover map, data was acquired from open source geospatial data sources. The map used as a starting point was the 15m resolution Southern Ontario Land Resource Information System 3.0 (SOLRIS) raster (OMNRF, 2019). This was chosen due to its standardization, regular updates, comprehensive coverage of the study area, and use of Ecological Land Classification (ELC) cover types, which are used widely by environmental practitioners (Lee et al., 1998). However, several weaknesses were identified, and additional geospatial processing was conducted to improve the map.

First, land cover rasters from the Grand River Conservation Authority (GRCA, 2019) and Agriculture and Agri-Food Canada (AAFC, 2022) were used to reclassify "Undifferentiated" land cover cells, reducing them from 34% to 1.6% of the buffered study area. Second, land cover accuracy was improved through the use of vector data produced by the Ontario government, including wetland (OMNRF, 1978), waterbody (OMNRF, 2010), road (OMNRF, 2001), and railway (OMNRF, 2012) data. Third, the base map was evaluated against ArcGIS Pro's "World Imagery" base map layer (ESRI, 2009). For the study area evaluated, image sources within this layer were orthophotos of the City of Guelph (captured by First Base Solutions, 2020) and Maxar's (n.d.) "Vivid Standard" satellite imagery (captured in this area from 2020-2022). These images allowed for the manual reclassification of several new "Urban & Built-up" areas which had been recently developed. Fourth and finally, the land cover map was tidied of stray pixels and inconsistent boundaries, using a protocol recommended by ESRI (n.d.-b). The final land cover classes used for this study are included in Table 10 below, and a map of the resulting land cover raster is provided on the following page (Figure 15).

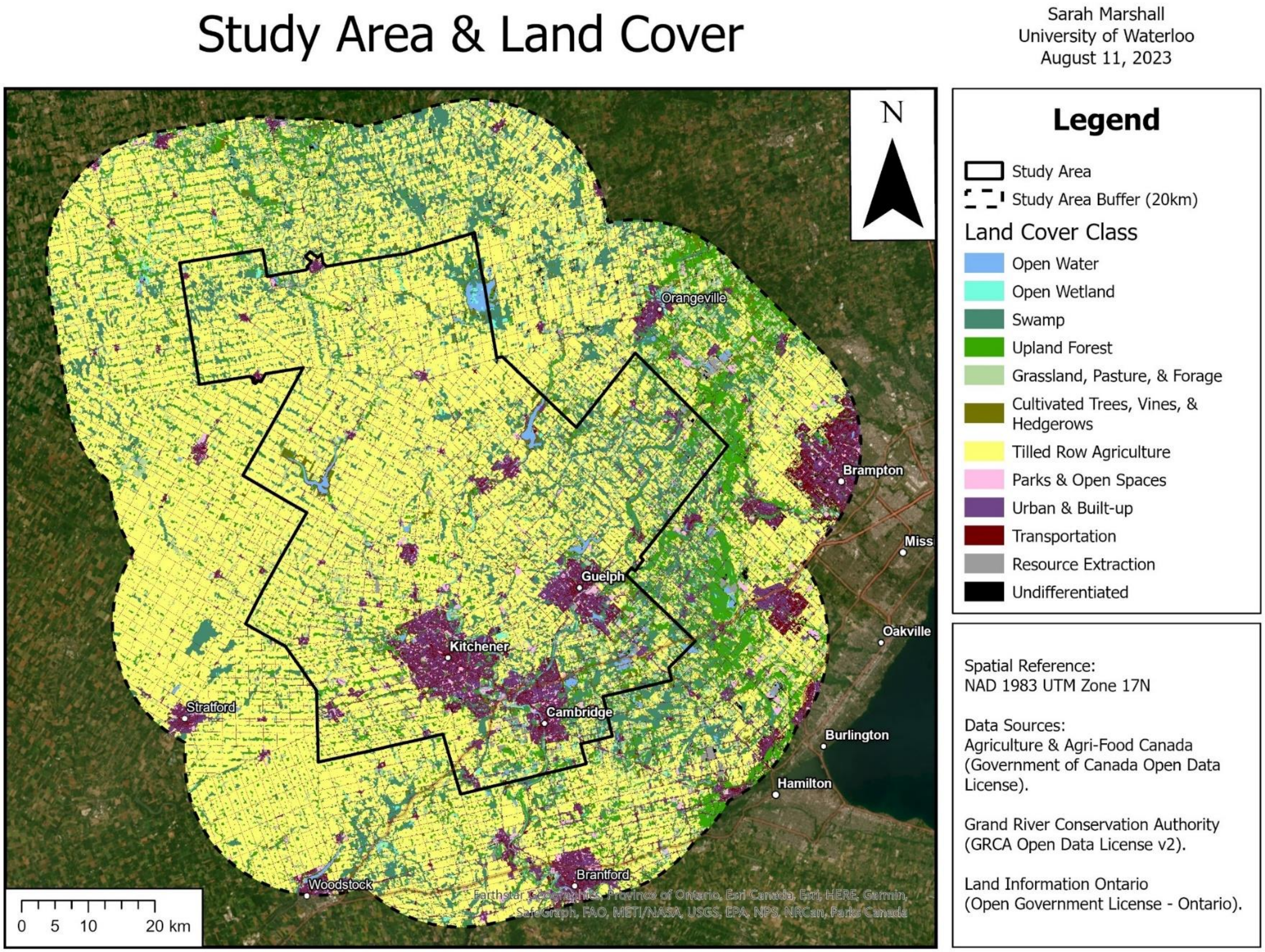
Table 10

Breakdown of Land Cover Classes Used Within Case Study Map

Land Cover Class	Total Raster Area (km^2)	% of Raster Area
Open Water	136	1.2%
Open Wetland	98	0.9%
Swamp	1,406	12.3%
Upland Forest	958	8.4%
Grassland, Pasture, & Forage	811	7.1%
Cultivated Trees, Vines, & Hedgerows	231	2.0%
Tilled Row Agriculture	6,309	55.0%
Parks & Open Spaces	132	1.1%
Urban & Built-up	650	5.7%
Transportation	635	5.5%
Resource Extraction	50	0.4%
Undifferentiated	48	0.4%

Figure 15

Map of Land Cover Types Used for the rare Case Study



Study Area & Land Cover

Sarah Marshall
University of Waterloo
August 11, 2023

Earthstar Geographics, Province of Ontario, Esri Canada, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, NRCan, Parks Canada

Spatial Reference:
NAD 1983 UTM Zone 17N

Data Sources:
Agriculture & Agri-Food Canada
(Government of Canada Open Data License).

Grand River Conservation Authority
(GRCA Open Data License v2).

Land Information Ontario
(Open Government License - Ontario).

3.4.3 Core Habitat Delineation

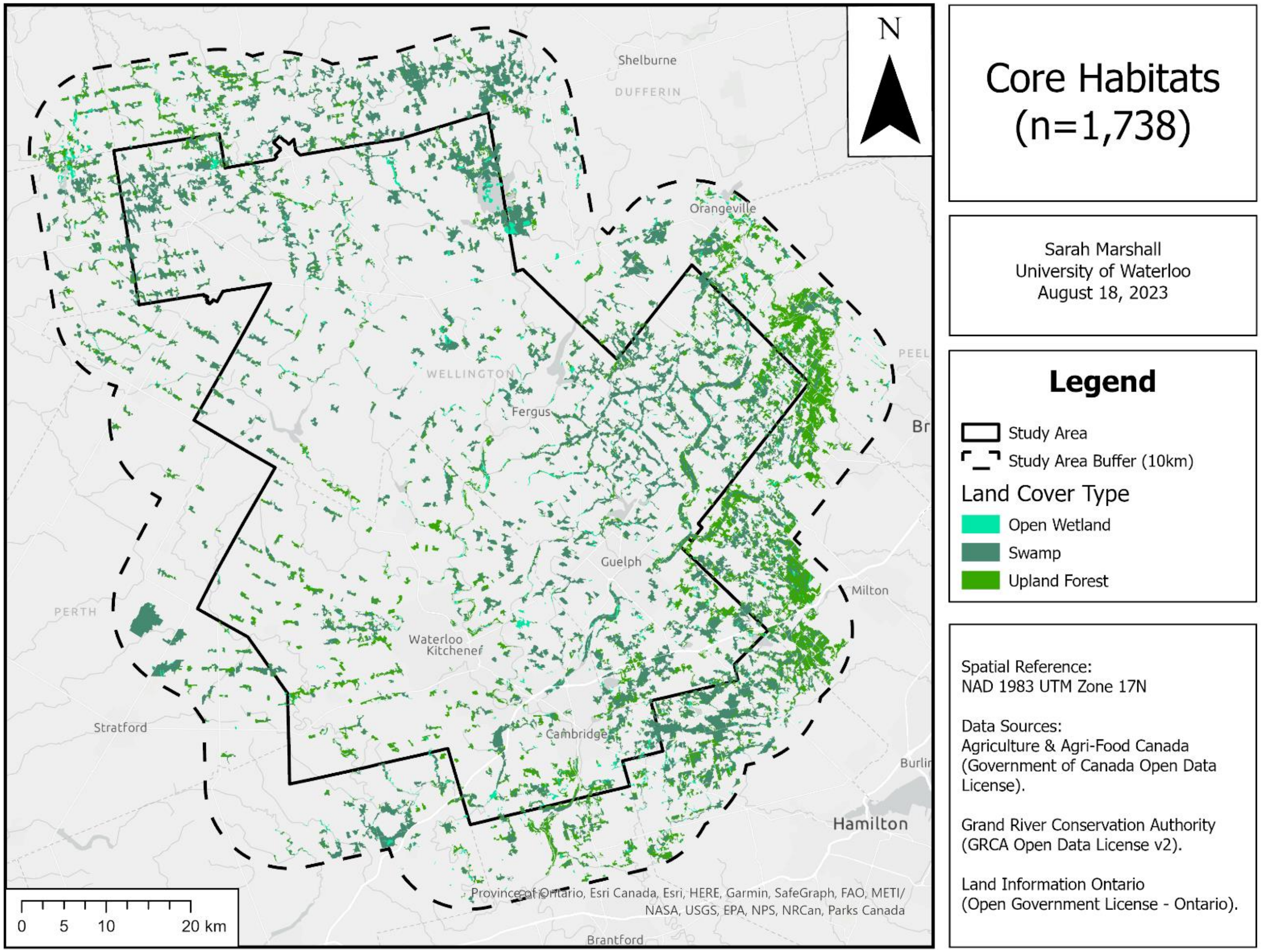
Based on consideration of species habitat preferences and consultation with the **raresites** committee, three land cover types (Upland Forest, Swamp, and Open Wetland) were chosen to represent potential core habitat. The Region Group, Reclassify, and Raster to Polygon tools in ArcGIS were employed to isolate these three land cover types and convert them into vector polygons for further consideration. This initially created 47,891 habitat polygons. Because the Conefor manual recommends a maximum of 2,000 nodes for computation of the PC index (Saura & Pascual-Hortal, 2007a), it was necessary to reduce the number of polygons significantly for this analysis. Adjacent polygons were dissolved along boundaries and treated as the same habitat patch regardless of land cover type (though the proportion of each cover type was retained for later analysis). This step reduced the number of patches dramatically, to 14,694. At this point, several exclusion rules were applied to reduce the number of patches for analysis. These are based on the species habitat preferences in Appendix B, and are defined as follows:

- “Patches made up of forest and/or swamp must be ≥5ha in total area” (removed 7,714 patches).
- “Open wetlands not adjacent to a ≥5ha forest/swamp habitat patch must be ≥2ha” (removed 705 patches).
- “Patches made up of forest and/or swamp which are not adjacent to an open wetland must preserve ≥3ha of interior habitat with an 85m edge effect” (removed 3,593 patches).

These rules effectively reduced core habitat patches from 14,694 to 2,682. At this point, it was noted that many of the habitat patches remaining fell outside of the study area boundary itself, instead existing in the 20km buffer region. While these patches are helpful for ensuring the accuracy of the connectivity importance scores near the edge of the study area, it was decided that it is better to reduce the size of the study area buffer rather than continue to remove potentially beneficial habitat from consideration. Therefore, the study area buffer was halved, from 20km to 10km, which reduced the number of core patches to 1,738. Of these, 922 (53%) are within the **rare** study area, while the other 47% exist in the buffer and function to provide accurate connectivity information for the patches that fall near the study area edge. A map of these core habitat patches is provided in Figure 16 on the following page.

Figure 16

Map of Core Habitat Patches Used as Nodes in the rare Case Study



3.4.4 Interpatch Distances

Beyond the core habitat patches (nodes) themselves, the Conefor model requires information about the distance between each pair of nodes on the studied landscape. Conefor offers the option to input either Euclidean distance or “effective distance” between nodes, which allows the user to choose between structural and functional connectivity measurement, respectively. Due to time limitations for geospatial analysis, it was decided that Euclidean distance calculated with the Generate Near Table tool in ArcGIS would be sufficient for a connectivity model at this stage. Additionally, the maximum possible distance for which nodes would be considered connected was set at 20km, reducing the pairs of nodes which needed to be processed. This decision reduced inter-patch distance processing from three days to six hours. Once distances were produced, the Select by Attributes tool was used to delete half of the lines which were duplicates (i.e., node *a* to *b* and node *b* to *a*).

3.4.5 Dispersal & Conefor Calibration

During consultation with the **rare** Planning Ecologist, it was agreed that it would be ideal to run the connectivity analysis five times on the same node and distance files, varying the dispersal distances to create a set of connectivity maps. The median dispersal distances chosen, corresponding to a 50% probability of dispersal, were 1m, 30m, 100m, 1,000m, and 20,000m. These distances are based primarily on the abilities of chosen focal species (Appendix B), with some consideration for the interests of the **rare** team. In particular, the 1m dispersal distance (while not directly related to focal species preference) was chosen with curiosity regarding how Conefor may treat connectivity for hypothetical species that cannot effectively traverse non-habitat areas. The Node file (containing node ID’s and areas in m^2), and Connection file (containing pairs of node ID’s and Euclidean distances in m) were uploaded into Conefor 2.6, which was then run for each of the previously mentioned dispersal distances.

3.5 Results

Each run of Conefor took 10-12 hours, and was completed over a total of three days. The dPC values generated for each dispersal distance were exported as five ASCII files, and the values for each node were appended to the attribute table of the core habitat map from Section 3.4.3. From this re-spatialized data, a composite map was created showing the dPC value of each habitat patch at each of the five dispersal distances (see Figure 17). These maps were clipped to show only the habitat patches within the un-buffered study area, as the dPC values in the buffer are not of significant concern for the **rare** LSS. The dPC values were also averaged across the five dispersal distances to produce an “average” connectivity importance map (see Figure 18). Both the maps showing single dispersal distances and the “average” map can be used to identify critical areas for protection based on their importance to regional connectivity.

As seen in the following maps, the patch importance to connectivity (dPC) fluctuates based on the median dispersal distance set in the software. Because the 1m dispersal is less than that of the initial raster resolution (15m), any dispersal is unlikely, and therefore connectivity importance is highly concentrated on patches that have a large physical area. As dispersal distance increases, more patches increase in their relative importance to connectivity. Notably, this phenomenon seems to peak around the 1km dispersal distance, with the 20km dPC values again showing very few stand-out patches of high importance. This may be explained by two factors: (1) The 20km dPC is likely skewed by the 20km inter-patch distance limit placed, beyond which patches were not considered connected, and (2) species with both very low (1m) and very high (20km) dispersal behaviour may value inter-patch distance less discriminately provided their habitat requirements (i.e., patch area) are met.

Figure 17

Connectivity Maps Showing Importance to Connectivity (dPC) at Five Dispersal Distances in the rare Study Area.

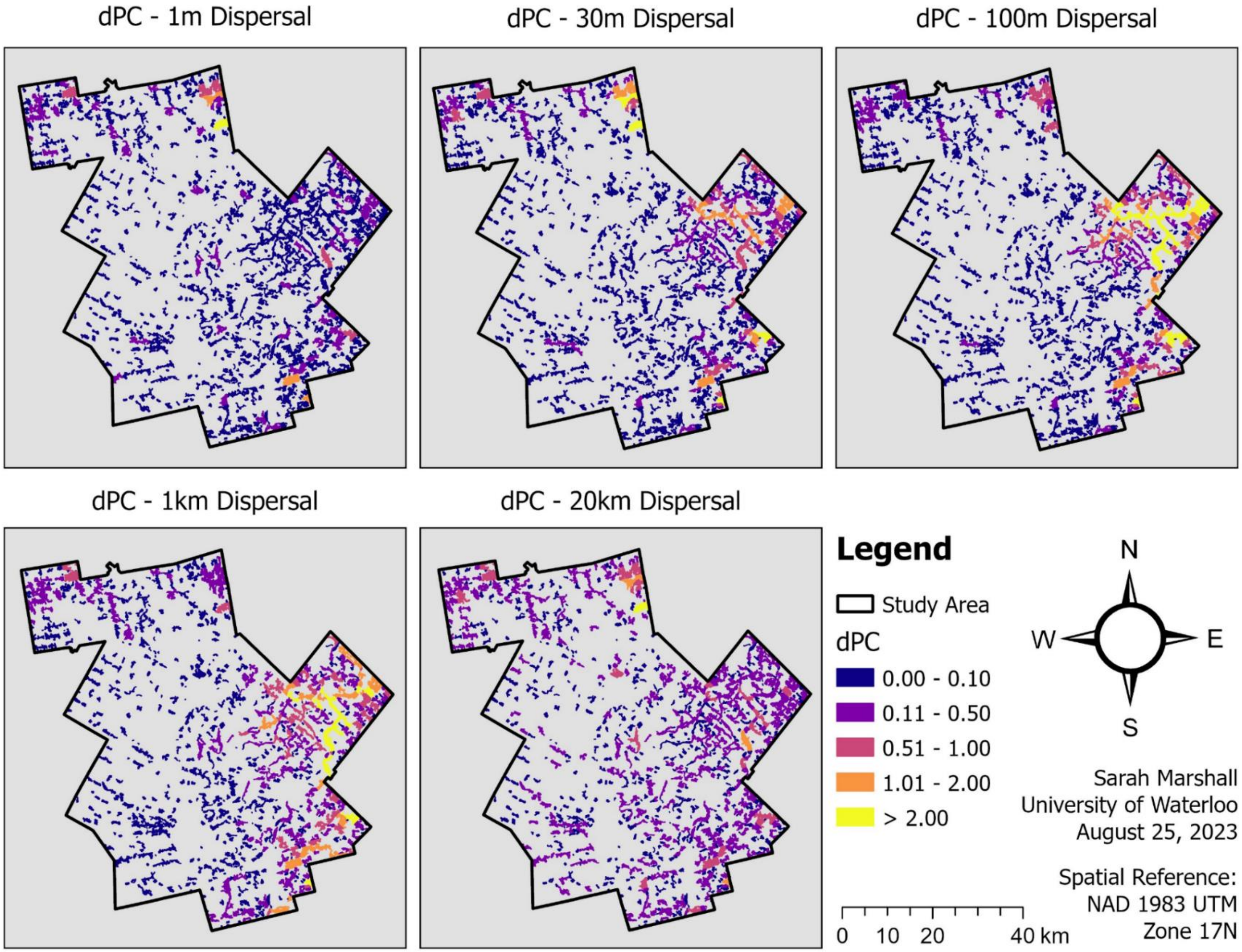
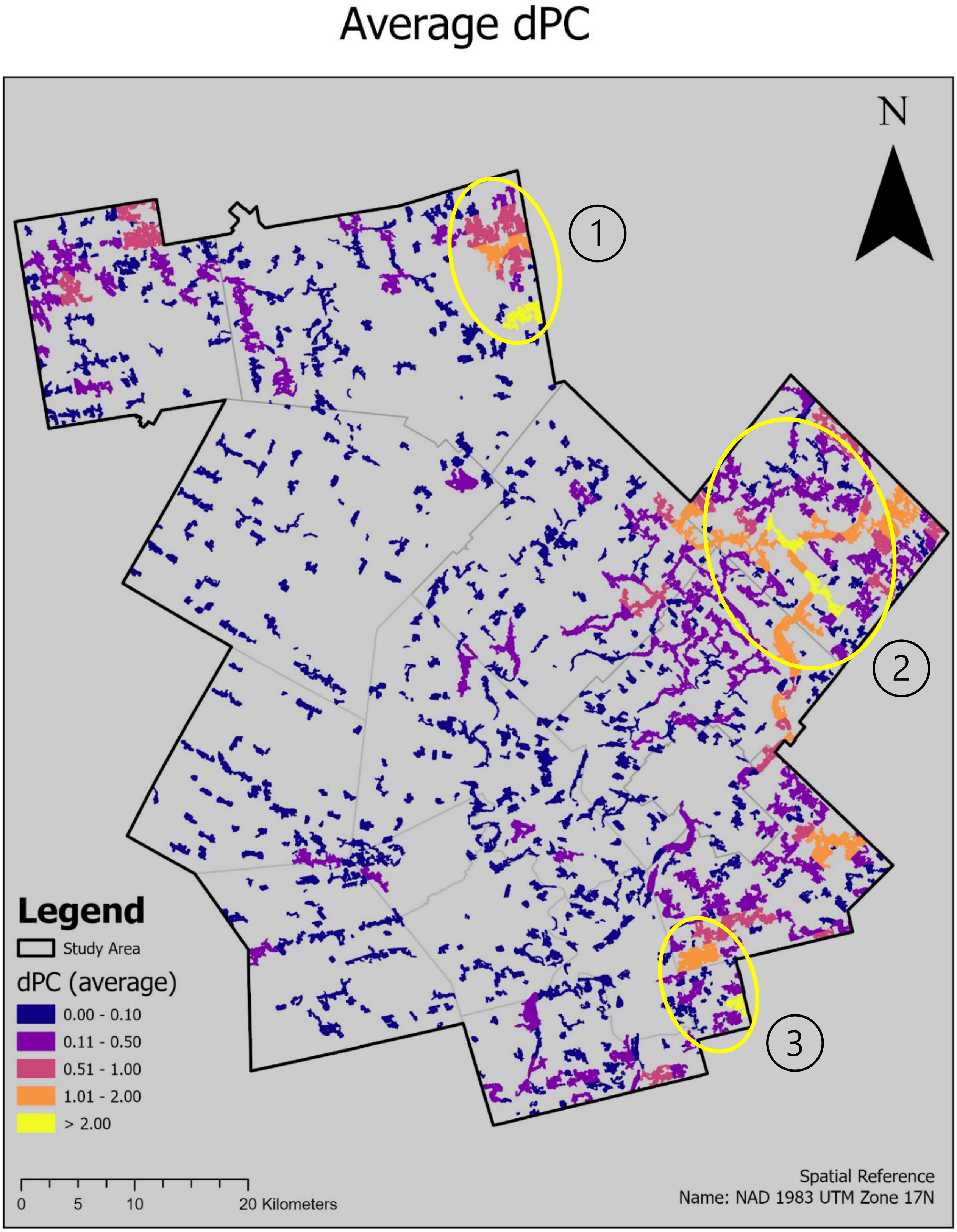


Figure 18

Importance to Connectivity (dPC) Averaged Between Five Dispersal Distances



The latter map (Figure 18) shows habitat patches with the highest average connectivity importance in yellow. Three areas are highlighted for their importance to connectivity across several dispersal distances, and have been presented to the **raresites** committee as potential areas of focus. These are: (1) the surroundings of Luther Marsh, (2) the Eramosa River-Blue Springs Creek and Speed-Lutteral-Swan Creek wetland complexes, and (3) Beverly Swamp wetland complex (OMNRF, 1978). These sections are also highlighted as "focal areas" within the 2018 LSS, validating the work that **rare** has done securing conservation lands under the previous system.

It is worth noting that the "average" dPC map is a simplification of true connectivity on the landscape. While averaging is convenient to pinpoint importance to habitat connectivity in a general way, visual inspection of the five separate dispersal distances show distinct differences in the valuation of habitat by species with varying movement behaviours. Each dispersal distance map also features its own inaccuracies – The 1m dispersal map's accuracy is limited by input data accuracy (e.g., land cover data, satellite imagery), while the 20km dispersal map is limited by the maximum inter-patch distance of 20km. With these notes in mind, it is recommended that "average" connectivity maps be viewed with caution, considering that they will both obscure inaccuracies and produce a smoothing effect in which lands that are highly critical for one dispersal group may be lost through the averaging process.

In addition to the connectivity scores produced through Conefor, the core habitat delineation process (Section 3.4.3) allowed for the creation of a core habitat database. The database lists each Node ID and provides a breakdown of the land cover types present, including the area and percent cover of each cover type. Finally, a list of species codes is included, showing which of the fifteen focal species from this study may be supported by the particular land cover complex present at each node. I am hopeful that this spreadsheet can be used in concert with the dPC data to support informed conservation planning for the sensitive habitats in this region.

3.6 Case Study Reflections

This case study has endeavoured to apply theoretical knowledge from my systematic literature review to a local context and real-world problem. Beyond the pragmatic benefit that this research has generated for the **rare** LSS, application of theory to a case study allows for a practical understanding of how pivotal decisions can affect the outcomes of landscape connectivity analysis. Several decisions in this study had a marked impact on the final product and their relevance to method selection guidelines should be discussed. In the following sections, I outline key decisions that were made throughout the case study, reflect on the implications of these choices (including research limitations), and consider future research directions for this project.

3.6.1 Tool Selection & Organizational Needs

While the 28 connectivity software tools reviewed in Chapter 2 initially seemed like a broad diversity of choices, the application of practical and technical limitations quickly whittled down my selection. My intent to be as inclusive to diverse organizational needs as possible resulted in elimination of tools based on availability, popularity, simplicity, and flexibility in working with other software. Ultimately, this elimination strategy was effective. However, if broad theoretical limitations (e.g., analytic approach) had been applied before tools were considered, it may have been difficult to produce an acceptable result. With this in mind, it is recommended that organizations apply inflexible practical limitations before narrowing down flexible philosophical preferences.

3.6.2 Spatial Data Considerations

The choice of spatial data used for land cover mapping likely had a considerable effect on the final connectivity product. My choices were made with consideration for data availability, year that the data was most recently updated, and the data’s presumed accuracy. An important step in my processing of geospatial data and land cover map creation was the acquisition and review of metadata to identify weaknesses that could be improved upon. This improvement was achieved through the supplementation of SOLRIS 3.0 with other land cover data. I additionally found that the decisions made while processing and overlaying spatial data are important, such as the choice to integrate GRCA and AAFC land cover layers with SOLRIS with different priority to see how this affected the resulting land cover map. In this case, the prioritization of AAFC data ignored individual houses in rural areas, whereas GRCA land cover data captured the presence of individual rural homes, barns, and other impervious surfaces.

Another spatial consideration is that of buffer size. By reducing my buffer size from 20km to 10km, I was able to reduce the number of core habitat nodes below 2,000 (as recommended by Saura & Pascual-Hortal, 2007a), but it's possible that this reduction in buffer size created edge effects for dPC values in the periphery of the study area, especially at a 20km dispersal distance. Despite this, I feel that the reduction of the buffer size was effective in increasing the percentage of relevant habitat patches used for the study. Because of the presence of the Niagara Escarpment within the eastern buffer of the study area, further patch elimination without buffer reduction would have resulted in less than half of the habitat patches being within the actual study area, reducing the usefulness of the study for **rare's** LSS. In future studies, it may be interesting to track how the size of study area and buffer affects the reduction of core habitat patches and overall dPC index across the landscape.

3.6.3 Multi-Species Habitat Delineation

It was noted in the literature review that several research articles choose "objects of study" that transcend individual species, instead focusing on connectivity for blue-green infrastructure or the landscape as a whole. Such studies use MSPA or human boundaries like “parks & protected areas” to delineate habitat patches. Based on the interests of the **raresites** committee, this study aims to measure habitat connectivity using “multiple species” as a study object. Through the process of conducting this research, it became clear that multi-species connectivity is challenging to measure. The importance of each focal species’ habitat preferences must be weighed against each other, with an aim to reduce the habitat nodes <2,000 while maximizing the use of each patch across the 15 species considered. In addition to purely biological reasoning, consultation with organizational stakeholders may have value. For example, my decision to only consider upland forest, swamp, and open wetland cover types as habitat was partially related to **rare’s** preference to not incidentally prioritize agricultural lands (e.g., cover type “grasslands, pasture, & forage”) which may not be considered feasible for securement.

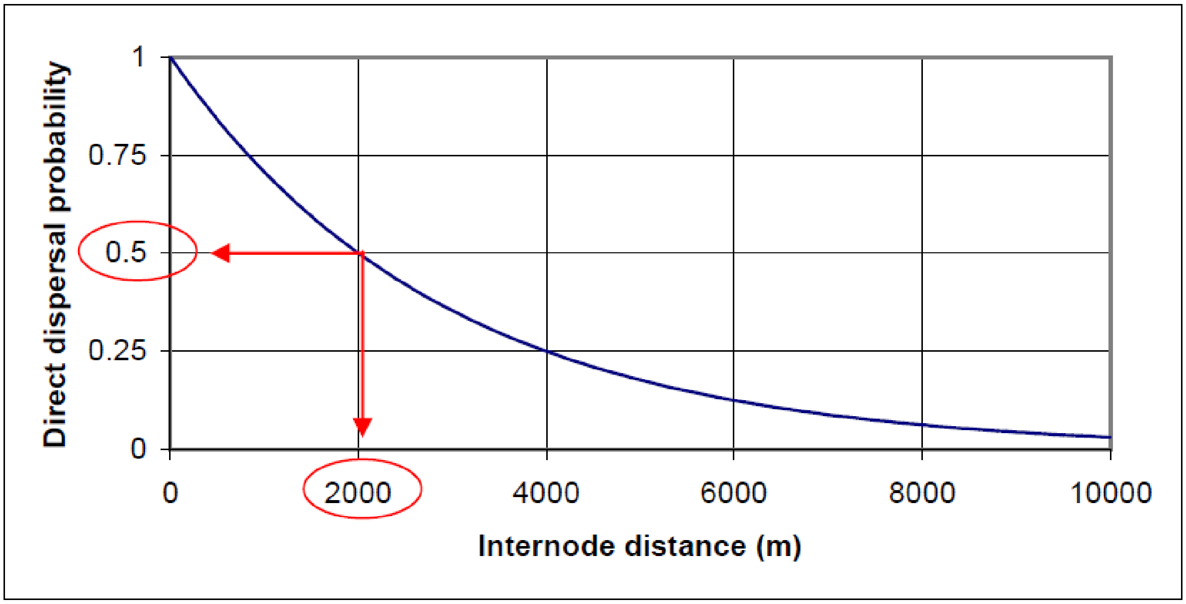
3.6.4 Inter-Patch Distance & Processing Time

Despite the reduction of nodes below Conefor’s recommendations for calculating dPC (<2,000; Saura & Pascual-Hortal, 2007a), preliminary testing in ArcGIS indicated that the time to compute Euclidean distance between every habitat patch would not be feasible within the time constraints of this case study. For this reason, it was decided that nodes further than 20km apart would not be treated as connected. As discussed in Section 3.5, this decision likely reduces the accuracy of the 20km dispersal dPC map.

Conefor calculates the dPC on a negative exponential curve, wherein the median dispersal distance sits at the 0.5 probability of dispersal, and dispersal follows the curve in both directions based on the internode distance (Saura & Pascual-Hortal, 2007a; see an illustration in Figure 19 below). Because my study assumes a probability of zero for all internode distances >20km, the probability only follows the exponential curve from internode distances of 0–20km, after which point it simply drops to zero.

Figure 19

Negative Exponential Function of Maximum Product Probability used in Conefor Calculations. Source: Saura & Pascual-Hortal, 2007a (p.17).



While imperfect, the decision to limit inter-patch distance calculation also effectively reduced the processing time and made the overall connectivity analysis possible. The issue could be corrected in later updates of the dPC scores by allowing for enough processing time to compute the distance between all nodes, rather than only those within 20km of each other. An interesting research direction may be to compare the effect that a limited vs. unlimited maximum dispersal distance has on dPC scoring when using otherwise identical Conefor inputs.

3.6.5 Structural vs. Functional Connectivity

Functional connectivity is practically defined for this study as that which uses a resistance distance (rather than Euclidean distance) to model wildlife perception of the landscape (Almenar et al., 2019). While functional connectivity has been lauded for its importance to biodiversity and ecological processes, it requires an often-prohibitive amount of preliminary research to support, and is much easier to represent incorrectly without sufficient consideration (LaPoint et al., 2015).

Calculation of functional connectivity is possible with Conefor, but it requires the creation of a cost surface that is based on each land cover type's resistance to focal species movement (as shown in the flowchart in Figure 14). This is a substantial undertaking that often includes expert consultation, decision support systems, and sensitivity analyses to weigh importance of various landscape factors to species movement (Zeller et al., 2012). The time constraints of this thesis prevented a sufficiently in-depth undertaking such as this, and it was decided that a defensible measure of structural connectivity (i.e., using Euclidean distance) should be considered more valuable than a functional connectivity measurement without sufficient research and analysis behind it.

Encouragingly, **rare** has expressed interest in working with student partners to support the creation of wildlife cost surfaces, which would allow them to produce a functional connectivity model with the same initial habitat data. This would also allow for interesting comparative study in the future, evaluating the difference between the structural and functional dPC scores for the **rare** study area.

The process of this case study illustrates the number of decisions that must be made (and tracked) to produce a robust connectivity map for a conservation organization. Many of these decisions required stakeholder contributions, review of available literature, and personal judgement to keep the analysis moving. This complexity may be better facilitated through the use of SDSS, not just in the application of final connectivity scores, but also throughout the connectivity analysis process (e.g., definition of cost surface weights). The calculation of functional connectivity and the use of SDSS is beyond the scope of this thesis, but it is possible that these strategies could help the **raresites** committee in future improvement of both their connectivity analysis and land securement strategy in general.

As stated in the objective for this case study, the procedure above has produced connectivity scores which can be integrated within the existing framework of the “**rare** score” to support systematic conservation planning and land securement in Waterloo Region and Wellington County. It has also produced useful guidance regarding the choice of connectivity methods in the context of practical application by a non-profit. In Chapter 4, I will broaden my discussion from this case study to the overall themes of my thesis, including the broad contributions this research makes to the fields of conservation biology and planning, recommendations for organizations interested in using landscape connectivity analysis, and guidance for integrating an ethical framework into conservation planning practice.

Chapter 4: Discussion

This chapter synthesizes my observations from the preceding literature review and case study, and aims to present best practices in landscape connectivity analysis that can be used by conservation planners. This includes a summary of operational decisions required of analysts and practitioners, recommendations to integrate connectivity into conservation planning strategies, and discussion of the ethical implications of conservation planning as a whole. While my case study spotlights the specific context of a non-profit operating in Southern Ontario, these reflections are intended to provide value to the industry of urban/peri-urban conservation planning as a whole.

Based on the results of my systematic literature review and case study, I am proposing a framework for landscape connectivity analysis for conservation planning that is made up of seven steps: (1) Project Understanding, (2) Study Area Definition, (3) Methods Selection, (4) Data Collection & Base Map Creation, (5) Core Habitat Delineation, (6) Tool Calibration & Connectivity Measurement, and (7) Practical Application. Each of these steps includes several key decisions and opportunities to optimize for effective, flexible, and transparent conservation planning.

For the purpose of this discussion chapter, I have grouped the aforementioned steps into three broad phases: set-up (steps 1-3), analysis (steps 4-6), and application (step 7). In the following sections, I reflect on each of these three phases in turn, and then I introduce a fourth section which considers the ethical implications of conservation planning as a whole. I close this chapter with a visual framework of my proposed connectivity analysis steps and the decisions, factors, and guidelines that should be considered by conservation practitioners.

4.1 Project Set-up: Context, Geography, & Methods

In Chapter 2’s systematic literature review takeaways, I consider the ways in which a project’s priorities may vary, depending on the type of organization conducting the landscape connectivity analysis. For example, I observed that research institutes tend to subscribe to a planning culture of “scientific frontiers,” while government and private sectors tend to focus on “practical applications” (Forsyth, 2012). Such differences should be considered when framing a connectivity analysis project, to ensure that the output of the project effectively meets stakeholder goals and priorities. Notably, over half of studies within my literature review considered multiple research priorities, including the single non-profit study (Choquette et al., 2020) which paired theory generation about wildlife with site selection for on-the-ground planning.

Similarly, I observed projects which consider multi-scale study objects (e.g., measuring connectivity for both individual species and the entire landscape). Resources are an important consideration in this regard: multi-species connectivity in particular was demonstrated in my case study to be challenging, as additional research and decision-making is required to balance the importance of individual species to overall connectivity scores.

In any case of added complexity at this phase of the project (e.g., multi-priority, multi-species, multi-object studies), care should be taken to ensure that adequate time and resources are available. Additionally, it is important that projects maintain some flexibility, in the event that goals change or limitations surface later in the analysis process. Step 1 (Project Understanding) should conclude by identifying the organizations and stakeholders involved in the process, establishing research goals, and determining the object(s) of study for which connectivity will be measured.

Once the aspatial basis of the connectivity analysis project has been established, the spatial context should be considered. First, the spatial scale of the study (i.e., neighbourhood, city, region, province, etc.) should be chosen. As introduced in Chapter 2, the spatial scale of analysis profoundly affects later decisions about the use of spatial data, software tools and connectivity metrics (Pascual-Hortal & Saura 2007). Care should be taken not to frivolously increase the spatial scale of analysis more than necessary to accomplish project priorities.

Beyond the scale of analysis, information should be gathered about the study area itself (i.e., urban/rural balance, city population density, key natural areas), and a buffer should be established surrounding the study area. Buffering the study area for landscape connectivity analysis is useful because it can minimize edge effects that skew the value of patches near the outskirts of the study area (i.e., by not considering their neighbours beyond the boundary) (Beier et al., 2011). The effects of buffer size should be monitored during later analysis. As demonstrated in my case study, a 20km buffer (chosen based on approximate study area to buffer ratios in Beier et al., 2011, Tarabon et al., 2020, and Wei et al., 2022) proved to be problematic, as the presence of the Niagara Escarpment in the buffer area to the east drew conservation focus away from the study area itself. With the spatial scale, geographic context, and buffer size established, Step 2 (Study Area Definition) can be completed.

Methods Selection (Step 3) and the implications of those selections are discussed at length in section 3.6 of the case study. Key decisions include: validation strategy (i.e., literature review, expert opinion and/or field work), GIS platform, connectivity software tool, connectivity output (map, metric, index, etc.), and analytic approach used. Through my case study, I demonstrate how practical and technical requirements (e.g., software availability) can be the most limiting factors in an analysis, and should be considered prior to philosophical preferences (e.g., graph vs. circuit theory).

Extensive consultation with organizational partners is important in this regard, especially if (as in my case) the connectivity project and output will be passed along for further use and modification. Examples of important questions to ask include:

- What GIS platform is the team most comfortable using?
- Are there licensing restrictions which may prevent certain organization types from using software?
- Is the connectivity output compatible with the chosen spatial scale/study object? and
- What is the present/future capacity for gathering of expert opinion and field data?

With the parameters of the landscape connectivity project understood, the study area defined, and the study methods selected, the project enters the phase of analysis.

4.2 Analysis: Data, Geoprocessing, & Measurement

The analysis phase of connectivity analysis begins with data collection and base map creation (Step 4). The map created through this process (usually based on spatial and field data) serves as the canvas upon which core habitats are delineated and connectivity is ultimately calculated. In Chapter 2, I divide the data used for connectivity analysis into “field data”, “spatial data”, and “measures.” For each of these, the choice of data to collect and analyze will be based on its accuracy, resolution, usefulness, and difficulty to acquire.

For field data, this ranges from simple species observation (which generates point occurrence data) to demanding field work like radio telemetry (which can produce a record of wildlife movement over time). The choice of field data (if any) depends greatly on the organizational capacity for training, field hours, and equipment. Spatial data types and measures (as defined in Appendix A) similarly depend on availability and organizational resources. Open source data is preferred where available, as it allows for easy transparency and replication by other parties. The quality of spatial data and measures will likely be based on the available resolution of data, and the known inaccuracies reported in the metadata. These can be improved through geoprocessing techniques like overlaying multiple land cover layers to fill in gaps, or using vector data to ensure raster resolution does not eliminate small linear features like roads (as shown in Chapter 3).

Once a reasonably accurate base map is produced, it can be used to define and delineate the “resource patches” among which the landscapes’ facilitation of species movement can be measured (Taylor et al., 1993). The terminology for these patches varies (resource patches, habitat patches, core habitat, nodes, etc.), but for the purpose of my framework this step (Step 5) is referred to as “Core Habitat Delineation”. The method of core habitat delineation is variable, dependent on the chosen study object and validation strategies. Some methods observed within my literature review include:

- Using the boundaries of existing parks and protected areas (Perkl et al., 2018),
- Using “core” areas generated by MSPA in Guidos software (Guo et al., 2018),
- Creating an “ecosystem services” scoring system and delineating core habitat based on patches with the highest ecosystem service provision (Li et al., 2022b),
- Basing habitat on known species occurrence data (Beaujean, 2021), and
- Scoring patches based on species preference and habitat suitability data, derived from fieldwork (St-Louis et al., 2014), expert opinion (Choquette, 2020), and/or literature review (Alvarez, 2020).

Of the reviewed studies aiming to improve connectivity for multiple wildlife species (as is the case for the **raresites** committee), the most common method of defining core habitat it to use species preference and habitat suitability data derived from the literature (as discussed in section 2.3.4). While in many ways this could be considered a simple approach (i.e., no need to arrange field work or track down experts), there should be consideration of two key factors. First, care should be taken to track differences in terminology across habitat suitability studies. For example, it was noted that some studies would group swamp habitats in with forests based on canopy cover, while others would group swamps in with wetlands based on moisture. Because of this, I chose to conduct additional research beyond the literature review studies to establish swamp use by the 15 focal species in my study (see Appendix B). Second, delineation of core habitat should include stakeholder consultation to determine non-ecological preferences (as shown by **rare's** preference to not incidentally prioritize agricultural patches). Finally, the capacity of the connectivity tool being used must be considered when finalizing the patches delineated, as demonstrated by Conefor's recommended <2,000 nodes for calculation of dPC scores (Saura & Pascual-Hortal, 2007a).

With habitat patches delineated, the actual calculation of connectivity must take place. This step (Step 6, Tool Calibration & Connectivity Measurement) will be highly variable, as it depends entirely on the choices made in the previous steps. In the case of using Conefor, as I did in my study, the crucial decisions are: (1) whether to measure structural connectivity through Euclidean distance, or functional connectivity through effective distance, (2) the dispersal distance(s) for which connectivity is calculated, and (3) the maximum distance for which patches are considered "connected".

When choosing between structural and functional connectivity (as discussed in Section 3.6.5) there should be an understanding of the extra validation and analysis required to predict (potential connectivity) or measure (actual connectivity) wildlife movement across the landscape (Calabrese & Fagan, 2004). For the creation of a functional cost surface that shows the relative difficulty for species to cross different land cover types, the use of spatial decision support systems may be desirable.

The choice of dispersal distance(s) used for the analysis may be based on a generic range (for studies of green space and general landscape connectivity), or they may specifically be derived from known dispersal behaviour of species in question (for studies of single or multi-species connectivity). A range of dispersal distances can be useful to visualize differences in connectivity across the same landscape, depending on the mobility of the species in question. Any potential inaccuracies caused by specific dispersal distances and their interactions with the model set-up should be noted as limitations of the connectivity study. In my case study, it was noted that a 1m dispersal distance may be skewed by the 15m resolution of the base map, while the 20km dispersal distance may be skewed by the maximum connection distance.

Despite potential inaccuracies, it may be desirable to place a maximum connection distance beyond which connectivity between patches is not calculated (Saura & Pascual-Hortal-2007a). This may be effective in reducing processing time, but consideration should be given to the effect that the maximum limit will have on connectivity scores (as discussed above, and in Section 3.6.4).

Upon completion of Step 4 (Data Collection & Base Map Creation, Step 5 (Core Habitat Delineation), and Step 6 (Tool Calibration & Connectivity Measurement), the connectivity output should have been produced, and can be visualized through integration with GIS software to map connectivity for the study area. This final product can be provided to relevant stakeholders and used for conservation planning as appropriate.

4.3 Application: Translating Connectivity to Conservation

While the production of connectivity data for a given landscape is informative, it is the practical application of that data in support of pragmatic conservation action that brings true benefit to biodiversity. The practical application (Step 7) of connectivity data can take several forms, depending on the priorities established at the beginning of the project and the organization type (e.g., government, private sector, government) that wields this connectivity data to plan conservation action. While the integration of connectivity data into all types of conservation planning is beyond the scope of my thesis, my review of the **rare** land securement strategy in Chapter 3 has provided one example of how this may be done.

In general, practitioners may consider the use of SDSS in their selection of key sites for conservation or their development of connectivity networks in urban/peri-urban areas. The use of SDSS can allow for more accountability and transparency in the formulation of planning decisions, a feature that is encouraged in Margules & Pressey’s (2000) guidelines for systematic conservation planning. In addition, there are several ethical considerations that conservation planners and land managers should work into their process, especially in geographic areas where colonization has played a major role in the management of land over time (Innes et al., 2021). This is discussed in more detail in the following section.

4.4 Ethical Conservation & Indigenous Perspectives

While a landscape connectivity approach to optimizing conservation land securement has the potential to provide many positive outcomes for wildlife movement, biodiversity, and nature conservation (Saunders et al., 1991), it must be noted that land securement for conservation is build upon a colonial history in which the lands being proposed for “protection” were once occupied by Indigenous Peoples. To quote Innes, Attridge, & Lawson: "For more than a century, conservation in Canada has been synonymous with the dispossession of Indigenous land or the restriction of Indigenous rights in the name of protecting wildlife or scenic places" (2021, p. 4). To ensure that this thesis does not perpetuate the colonial tradition of dispossession and the silencing of Indigenous voices in the name of land conservation, some key Indigenous perspectives on this issue are warranted.

An unspoken assumption that commonly follows the colonial style of conservation planning is the perceived separation between "nature" and "humans" (Tanskanen, 2009). This dichotomy is further reflected upon in Cronon's "The Trouble with Wilderness" (1996), which considers the ways in which colonial society has viewed nature throughout history, from wasteland, to frontier, to romantic sublime. In all of these views, he argues, colonial conceptions of wilderness feature an intrinsic belief that humans are not a part of nature, and that our presence in it brings about its destruction (Cronon, 1996; Bliege Bird & Nimmo, 2018; Fletcher et al., 2021). In contrast to this view, many Indigenous Peoples consider nature to be deeply intertwined with their humanity, and feel a deep spiritual connection to lands that have been stewarded for thousands of years. In short, many Indigenous Peoples see themselves as an integral part of (rather than the antithesis of) nature (Garnett et al., 2018).

Unfortunately, this conflict in perspectives often supports what Cernea (2005) describes as "Conservation Displacement", the physical removal of residents from their homes, and/or the economic displacement and exclusion of those who historically used natural lands for their survival. The preservation of nature as separate from humanity (sometimes called "fortress conservation") has often been used as a justification for the forceful eviction and exclusion of Indigenous Peoples from conservation lands, through the creation of conservation reserves (Cronon, 1996; Dominguez & Luoma, 2020; Fletcher et al., 2021). Not only has this practice destroyed culture and knowledge, led to starvation, and prevented access to sacred lands for Indigenous Peoples (Dominguez & Luoma, 2020), it has often resulted in degradation of the conservation lands themselves, because beneficial Indigenous stewardship practices (such as prescribed burning; Hoffman et al., 2021) are suppressed.

While this information is jarring and uncomfortable for many conservationists, it is critical to reflect on the ways in which conservation planning can be done in an ethical way which respects Indigenous environmental perspectives and practices. Some examples of how this may be done are included below:

1. The **cultivation of positive relationships** with Indigenous communities is a first step to successful conservation actions in areas with historic or current Indigenous land connections (Ban et al., 2018; Canada Land Trust Alliance, 2019). Organizations intending to pursue conservation securement should set aside time and effort to identify local Indigenous band councils, advocacy and leadership organizations, and interested Indigenous individuals, as well as to understand the political landscape of Indigenous land relations in a given area (Ban et al., 2018; Canada Land Trust Alliance, 2019; Verschuuren et al., 2021).
2. Beyond relationship cultivation, conservation organizations should **demonstrate inclusive governance** practices. This may look like appropriate recruitment of Indigenous persons into decision-making roles, such as Boards of Directors and/or Land Securement Committees (Canada Land Trust Alliance, 2019).
3. In understanding and evaluating the landscape, it is necessary to **recognize and respect systems of Indigenous Knowledge** that may present an alternative perspective. This may include providing room in conservation planning frameworks for qualitative valuation, rather than solely quantitative

measures. It is also necessary to ensure that any knowledge shared serves a benefit to the communities providing it (Ban et al., 2018).

4. Development of **meaningful consultation** processes should be done by ensuring that engagement occurs from the beginning of conservation decision making, and that barriers to consultation are removed (Young et al., 2020). The attitude toward conservation land securement should not be “whether there is a duty to consult”, but “how to meaningfully engage with... and respect” Indigenous governments and jurisdictions (Innes et al., 2021, p. 57).
5. A **fair land securement process** should also include respect and transparency, especially in lands that may have Indigenous interest (such as land claims, resource use, or cultural/spiritual significance) (CLTA, 2019; Innes et al., 2021; Verschuuren et al., 2021). This may include donation of conservation lands to Indigenous leadership as a next step toward reconciliation (Innes et al., 2021).

Each step in the connectivity analysis process includes several key decisions, limiting factors, and best practices that may direct practitioners toward ethical and effective conservation planning outcomes. There are several opportunities within this framework to incorporate Indigenous perspectives. The five examples above have been integrated within the final connectivity analysis framework to suggest in which steps of the process they could be considered. While conservation is generally regarded as a positive outcome for all parties involved, it is possible for the protection of land to reflect a colonial history that uses conservation as an opportunity for Indigenous dispossession, exclusion, and silencing (Innes et al., 2021). Therefore, practitioners have an opportunity (and a responsibility) to ensure that their conservation activities successfully empower local Indigenous communities. My framework summarizes this chapter, and is included in Table 11 below.

Table 11

Landscape Connectivity Analysis for Conservation Planning: A Framework.

Connectivity Analysis Steps	Key Decisions	Important Factors & Implications	Guidelines
Project Understanding	• Partner organizations & stakeholders • Research goals & priorities • Object(s) of study	• Capacity for multi-goal or multi-object research varies based on resources & time • Larger scale study objects (e.g., green space) require less justification than smaller scale (e.g., species habitat) • Focal species should be selected with consideration for data availability	• *Cultivate positive relationships* • *Demonstrate inclusive governance* • Establish early the planning culture and priorities of the organization (see Forsyth, 2012) • Ensure flexibility & expect goal changes & limitations to surface • If using species-level study object, consider early how core habitat will be delineated
Study Area Definition	• Spatial scale • Geographic context • Study area buffer size	• Spatial scale will affect level of detail, field work possibilities, and available metrics • A buffer too small will produce edge-effects; Too big may draw focus outside of study area – neither are desirable	• Consider organizational capacities and priorities in relation to spatial scale; If analysis can be more targeted to a smaller area, higher detail may be possible • Assess the land cover of the buffer area and consider how it may affect connectivity output
Methods Selection	• Validation strategy • GIS platform • Software tool(s) • Connectivity output • Analytic approach	• Species-level and functional connectivity will require more robust validation strategies • Connectivity output must be compatible with chosen spatial scale • Analytic approach will be dictated by tools and output chosen	• Develop a list of practical requirements for selected methods, prioritize these over philosophical preferences • Discuss early the capacity for gathering field data and expert opinion for validation • Establish the software tools already used (e.g., GIS), and discuss openness to novel tools; where possible, use software already familiar to partners
Data Collection & Base Map Creation	• Field data • Spatial data • Calculations & measures • Geoprocessing steps	• Field data intensity ranges from simple observation to hands-on wildlife tracking • Open-source data availability may be a limiting factor • Depending on spatial scale, resolution of spatial data may be a limiting factor	• Critically consider what type of field data, if any, is most useful/feasible for analysis • Read metadata to assess strengths and weaknesses of spatial data • Track all calculations and geo-processing steps taken throughout

Core Habitat Delineation	• Patch delineation strategy • Importance of individual species' needs	• Delineation method is dependent on chosen study object & validation used • When using multiple literature sources to determine species' habitat, ensure consistent definition of habitat types	• *Incorporate Indigenous knowledge systems, where possible* • Track how patch elimination changes patch usefulness to focal species during each step of analysis • Consult with stakeholders to establish other reasons for patch elimination (e.g., feasibility for acquisition)
Tool Calibration & Connectivity Measurement*	• Structural vs. functional connectivity • Euclidean vs. effective distance • Dispersal distance(s) • Max. connection distance	• Functional connectivity, while useful, requires more time and research commitment • Multiple dispersal distances can improve the functionality of a structural connectivity analysis • If max. connection distance is not infinite, note effect on final scores at each dispersal distance (see Figure 19) • Power of available software will dictate time required for this phase	• If measuring functional connectivity, incorporate SDSS to systematically create a defensible cost surface and/or effective distance measure • When defining dispersal distances for analysis, both species characteristics and base map resolution should be considered • Plan for distance calculation and connectivity modelling to take several days of uninterrupted processing
Practical Application	• How to integrate connectivity within a conservation planning strategy?	• The spatial scale of the connectivity output (e.g., patch-level vs. landscape-level metrics) will dictate how connectivity scores can be used for conservation planning	• Consider use of SDSS to incorporate connectivity output within a multi-criteria prioritization system • *Incorporate Indigenous knowledge systems* • *Practice meaningful consultation* • *Ensure a fair land securement process*

Note: Guidelines in italics are specific to Indigenous perspectives, defined and discussed in Section 4.4.

*This is specific to calibration in Conefor, as the only connectivity software used in this study. However, there is likely considerable overlap between this and other connectivity tool calibration options.

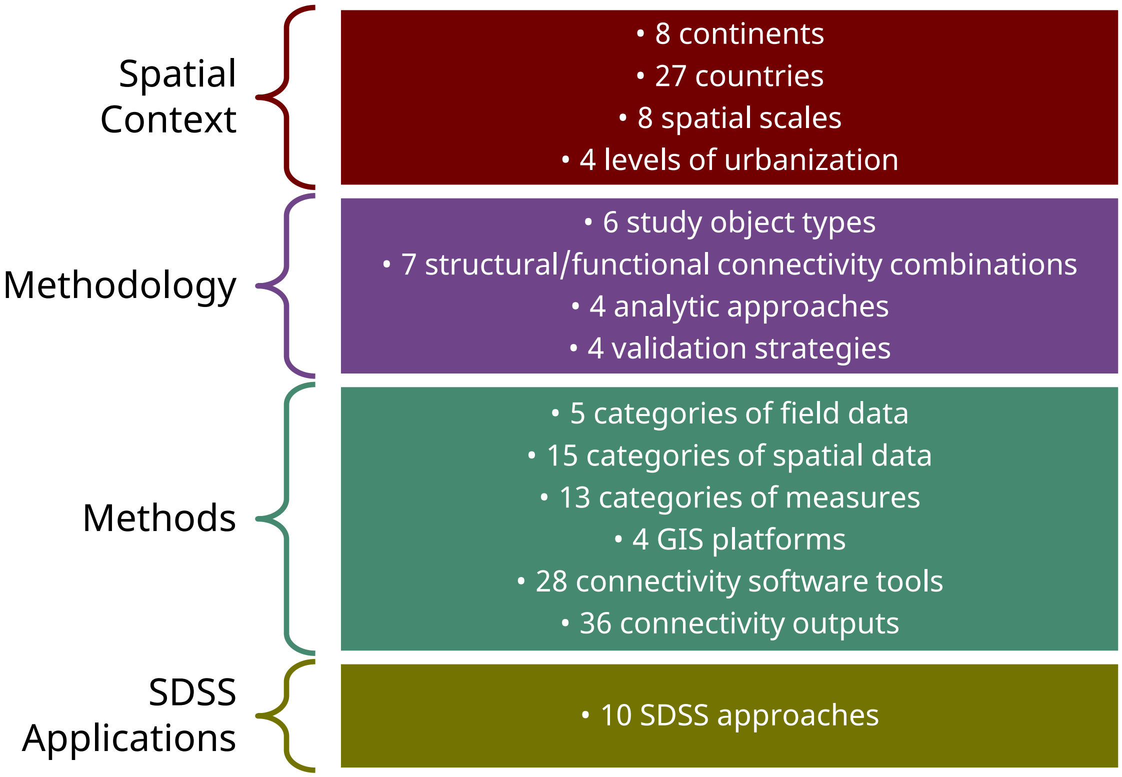
Chapter 5: Conclusion

The aim of this thesis has been to investigate methods for conservation organizations to integrate landscape connectivity analysis into systematic conservation planning. This has taken the form of a two-phase research project: first presenting urban/peri-urban connectivity analysis methods that are currently being used in the academic literature, and then applying this knowledge to a relevant case study in Waterloo Region and Wellington County. The two prongs of my research have generated several takeaways (more specifically discussed in previous chapters), including general trends across organizational contexts, challenges facing practitioners throughout the analysis process, and the implications of key decisions on resulting connectivity analysis outcomes.

Through my systematic literature review, I consider landscape connectivity analysis methodology in its use for urban and peri-urban conservation efforts. A major takeaway from this literature review is the remarkable diversity of connectivity analysis approaches, tools, and indices – this has been echoed in other literature reviews on this topic, including Rayfield et al.'s (2011) report on 60 connectivity measures, Correa Ayram et al.'s (2016) in-depth review of analysis methods, and Lookingbill et al.'s (2022) remarks on the proliferation of connectivity analysis since 2015. Compared to the 33 papers evaluated for Tischendorf & Fahrig's seminal review of landscape connectivity analysis (2000), my literature review demonstrates the increasing nuance and complexity of this field even when narrowed to only articles considering urban and peri-urban areas. A quantitative breakdown of the various of contexts and methods observed in my literature review is provided in Figure 20 below.

Figure 20

Graphic Showing the Variety of Contexts and Approaches Across 116 Urban/Peri-Urban Connectivity Papers.



The increasing diversity in the field of connectivity analysis has led to a lack of clarity in the definition and application of terms (Tischendorf & Fahrig, 2000; Rayfield et al., 2011; LaPoint et al., 2015), an inconsistent application of methods across studies (Tischendorf & Fahrig, 2000; Rayfield et al., 2011; LaPoint et al., 2015), and an absence of updated selection guidelines for practitioners (Rayfield et al., 2011). In response to the inconsistencies across literature, I have proposed increased support for the Conservation Corridor website (CCSG, n.d.-a; n.d.-b) as a flexible and authoritative digital hub for landscape connectivity ideas, concepts, and research. I have also attempted to produce connectivity analysis guidelines for conservation planners based on my own observations in this systematic literature review and my local case study.

The application of my literature review to a case study in Chapter 3 has cultivated a practical understanding of pivotal decisions, limitations, and context-dependent factors which influence the choice of landscape connectivity methods. Influential factors noted in this study include: (1) the relationship between organizational needs and software tool selection, (2) the method of data acquisition and processing, (3) the complexity of habitat delineation for multiple species, (4) the technical limitations surrounding distance calculations, and (5) the implications of measuring structural vs. functional connectivity.

Beyond the information this case study generates to produce best practices (Table 11), its output produces pragmatic benefit as well. The connectivity maps produced through the analysis process provide **rare** with a new quantitative ranking of patch importance which can be integrated within the upcoming revisions of their Land Securement Strategy. In addition to the provision of these connectivity maps, my work has produced in a database of habitat patches within the study area, including relative proportions of each land cover type and patch suitability for the fifteen focal species chosen for the study. These resources are intended to provide material benefit to an organization that is actively securing and stewarding natural lands in Southern Ontario (**rare**, 2023), where contested land use, encouragement of suburban sprawl, and undermined environmental protections are a significant threat to biodiversity (Kraus & Hebb, 2020; McIntosh & Syed, 2022; 2023). I am hopeful that the data produced by this case study will benefit the **rare** Charitable Research Reserve in coming years of conservation work.

Through analysis of academic literature and immersion in the practical facets of stakeholder consultation, geospatial analysis, and interpretation of connectivity results, I have endeavoured to disseminate knowledge about the use of connectivity analysis for conservation planning. This includes the decisions made throughout the connectivity analysis process, the organizational contexts which may limit or enable analysis choices, and the best practices that may improve connectivity analysis outputs. Beyond methodology, the culture of conservation planning must broaden its vision toward appropriate organizational values and practices, room for subjectivity and culture, Indigenous engagement, stakeholder representation, and an understanding that valuation of conservation lands cannot be wholly quantitative. Finding ways to effectively capture the qualitative value of conservation lands may be an interesting direction for future conservation planning research.

In closing, the value of natural lands transcends numeric scores, but landscape connectivity analysis allows for a unique perspective within conservation land valuation. This perspective goes beyond the consideration of habitat patches in isolation to account for dynamic and interactive processes occurring between patches on a diverse landscape (Saunders et al., 1991; Taylor et al., 1993). Connectivity analysis can thus produce outputs that facilitate efficient use of resources, effective valuation of competing land uses, and accountable decision making. As discussed in Chapter 1, these three characteristics are considered broad requirements for high quality systematic conservation planning (Margules & Pressey, 2000). The use of landscape connectivity analysis within a framework of systematic conservation planning can effectively support the protection and stewardship of ecologically sensitive lands, particularly in the contested urban/peri-urban areas of Southern Ontario and other similar landscapes.

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Appendix A: Spatial Data & Measurement Glossary

Spatial Data Definitions

Administrative Boundaries: Any anthropogenic (district, watershed, municipal, etc.) boundary explicitly used for analysis, including zoning and parcel fabric.

Discrete Structures: Discrete polygons showing individual buildings & other non-linear infrastructure, going beyond the detail of a land-use map.

Geology / Soils: Any sort of soil or rock data.

Habitat Classification & Management: Includes detailed habitat data such as ELC, forest age class, habitat “sensitivity” and “rarity” information; Also includes management data like frequency of grassland burn/mow, resource harvesting, and/or agricultural crop data.

Human Activity: Socio-demographic, economic, movement, and human impact data; May include population, GDP, property value, household income, traffic / transit data, light/noise pollution, impervious surfaces, and sociotope maps.

Hydrographic Data: Data about the location and attributes of aquatic features on the landscape. Includes streams, lakes, wetlands, ponds, etc.

Land Use / Land Cover: Map of land use or land cover types.

Meteorological Data: Rainfall, temperature, climate info, etc.

Parks & Protected Areas: Discrete features that may include city parks, conservation areas, provincial / national parks, nature reserves, or other protected land.

Planning Projections: Governmental data including projections for new development, new conservation priorities, or general new directions in urban / regional planning.

Remote Sensing / Imagery: Satellite or aerial imagery which is processed for connectivity analysis; May be used for NDVI, MSPA, or manual land cover assignment.

Slope & Terrain: Includes any data from a digital terrain, elevation, or slope model; also, any other kind of topographic map or slope measurements.

Species Occurrence / Distribution Data: any data about specific species ranges, occurrences, and distributions. May include wildlife atlas, citizen science, or data gathered from previous studies. Should not apply to occurrence or distribution data that has already been captured under “field data”.

Transportation Network: Includes road, rail, and trail networks.

Tree / Woodland Inventory: Quantity-based forest and tree data, including woodland inventory, individual street tree inventory, and urban canopy density.

Measurement Definitions

Combination Landscape Indices: Any indices more complex than those listed below that are not a direct measure of connectivity. Similar to a “wastebasket taxon” in that anything which didn’t fit elsewhere was lumped here.

Density / Intensity Measures: Measures that quantify a level of concentration, either of matter (density) or energy (intensity). Examples may include canopy density, urban development density, or intensity of resource use.

Dimensional Measures: Measures that quantify the size, shape, and/or relational distance of a given feature. These measures include length, height, width, distance, area, volume, and shape complexity (e.g., perimeter to area ratio).

Genetic Measures: Measures calculated during genetic analyses that may indirectly quantify connectivity on the landscape. Examples may include Genetic Drift or Linkage Disequilibrium.

Morphological Spatial Pattern Analysis (MSPA): Structural connectivity analysis method featuring the binary segmentation of the landscape into “foreground” (habitat) and “background” (matrix) pixels based on either satellite imagery or a land-use map, followed by definition of the resulting foreground shapes into morphological classes (core, edge, perforation, bridge, loop, branch, & islet; Vogt & Riitters, 2017).

Net Primary Production (NPP): Amount of biomass or carbon produced by primary producers per unit of area and time.

Normalized Difference Vegetation Index (NDVI) & Modified Normalized Difference Water Index (MNDWI): Vegetation differentiation and water differentiation measures calculated using multispectral imagery gathered by satellite or remote sensing.

Presence / Quantity Measures: Measures that quantify the existence and quantity of a feature (e.g., # of patches)

Quality Measures: Measures that represent the value quality of a feature, either expressed in words or quantified through a created scale and/or equation (e.g., patch importance, habitat quality, restoration value).

Statistical Measures: Measures that use statistics to validate some part of analysis. Examples include significance, uniformity, P value, and linear mixed models.

Temporal Measures: Measures that relate a phenomenon to a unit of time. Examples include rate of urbanization, # of years after intervention, and response time.

Threat / Disturbance Measures: combination measure, often including proximity to threats, intensity of threats, human activity data, intensity of development, etc.

Appendix B: Species Preferences & Habitat Suitability

This appendix shows the literature used to reflect the 15 focal species' preferences within my case study. This includes a table of the wildlife data gathered and a brief summary of the thought process guiding its application to my case study.

As discussed in Chapter 3, my focal species were chosen based on literature already gathered for my systematic literature review. I filtered the review data to find studies that measure connectivity with graph theory, consider specific wildlife species, conduct research into species preferences and habitat suitability, and occur in North America. I then reviewed these studies to determine whether they included criteria specific to definition of core habitat, and whether the species of study also occur in Waterloo Region and Wellington County. I finally used fifteen species from three North American studies (Lookingbill et al., 2010; Albert et al., 2017; Stille et al., 2018). Because of the inconsistent categorization of swamp habitat across these studies (described in Chapter 4), I conducted additional research to establish the use of swamp and wetland areas by the focal species. A table showing the original data is included on the following page.

The habitat patches that result from core habitat delineation, in my view, provide the best balance between ensuring that considered patches provide good habitat to a large spread of the focal species, while also minimizing the deletion of habitat patches that would have been adequate for generalist species. In any case, creating a single core habitat map for multiple species with diverse needs requires some compromise. I feel that this maximized the potential of habitat for a set of focal species in Waterloo Region and Wellington County. A table of how different patch types performed in their provision of wildlife habitat is included in Table 13.

Table 12

*Habitat Suitability and Dispersal Data Collected for 15 Focal Species Used in the **rare** Case Study*

Focal Species	Latin Name	Suitable Habitat Description	Forest, Swamp, & Wetland Usage*	Dispersal Distances (m)	References
Spring Peeper	*Pseudacris crucifer*	All wetlands with ≥30% forest cover within 300m AND all wetlands >2ha in area	F S W	300**	Stille et al., 2018
Wood Frog	*Rana sylvatica*	Dense forests ≥0.5ha in close proximity to wetland; sensitive to edge effect	F S	39 (gap-crossing) 564 (natal)	Albert et al., 2017
American Toad	*Anaxyrus americanus*	Open fields, mixed or deciduous forest ≥0.5ha in close proximity to wetland	F S W	73 (gap-crossing) 2,795 (natal)	Albert et al., 2017
Red-back Salamander	*Plethodon cinereus*	Dense mixed or deciduous forest ≥0.27ha; sensitive to edge effect	F*	10 (gap-crossing) 16 (natal)	Albert et al., 2017; Simmons, 2008
Red-breasted nuthatch	*Sitta canadensis*	Dense and old mixed or coniferous forest ≥3ha; sensitive to edge effect	F S*	44 (gap-crossing) 1,827 (natal)	Albert et al., 2017; Audubon, n.d.-a
American Woodcock	*Scolopax minor*	Open fields and low-height mixed or deciduous forest ≥5ha	F S*	195 (gap-crossing) 34,317 (natal)	Albert et al., 2017; Audubon, n.d.-b
Pileated Woodpecker	*Dryocopus pileatus*	Dense and old mixed or deciduous forest ≥1ha	F S*	112 (gap-crossing) 8,187 (natal)	Albert et al., 2017; Audubon, n.d.-c
Barred Owl	*Strix varia*	Old mixed or deciduous forest ≥1ha	F S*	209 (gap-crossing) 40,889m (natal)	Albert et al., 2017; Audubon, n.d.-d
White-tailed Deer	*Odocoileus virginianus*	Moderately dense mixed or coniferous forest ≥5ha	F S*	160 (gap-crossing) 20,521 (natal)	Albert et al., 2017; Larson et al., 1978
Snowshoe Hare	*Lepus americanus*	Low-height mixed or coniferous forest ≥2ha	F S*	99 (gap-crossing) 6,038 (natal)	Albert et al., 2017; Pietz & Tester, 1983

White-footed Mouse	*Peromyscus leucopus*	Dense mixed or deciduous forest ≥2.4ha	F*	71 (gap-crossing) 2,533 (natal)	Albert et al., 2017; Getz, 1968
Northern short-tailed shrew	*Blarina brevicauda*	Open fields, or dense and old mixed/deciduous forest ≥1ha	F S* W	39 (gap-crossing) 549 (natal)	Albert et al., 2017; Getz, 1961
Little Brown Bat	*Myotis lucifugus*	Foraging: Waterways, mixed forest/field <100ha; Roosting: buildings and tree cavities <4ha	F S	>2,600 (foraging) 275 (roosting)	Lookingbill et al., 2010
Northern Long-eared Bat	*Myotis septentrionalis*	Foraging: Intact forest, vernal pools, and upland streams <100ha; Roosting: Tree cavities <1ha	F S	<700 (roosting)	Lookingbill et al., 2010
Tricolored Bat	*Perimyotis subflavus*	Foraging: Waterways, mixed forest/field ~400ha; Roosting: Tree foliage, buildings <1ha	F S	~1,100 (foraging) 151 (roosting)	Lookingbill et al., 2010

F = Upland Forest; S = Swamp; W = Open Wetland;

* if an entry is starred, it required additional research to verify, which can be found in the secondary reference (if listed).

**estimated based on reported gap-crossing ability to reach forest from wetland

Table 13

Utility of the Seven Different Types of Core Habitat Complex Based on Focal Species' Needs

Habitat Complex Type	Statistics	# Species Served (at min. size)	Species Served (at min. size)
Isolated Open Wetland (W)	# Patches: 256 (14.7%) Min Area (W): **2.0 ha**	3	AT NS SP
Isolated Upland Forest (F)	# Patches: 14 (0.8%) Min Area (F): **18.6 ha** Min Core Area (F): 3.0 ha	12	AW BO LB NB NS PW RN RS SH TB WD WM
Isolated Swamp (S)	# Patches: 39 (2.2%) Min Area (S): **17.8 ha** Min Core Area (S): 3.0 ha	13	AT AW BO LB NB NS PW RN SH SP TB WD WF
Swamp-Wetland Complex (SW)	# Patches: 69 (4.0%) Min Area (S): 5.1 ha Min Area (W): 0.5 ha Min Area (SW): **6.6 ha**	10-13	AT AW BO LB NS PW SH SP TB WD *NB RN WF (depends on configuration)*
Forest-Wetland Complex (FW)	# Patches: 24 (1.4%) Min Area (F): 5.1 ha Min Area (W): 0.5 ha Min Area (FW): **5.6 ha**	11-15	AT AW BO LB NS PW SH SP TB WM WD *NB RS RN WF (depends on configuration)*
Forest-Swamp Complex (FS)	# Patches: 574 (33.0%) Min Area (F): 0.5 ha Min Area (S): 0.5 ha Min Area (FS): **17.6 ha** Min Core Area (FS): 3.0 ha	13-15	AT AW BO LB NB NS PW RN SH SP TB WD WF *RS WM (depends on configuration)*
Forest-Swamp-Wetland Complex (FSW)	# Patches: 762 (43.8%) Min Area (F): 0.5 ha Min Area (S): 0.5 ha Min Area (W): 0.5 ha Min Area (FS): 5.0 ha Min Area (FSW): **6.4 ha**	10-15	AT AW BO LB NS PW SH SP TB WD *NB RN RS WF WM (depends on configuration)*

F = Upland Forest; S = Swamp; W = Open Wetland; "Core Area" is based on species with edge sensitivity.

AT = American toad; AW = American woodcock; BO = Barred owl; LB = Little brown bat; NB = Northern long-eared bat; NS = Northern short-tailed shrew; PW = Pileated woodpecker; RS = Red-back salamander; RN = Red-breasted nuthatch; SH = Snowshoe hare; SP = Spring Peeper; TB = Tricolored bat; WM = White-footed mouse; WD = White-tailed deer; WF = Wood frog.