Urban Landscape Connectivity in Southern Ontario: Evaluating Current Approaches and Exploring the Potential of Climate Connectivity Considerations

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Landscape connectivity facilitates the movement of organisms, is important for the maintenance of ecological integrity, and supports the resilience of ecosystems to withstand the impacts of climate change. Land use change resulting from urbanization increases landscape fragmentation and habitat loss which negatively impacts the foraging, dispersal, and migration capabilities of species which can result in decreases in species abundance, diversity, and overall ecosystem function. At the same time, climate change is driving shifts in the ranges of some species as a result of changes in the suitability of habitat and climate conditions. Southern Ontario is the most densely populated region in Canada and is expected to accommodate significant population growth over the next 20-30 years. As a result of the expected growth in this area, the long-term protection and enhancement of landscape connectivity will be an important consideration in southern Ontario. The objectives of this research were to assess the effectiveness of current approaches to protecting and enhancing landscape connectivity in southern Ontario and to examine ways urban areas can support species movement under climate change. These objectives were explored at two different scales. Finer-scale analysis was undertaken through a case study of Waterloo Region ("the Region") using a combination of spatial and policy analysis. Using circuit theory, we modelled structural connectivity of forests and wetlands across the Region between 2000-2015. Then, we undertook content analysis of provincial and regional land use policies to examine the trends and evolution of land use policy guiding growth and development in the Region between 1996-2020 focusing on requirements to protect and enhance landscape connectivity. Our results showed that existing corridors have remained stable and land use policies for the protection of landscape connectivity have strengthened over time but also highlighted the need for greater emphasis on enhancing landscape connectivity within urban areas. Coarser-scale analysis was then undertaken to analyze existing climate connectivity literature to understand the potential role of urban areas in supporting broad scale ecosystem function and range shifts under climate change. Our analysis found very few discussions on the potential role of urban areas in supporting climate connectivity. In response, we present a perspective piece on potential opportunities for considering climate connectivity in conjunction with existing approaches to protecting and enhancing landscape connectivity.

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Chapter 1 : Introduction and Context

1.1 Research Overview

Landscape connectivity facilitates the movement of organisms, is important for the maintenance of ecological integrity (LaPoint et al., 2015; Rudnick et al., 2012), and supports the resilience of ecosystems to withstand the impacts of climate change (Costanza & Terando, 2019). Landscape connectivity can be defined as the "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor et al., 1993). The loss of landscape connectivity due to fragmentation and habitat loss impacts the foraging, dispersal, and migration capabilities of species which can result in decreases in species abundance, diversity, and overall ecosystem function (Bowers & McKnight, 2012; Calabrese & Fagan, 2004; Rudnick et al., 2012). Fragmentation can impact species movement by increasing the distance between habitat patches and introducing incompatible land uses (Rudnick et al., 2012). Edge effects from the breaking up of habitat into smaller patches can also impede or discourage movement for some species (Rudnick et al., 2012). However, some studies have found positive effects of fragmentation including increases in species abundance and diversity, improved predator-prey systems, and increased habitat diversity (Fahrig, 2017). As a result, the effects of fragmentation independent of habitat loss are a highly debated topic (Fahrig, 2017; Fahrig et al., 2019; Fletcher et al., 2018; Riva & Fahrig, 2023). Despite the benefits of landscape connectivity, there are concerns that corridors can also increase the spread of invasive species, predators, and pathogens (Haddad et al., 2014; Rudnick et al., 2012). However, a meta-analysis by Haddad et al. (2014) found no evidence that these potential negative effects consistently outweigh the ecological benefits of corridors. Fragmentation and habitat loss are key symptoms of land use change in urban environments and together pose a significant threat to ecological integrity and capacity for climate change resilience and adaptation (Costanza & Terando, 2019; Rudnick et al., 2012). At the same time, climate change is driving shifts in the ranges of some species as a result of changes in the suitability of habitat and climatic conditions (Costanza & Terando, 2019; Littlefield et al., 2019). These range shifts have led to studies assessing climate connectivity, which can be defined as "the ability of a landscape to promote or hinder species movement when responding to a changing climate" (Parks et al., 2020). Landscape connectivity in urban areas has garnered significant attention in land use planning research and practice (LaPoint et al., 2015; Lookingbill et al., 2022) but the effectiveness of current approaches for maintaining this connectivity remains understudied. In particular, the effectiveness of efforts to integrate landscape ecology into planning policies and processes requires more attention (Park, 2015). Additionally, climate connectivity is an emerging area of research and studies have yet to explore the role urban areas can play in supporting climate connectivity across broad spatial and temporal scales.

Southern Ontario is the most densely populated region in Canada (Aziz & Van Cappellen, 2019) and can be characterized by its mix of rural and urban landscapes with significant urbanization concentrated in the Greater Golden Horseshoe. In southern Ontario, a large portion of the natural landscapes have been converted to urban and agricultural uses (Aziz & Van Cappellen, 2019). Over the last two decades, planning for growth and development in the Greater Golden Horseshoe has been guided by key provincial land use policies including the Provincial Policy Statement (Province of Ontario, 2020) and Growth Plan for the Greater Golden Horseshoe (Province of Ontario, 2019b). Given the importance of landscape connectivity for maintaining ecosystem function, as well as climate change resilience and adaptation capacity of natural systems, my research explores whether urban environments in southern Ontario are being planned and managed to accommodate urban growth in a manner that maintains and enhances landscape connectivity as well as examining ways urban areas can support species movement under climate change.

My research explores these ideas at two different scales. The first is a finer-scale analysis of landscape connectivity change through a case study of Waterloo Region ("the Region"). As a rapidly growing region, the population of Waterloo is projected to grow by 56% from 2021 to 2046 which is significantly higher than the overall provincial projected growth (38%) and consistent with and in some cases higher than regions within the Greater Toronto Area (GTA) such as Halton (56%), Peel (52%), Durham (39%), and York (35%) (Province of Ontario, 2022a). The land use policy context of the Region is similar to other southern Ontario jurisdictions including those in the GTA. As a result, the outcomes of this case study are anticipated to be transferable and/or informative to other growing regions in southern Ontario. There are two specific questions guiding this portion of my research:

(1) *In the last two decades, how has landscape connectivity changed in the Region in comparison to urban growth and development?*
(2) *In the last two decades, how have land use policies guiding growth and development in the Region changed with respect to requirements to maintain and enhance landscape connectivity?*

The second component of my research is a coarser-scale analysis of the potential role urban areas can play in supporting climate change-induced range shifts through landscape connectivity.

My thesis is structured as follows: this chapter (Chapter 1) provides an overview of my research as well as background information on landscape connectivity in the context of urbanization and climate change; Chapter 2 addresses research questions (1) and (2) through spatial modelling and policy analyses; Chapter 3 addresses the coarser-scale analysis through an examination of climate connectivity literature; and Chapter 4 provides a high-level summary and synthesis of the ideas presented in my thesis including future directions. Chapters 2 and 3 are coauthored by Andrew Trant (University of Waterloo) and Michael

Drescher (University of Waterloo) and are consequently written in first person plural. The remaining chapters are written in first person singular.

1.2 Landscape Connectivity Context

1.2.1 Land Use Change, Urbanization, and Ecological Integrity

Land use change resulting from urbanization is one of the major drivers affecting ecological integrity including loss of biodiversity and habitat degradation in urban areas (Beninde et al., 2015; Costanza & Terando, 2019). Urban environments are warmer than non-urban areas, a phenomenon referred to as the urban heat island effect, experience elevated levels of nitrate in waters, and are particularly susceptible to climate change including impacts from extreme weather events such as droughts, heat waves, and flooding due in part to higher temperatures and impervious surfaces (Pickett et al., 2013). While these negative impacts do exist and cannot be entirely offset, urban areas can be planned and managed to conserve biodiversity, protect ecological integrity, and provide ecosystem services including positive impacts on human well-being such as benefits to mental health, and immune system function (Beninde et al., 2015; LaPoint et al., 2015; McDonnell & Hahs, 2013; Muratet et al., 2013).

Urban environments are especially vulnerable to increased landscape fragmentation, habitat degradation, and biodiversity loss as a result of considerable land conversion to residential development, infrastructure, and other urban uses (Beninde et al., 2015; Muratet et al., 2013; Park, 2015). Protecting and enhancing landscape connectivity has been shown to reduce these negative impacts and support the maintenance of ecological integrity when coupled with improving land use compatibility of surrounding uses (Esbah et al., 2009). Ecological integrity can be defined as “the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region” (Karr & Dudley, 1981). A component of ecological integrity is the ability to withstand disturbance and is closely linked to the concept of resilience (Gonzalez, 2023; Reza & Abdullah, 2011). Ecological integrity is often measured based on the structural, functional, and compositional attributes of an ecosystem (Reza & Abdullah, 2011; Theobald, 2013; Torres et al., 2018). Metrics include compositional attributes like land use and species diversity, structural attributes like species distribution and landscape connectivity, and functional attributes like competition, succession, and predation (Carter et al., 2019; Reza & Abdullah, 2011). Landscape fragmentation resulting from land use change can negatively impact the structural, functional, and compositional attributes of an ecosystem including loss of species abundance and diversity as well as loss of important ecosystem functions such as nutrient cycling, seed dispersal, and population dynamics (Reza & Abdullah, 2011).

The protection and enhancement of corridors between habitat patches is a key requirement for conserving connectivity (Henson et al., 2005; Rudnick et al., 2012). This is of particular importance in urban contexts as it can be difficult to conserve large habitat patches (Muratet et al., 2013). Urban parks and open space also support the enhancement of landscape connectivity in urban areas as they may function as stepping stones for many species (Ignatieva et al., 2011; Ikin et al., 2013; Ossola et al., 2019). It is important to note that connectivity is context specific with various species interacting with the landscape in different ways and thus the degree to which the landscape facilitates movement will also depend on the behaviours and preferences of the species being considered (Calabrese & Fagan, 2004; Rudnick et al., 2012).

There are two main categories of connectivity analysis that are typically described in the literature: structural connectivity and functional connectivity. Rudnick et al. (2012) define structural connectivity as "the physical characteristics of a landscape that allow for movement, including topography, hydrology, vegetative cover, and human land use patterns" and functional connectivity as "how well genes, propagules, individuals, or populations move through the landscape." The most significant difference between structural and functional connectivity is that structural connectivity focuses on how landscape structure facilitates or impedes movement whereas functional connectivity focuses on species behavioural responses to the landscape (LaPoint et al., 2015).

1.2.2 Climate Change

Both land use change and climate change are negatively impacting the diversity and abundance of many native species and are both significant drivers of habitat loss (Costanza & Terando, 2019). While land use change results in increased landscape fragmentation and habitat loss, climate change is necessitating the ranges of some species to shift in order to maintain suitable habitat and climate conditions (Costanza & Terando, 2019; Littlefield et al., 2019; McGuire et al., 2016; Rudnick et al., 2012). In fragmented landscapes the ability of ecosystems and species to withstand and adapt to the impacts of climate change is reduced (Costanza & Terando, 2019; Littlefield et al., 2019). Landscape fragmentation impacts both the resilience of species to adapt to climate change within their current ranges as well as the ability for others to shift their geographic range (Costanza & Terando, 2019). As a result, the maintenance and enhancement of landscape connectivity is increasingly viewed as a key component of climate change adaptation strategies (Bowers & McKnight, 2012; Costanza & Terando, 2019; Littlefield et al., 2019).

Many studies that address landscape connectivity focus on land use change with only a few also incorporating climate change considerations into their analysis (Costanza & Terando, 2019; Littlefield et al., 2019). However, as indicated by Littlefield et al. (2019), maintaining and enhancing connectivity in general will still support the ability of ecosystems and species to adapt to climate change since such strategies still increase the degree to which the landscape facilitates movement. However, such approaches may not account for nuances in individual species behaviour. Many studies that do address climate connectivity rely on adaptive approaches that consider projected range shifts and changes in climate conditions over broad temporal and spatial scales (Costanza & Terando, 2019; Littlefield et al., 2019). These approaches are intended to account for future dynamic shifts in connectivity as climate change causes habitat and corridor suitability to change (Costanza & Terando, 2019).

Successful range shifts requires species to keep pace with climate change which requires the availability of newly suitable habitat as well as connectivity and appropriate conditions between current and future locations (Marrotte et al., 2020; Senior et al., 2019). In expanding their geographic range, species will encounter natural and anthropogenic barriers such as landscapes that do not support their niche requirements (Marrotte et al., 2020). A common mechanism to enhance connectivity between current and future habitat locations is the protection and enhancement of climate corridors (Sonntag & Fourcade, 2022). Although this research does not model climate connectivity and instead explores the potential role of urban areas in supporting climate connectivity at a coarse-scale, it is important to note two metrics commonly used for identifying climate corridors: climate velocity and climate exposure. Climate velocity represents “the speed and direction in which a species would need to move to maintain its current climate conditions under climate change” (Brito-Morales et al., 2018) and climate exposure represents landscape resistance to movement by quantifying “the amount of climatic dissimilarity encountered as organisms migrate in response to climate change” (Parks et al., 2020).

1.3 Modelling Landscape Connectivity

1.3.1 Landscape Resistance

Landscape resistance represents the difficulty of moving across various landscape features (Adriaensen et al., 2003; Graves et al., 2014; Wade et al., 2015; Zeller et al., 2012). When modelling landscape connectivity, resistance surfaces (also referred to as cost-surfaces) are used to estimate the permeability of the landscape which is then used to model landscape connectivity. Resistance surfaces provide a means to quantitatively analyze the ease of movement across the landscape where resistance represents “the hypothesised relationships between landscape features and a variety of ecological flows, such as movement of organisms, genes, or processes” (Wade et al., 2015). The resistance surface is a foundational component of the modelling process.

As indicated previously, there are two main categories of connectivity analysis: structural connectivity and functional connectivity. In line with these two categories of analysis, there are two broad methods for calculating and assigning resistance values. Structural connectivity methods focus on the impact of landscape structure on species movement whereas functional connectivity methods focus on species behavioural responses to the landscape through incorporation of biological data into calculations of resistance such as mortality risk, species presence, and dispersal data (Etherington & Holland, 2013; Godet & Clauzel, 2021; Keeley et al., 2016; Rudnick et al., 2012). It is critical that resistance estimates are appropriate to ensure that connectivity modelling is representative and to ensure the implementation of relevant connectivity protection and management regimes (Keeley et al., 2016). The most appropriate method depends on the objectives of the analysis, the availability of data, and the type of connectivity being assessed.

When the focus of the research is on examining broader patterns of connectivity for a particular landscape or ecosystem, and not on individual or focal species, resistance values assigned to assess structural connectivity are often generalized for species associated with that landscape or ecosystem. For example, Theobald et al. (2011) focused on forest ecosystems in the western United States. In this region, many of the forest associated species are particularly sensitive to fragmentation and, as a result, the researchers assumed that intact forest ecosystems provide habitat for wide-ranging forest carnivores such as lynx and pine martens and smaller forest specialists such as voles and squirrels (Theobald et al., 2011). From this assumption, resistance values were assigned based on increasing resistance to movement of non-forest land cover as their vegetation characteristics become less and less like forest conditions (e.g. stand height and density) (Theobald et al., 2011). In this case, the researchers assumed forest and riparian land cover were the least resistant to movement, shrubland and grassland are more resistant, and built-up areas are the most resistant (Theobald et al., 2011). This approach acknowledges that forest species do not move exclusively through forest land cover and may venture to other land cover types. In contrast, Pelletier et al. (2017) took a different approach to assigning resistance values. The research modelled forest connectivity in eastern Canada. Instead of the graduated approach undertaken by Theobald et al. (2011), Pelletier et al. (2017) assigned resistance values with the intent of creating a contrast between forest and non-forest land cover. The land cover data was grouped into three generalized classes: forest, non-forest, and no data. Forest land cover was assigned a resistance of 1, while non-forest and areas without data were assigned a resistance of 500.

For structural connectivity methods, assigning resistance values is often based on expert opinion and/or literature reviews (Godet & Clauzel, 2021; McRae et al., 2008). For example, Avon & Bergès (2016) undertook a literature review to collect information on forest mammal species and studies that have used generic forest species approaches to connectivity analysis to assign their resistance values. Of note, the researchers focused on studies that conducted sensitivity analyses to validate their models (Avon

& Bergès, 2016). This is particularly important because despite landscape resistance being a foundational component of the connectivity modelling process, there is no standard method for assigning landscape resistance and the most appropriate approaches for doing so are still under debate (Avon & Bergès, 2016; Graves et al., 2014; Zeller et al., 2012). This is further supported by Drielsma et al. (2022) who highlight that "in assessing landscape connectivity it is a significant challenge to adequately represent movement abilities across the full spectrum of life." This is particularly true for structural connectivity approaches as they have been criticized for being largely theoretical without the incorporation of biological data or being validated with empirical evidence (Drielsma et al., 2022; Godet & Clauzel, 2021).

Functional connectivity methods are most often used for modelling connectivity for individual or focal species, however, the analysis can be aggregated to provide insight on the functional connectivity of broader landscapes and ecosystems. This is done by assessing the functional connectivity for individual species and aggregating these individual assessments (Drielsma et al., 2022; Theobald et al., 2011). For functional connectivity analysis "the source, destination, path and movement abilities are explicitly linked to the biology of a defined species or functionally related group" (Drielsma et al., 2022). The most significant benefit to functional connectivity analysis is that it provides the most ecologically representative depiction of connectivity. However, this approach can be time consuming and costly to implement due to data requirements including technological, spatial and temporal constraints as well as the feasibility of collecting data for multiple species (Rudnick et al., 2012).

Regardless of the approach taken to evaluate connectivity there will always be a degree of uncertainty about the accuracy of the resistance values. Unfortunately, very few studies attempt to validate the chosen resistance values with many studies solely relying on expert opinion and the literature to inform their selection of values (Etherington, 2016; Rayfield et al., 2010). Of some comfort, studies that have assessed sensitivity of their models have discovered that models remain insensitive to moderate errors in resistance values as long as the ranking of the values is in the correct order (Beier et al., 2009; Simpkins et al., 2017). When validation of the resistance values is undertaken, a common approach is to verify results using biological data. For example, Verbeylen et al. (2003) tested the sensitivity of resistance values against field data to find the best fitting model. Starting with a simple resistance surface using two classes to distinguish suitable vegetation from everything else, the researchers gradually increased the number of classes used until they reached a model with 10 classes. The ranking of the classes from least to most resistant was based on expert opinion and the literature. They found that increasing the number of resistance classes improved the results of their least-cost analysis. However, the results of a model using 10 classes was not significantly different from a model using five classes. In this case, they determined that a moderately coarse division of resistance classes was sufficient for their assessment of red squirrels (Verbeylen et al., 2003).

Landscape resistance is now the most commonly used approach for modelling landscape connectivity. However, prior to its widespread use, Euclidean distance was used. Euclidean distance represents the topological distance between habitat patches (Adriaensen et al., 2003; Avon & Bergès, 2016). Euclidean distance is now considered an ineffective measure of connectivity because it only represents the distance between habitat patches and does not consider the cumulative cost of travel along an actual travel route (Avon & Bergès, 2016; Etherington & Holland, 2013).

1.3.2 Least Cost Analysis and Circuit Theory

Connectivity analysis typically results in the production of connectivity maps that identify predicted linkages and barriers to movement. These maps can then be used to inform conservation management decisions. The reliability of these maps depends significantly on the accuracy of the resistance surface. There are two common modelling methods for measuring and evaluating landscape connectivity: least-cost analysis and circuit theory. Least-cost analysis identifies the least-cost path based on the cumulative cost of movement between one area to another whereas circuit theory identifies multiple alternative paths across focal nodes and uses this in combination with cumulative cost to model connectivity (McRae et al., 2008; Rudnick et al., 2012). While both least-cost analysis and circuit theory can be used to assess connectivity of the landscape, their strengths and weaknesses have led to some scholars choosing to apply both approaches concomitantly (Beaujean et al., 2021).

<u>Least-Cost Analysis</u>

Least-cost analysis models connectivity and movement through identifying the least-cost path between habitat patches (also referred to as the most efficient route or optimal path) (Adriaensen et al., 2003; Etherington & Holland, 2013; McClure et al., 2016). As a resistance-based modelling approach, least-cost analysis considers the cumulative cost (i.e. distance travelled + difficulty) of travelling from one habitat patch to another and identifies “the most likely route an individual would take to move between the two habitat patches considered” (Avon & Bergès, 2016). Least-cost analysis assumes that the least-cost path provides the greatest probability for survival / successful movement (Adriaensen et al., 2003; McClure et al., 2016). There are two data components needed to undertake least-cost analysis: a resistance surface and a source layer. Resistance surfaces were discussed in *Section 1.3.1* and the source layer defines the start and end points to be connected (Adriaensen et al., 2003; McRae et al., 2012). In addition to these two components, some researchers choose to incorporate maximum effective distance into their least-cost models based on species dispersal data. The maximum effective distance recognizes that the least-cost path will be irrelevant if it exceeds the capacity of a species to make the journey (Sawyer et al., 2011).

Least-cost analysis is an effective tool for measuring connectivity between two locations and is considered more ecologically realistic than Euclidean distance due to its consideration of cumulative cost (Avon & Bergès, 2016; Etherington & Holland, 2013). The most significant benefit of least-cost analysis is that it offers a relatively simple and clear method to define priority corridors of connectivity (Beaujean et al., 2021; McClure et al., 2016). In a study by Beaujean et al. (2021), the researchers found that least-cost analysis was more effective than circuit theory (see below) at identifying priority corridors in homogeneous landscapes.

There are some limitations to the least-cost analysis approach. Least-cost analysis assumes that: 1) individuals have a comprehensive knowledge of the landscape, and 2) they know and will take the least-cost path (Adriaensen et al., 2003; Avon & Bergès, 2016; Marrotte & Bowman, 2017). Further, least-cost analysis does not consider alternative paths including the potential for other low-cost routes and this could result in other critical connectivity linkages being overlooked. In the previously discussed study by Beaujean et al. (2021), researchers found that the corridors identified using least-cost path and circuit theory were similar, but they did not always align. For one such corridor, the failure to align was because the circuit theory analysis considered alternative paths and redundancies which meant that a different corridor was identified than the least-cost path which was based solely on cumulative cost.

Circuit Theory

Circuit theory treats the landscape like an electrical circuit where an electric current, representing movement, flows through the landscape based on areas of varying resistance identified in the resistance surface (McClure et al., 2016; Rudnick et al., 2012). The most significant difference between least-cost analysis and circuit theory is that the latter identifies all the alternative paths between habitat patches. Instead of focusing on solely the cumulative cost of movement between two patches, circuit theory combines this cumulative cost with the availability of alternative routes to determine how well the landscape facilitates or impedes movement (McRae et al., 2008). Additionally, circuit theory is based on random walk theory which looks at the probability of a random walker travelling through the landscape (McRae et al., 2008). To model using circuit theory, a resistance surface and focal nodes layer are required.

Maps created using circuit theory show the current density across the landscape where high current density represents higher probability for movement. One of the benefits of circuit theory is that interpretation of these current density maps can be used as an effective tool for identifying corridors and pinch-points in connectivity (Beaujean et al., 2021; McClure et al., 2016; Rudnick et al., 2012). Corridors and pinch points are observed in areas with the highest current density because the surrounding areas will have fewer alternative paths for movement (Beaujean et al., 2021; McClure et al., 2016; Rudnick et al., 2012). Lower current density areas can represent high resistance to movement but in homogenous landscapes it can also indicate that there are several equally effective alternative routes for travel (Rudnick et al., 2012). Another benefit is that circuit theory assumes that species have no knowledge of the landscape beyond their immediate surroundings. The advantage of this is that modelling will identify all the alternative paths for movement as well as consider redundancy meaning that the model assumes that greater redundancy in paths enhances the flow of movement (McClure et al., 2016; McRae et al., 2008).

There are some limitations to circuit theory. First, while circuit theory models are able to identify priority corridors for conservation and management in heterogeneous landscapes such as urban environments, priority corridors are more clearly identified using least-cost analysis which identifies the optimal path (Beaujean et al., 2021). Second, because circuit theory is based on random walk theory, there is no learning or ‘memory’ incorporated into the model, meaning that the model cannot capture “changes in movement behaviour with time, or mortality rates that increase with an organism’s age” (McRae et al., 2008). A third limitation is that the computational power required to run the model can limit the spatial resolution and size of the area being modelled. However, as is highlighted in the following Pelletier et al. (2017) example, there are ways to work around the computational demands to model larger landscapes at finer resolutions than would otherwise be possible.

Consistent with methods for calculating and assigning resistance values described in *Section 1.3.1*, the use of circuit theory for modelling connectivity can be done for both an individual or a selection of focal species and broader patterns of connectivity for a particular landscape or ecosystem. An example of circuit theory being used to assess connectivity for an individual species is the analysis conducted by Pilliod et al. (2015). In their study, they used circuit theory to assess habitat connectivity between breeding locations of the Columbia spotted frog across the Great Basin in North America (Pilliod et al., 2015).

Returning to the Pelletier et al. (2017) example, this study is an example of applying circuit theory at a broad landscape scale. This study modelled forest connectivity regions of Canada (600 million hectares of forested ecosystems). Due to the large size of the landscape, running the entire study area through Circuitscape was not feasible. To address this, the researchers used a tiling approach where the landscape was broken down into 25 km x 25 km (1000 x 1000 pixels) tiles with a 1000 pixel buffer for overlap (Pelletier et al., 2017). Then, each tile was run individually through Circuitscape after which the buffers were removed and the tiles were reassembled (Pelletier et al., 2017). A key consideration when using the tiling approach is that the size of the tiles and the buffer used need to be chosen appropriately to balance computational capacity and limit the visibility of seams. An earlier study by Pelletier et al. (2014) tested different tile and buffer sizes and determined that either larger tiles or larger buffers were the most effective ways to reduce the visibility of seam lines. However, larger tiles are preferrable to reduce the chance of missing larger-scale patterns of connectivity (Koen et al., 2019). There is also the risk of overestimating the importance of smaller habitat patches when using smaller tiles. However, the significance of this risk depends on the objectives of the research (i.e. interested in larger or smaller-scale processes) (Koen et al., 2019).

To address research question (1), I used circuit theory to model structural connectivity in the Region. This decision was made because my research objective is to capture the broader patterns of connectivity in the Region based on generic assumptions of movement by land cover type for forest and wetland species. I was interested in capturing all the alternative paths to movement that are present in the landscape and not just the most efficient path between habitat patches. I was also interested in identifying the barriers and corridors of connectivity in the Region. As highlighted above, circuit theory is more effective than least-cost analysis at identifying pinch points in connectivity given its consideration of multiple paths and redundancy in movement (Beaujean et al., 2021; McClure et al., 2016). Further, although priority corridors are easier to identify using least-cost analysis, circuit theory is still an effective mechanism for doing so in heterogeneous landscapes such as urban environments (Beaujean et al., 2021).

Chapter 2 : Determining the Effectiveness of Current Approaches to Protecting and Enhancing Landscape Connectivity in Urban Areas of Southern Ontario

2.1 Introduction

Land use change resulting from urbanization is one of the major drivers of biodiversity loss and habitat degradation (Beninde et al., 2015; Costanza & Terando, 2019). In particular, land conversion to residential development and infrastructure increases landscape fragmentation and habitat loss in urban areas which negatively impacts the foraging, dispersal, and migration capabilities of species reducing species abundance, diversity, and overall ecosystem function (Beninde et al., 2015; Park, 2015; Rudnick et al., 2012). Urban land uses and infrastructure affect movement for many taxa including birds (Benítez-López et al., 2010; Dunford & Freemark, 2005; Ossola et al., 2019), reptiles (Crosby et al., 2009; Milne & Bennett, 2007), and mammals (Benítez-López et al., 2010; Ossola et al., 2019). Urbanization also impacts the dispersal, pollination, and growth rates of many plants as a result of fragmentation, increased temperatures, soil and air pollution, and biotic homogenization from replacing native species with non-native ones (Ruas et al., 2022). Protecting and enhancing landscape connectivity has been shown to reduce these negative impacts (Gilbert-Norton et al., 2010; Resasco, 2019). There are two main categories of landscape connectivity. Structural connectivity focuses on how landscape structure facilitates or impedes movement whereas functional connectivity focuses on species behavioural responses to the landscape (LaPoint et al., 2015; Rudnick et al., 2012).

While some species may do well in urban areas, many rely on stepping stones provided by urban parks and open space (Han & Keeffe, 2020; Ignatieva et al., 2011; Lynch, 2019; Ossola et al., 2019). Stepping stones are small habitat patches that reduce distances between larger core habitat areas by functioning as refuges with some resources to support species continued movement across a landscape (Han & Keeffe, 2020; Lynch, 2019). Stepping stones are not just important for animal movement but can also assist forest migration through supporting seed dispersal and plant establishment (Han & Keeffe, 2020). Stepping stones can function as part of a connected system of corridors (also referred to as linkages) and core habitat patches but where corridors are not feasible stepping stones are also beneficial in shortening the distance between core habitat and thus increasing landscape permeability (Lynch, 2019). Landscape permeability is the ability of a landscape to support the movement of species and is the inverse of landscape resistance (Han & Keeffe, 2020; Theobald et al., 2011). However, it is noted that the benefits of stepping stones are dependent upon the characteristics of specific species and the ability of an individual stepping stone to meet niche requirements (Lynch, 2019). Stepping stones and corridors are particularly important in urban areas as it can be difficult to conserve large habitat patches and doing so is often undesirable in urban areas where compact development and density are prioritized (Lynch, 2019; Muratet et al., 2013).

Protecting landscape connectivity includes long-term protection of corridors and habitat patches from urban development. Further, green infrastructure can assist in the enhancement of landscape connectivity in urban areas by providing additional habitat patches, stepping stones, and linkages that increase vegetation cover and biodiversity (Beaujean et al., 2021; Ignatieva et al., 2011; McPhearson et al., 2016). Green infrastructure can be defined as “natural and human-made elements that provide ecological and hydrological functions and processes” (Province of Ontario, 2020). Green infrastructure includes parks, green roofs, street trees, permeable paving, and natural heritage features and areas such as wetlands and woodlands (Province of Ontario, 2020).

Landscape connectivity research focused on urban areas has been growing annually over the past 40 years (LaPoint et al., 2015; Lookingbill et al., 2022). Given the increasing importance placed on landscape connectivity in urban environments over the last several decades, in this study we explore the effectiveness of current approaches to protecting and enhancing landscape connectivity in urban areas of southern Ontario. Southern Ontario is the most densely populated region in Canada (Aziz & Van Cappellen, 2019) and is expected to accommodate significant population growth over the next 20-30 years, especially in the Greater Golden Horseshoe (“GGH”) (Province of Ontario, 2022a). The Greater Golden Horseshoe is located on the western end of Lake Ontario and extends south to Haldimand County and Niagara Region, west to Waterloo Region and Wellington County, north to Simcoe County, and east to Peterborough County and Northumberland County. The Greater Toronto Area (“GTA”) is centrally located within the GGH on the northern edge of Lake Ontario. As a result of the expected growth in this area, growth management planning that integrates landscape connectivity will continue to be an important consideration in southern Ontario. Therefore, understanding the successes and failures of current approaches will provide valuable insight to ensure its long-term protection and enhancement. The objective of our study is to address the following research questions through a case study of Waterloo Region (“the Region”): (RQ 1) In the last two decades, how has landscape connectivity changed in the Region in comparison to urban growth and development? and (RQ 2) In the last two decades, how have land use policies guiding growth and development in the Region changed with respect to requirements to maintain and enhance landscape connectivity?

2.2 Case Study Area

Waterloo Region (43° 26' 56.4" N, 80° 29' 42" W; *Figure 1*) is an upper-tier municipality located in southern Ontario and is comprised of three cities (Kitchener, Waterloo, and Cambridge) and four rural townships (North Dumfries, Wellesley, Wilmot, and Woolwich). The population of the Region was estimated to be 647,540 in 2022 (Region of Waterloo, 2023). For the last 12 years, the Region has exceeded its residential intensification target of 45 per cent (Region of Waterloo, 2022a). In 2021, 68 per cent of new residential units were situated within the built-up area and 39 per cent were located along the Region's Central Transit Corridor – the area surrounding the Region's light rail transit system (Region of Waterloo, 2022a). As a rapidly growing region, the population of the Region is projected to grow by 56% from 2021 to 2046 which is higher than the overall provincial projected growth (38%) and consistent with and in some cases higher than regions within the GTA such as Halton (56%), Peel (52%), Durham (39%), and York (35%) (Province of Ontario, 2022a). The land use policy context of the Region is similar to other southern Ontario jurisdictions including those in the GTA. As a result, the outcomes of this case study are anticipated to be transferable to and informative for other growing regions in southern Ontario. We undertook modelling for the entire case study area (map extent of Figure 1) however, since the focus of our research was on urban environments our analysis of the results was centred on the three cities of the Region.

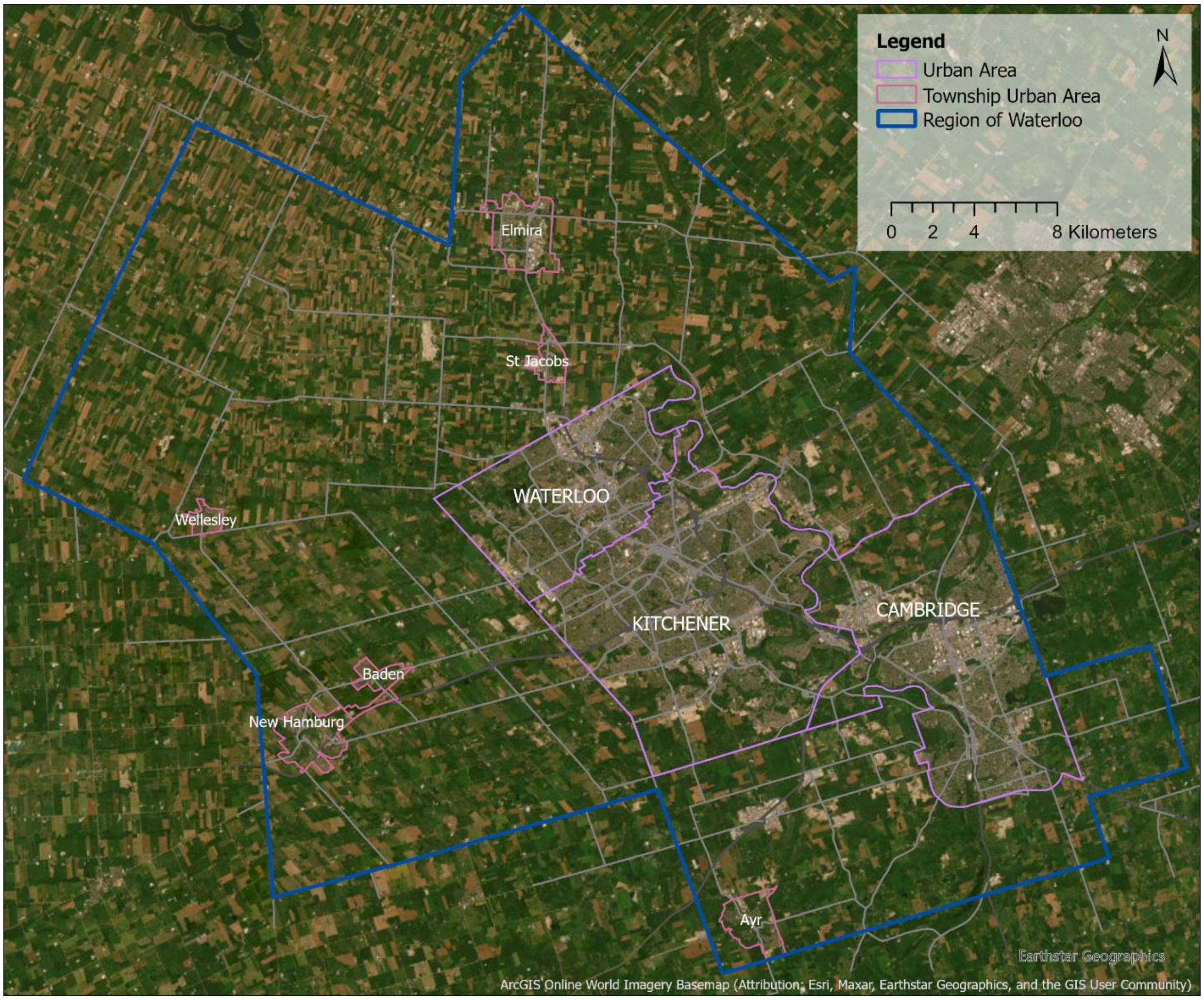

Figure 1. Context map of Waterloo Region showing the regional boundary (blue), urban areas (purple), and township urban areas (pink).

2.3 Methods

2.3.1 Study Design

To determine the effectiveness of current approaches to protecting and enhancing landscape connectivity in urban areas of the Region our research was conducted using a combination of spatial and policy analyses. This approach allowed us to evaluate the physical changes in landscape connectivity in comparison to urban growth and development and the evolution of land use policies guiding growth and development in the Region with respect to provincial and regional requirements to protect and enhance landscape connectivity.

To answer RQ 1, the spatial analysis component of our research needed to be undertaken at a scale that captured the broader patterns of connectivity for the Region. Lack of data availability as well as time and resource constraints to collect primary data limited the feasibility of undertaking connectivity analysis for a selection of focal species. As a result, we focused our research on structural connectivity using generalized assumptions of species movement based on land cover type. The predominant natural land cover in the Region are forests and wetlands and thus separate connectivity analyses were conducted for each of these land cover types (*Refer to Appendix A for a breakdown of land cover in the Region*). To model structural connectivity, the Southern Ontario Land Resource Information System (SOLRIS) data were used. This is an open dataset available on the Ontario GeoHub and is a landscape-level inventory of land cover for southern Ontario from 2000-2015 with data availability for the following intervals: 2000-2002, 2009-2011, and 2015. The minimum mappable unit is 0.5 hectares and the data is recommended for mapping analysis at a regional scale (Province of Ontario, 2019c). We modelled forest and wetland connectivity using circuit theory in Circuitscape (Anantharaman et al., 2020) for each data interval. Circuit theory was chosen for its ability to capture all the alternative paths to movement (McRae et al., 2008), its effectiveness at identifying pinch points in connectivity, and its capacity to identify priority corridors in heterogeneous landscapes such as urban environments (Beaujean et al., 2021). Further details on the spatial analyses are included in *Section 2.3.2*.

To answer RQ 2, the focus of the policy analysis was on provincial and regional land use policies as these are the jurisdictions in Ontario that have direct responsibility for growth management planning as outlined in the *Planning Act, R.S.I (1990)* and Provincial Policy Statement (2020). The land use policy context for the Region underwent numerous changes during the 2000-2015 timeframe with more recent changes occurring in 2019 and 2020. Policy documents assessed in our research include the Provincial Policy Statement (“PPS”) (1996, 1997, 2005, 2014, and 2020), Growth Plan for the Greater Golden Horseshoe (“GP”) (2006, 2013 Consolidation, 2019, and 2020 Consolidation), and the Waterloo Regional Official Plan (“ROP”) (1998 Consolidation, 2006 Consolidation, and 2015). These documents provide the primary land use policy direction for growth management in the Region and were selected using purposive sampling. Further details on the policy analysis are included in *Section 2.3.3*. It is noted that since the completion of the research there have been further changes to land use planning legislation and policies in Ontario. Most recently, in April 2023 the Province of Ontario proposed a new Provincial Planning Statement that is currently undergoing public consultation and is posted on the Environmental Registry of Ontario (Province of Ontario, 2023). This new Provincial Planning Statement proposes a new land use planning document that is adapted from the GP 2020 consolidation and PPS 2020.

2.3.2 Spatial Analysis

To analyze structural landscape connectivity in the Region we: (1) identified the main land cover types within the Region using the SOLRIS data, ranked them from high to low permeability, and assigned landscape resistance values; (2) measured connectivity using circuit theory and an omnidirectional approach to capture broad landscape-level patterns of connectivity; and (3) assessed the sensitivity of model inputs to variations in assumptions.

Land Cover Rankings & Landscape Resistance

To identify and rank the land cover types in the Region, we first consolidated the SOLRIS data into the following 10 land cover classes: Forest, Grassland, Wetland, Parks/Open Space, Cultivated Trees & Hedgerows, Water, Agriculture, Urban, Infrastructure, and Extraction. An overview of our land cover classes is provided in *Tables 1 & 2*. Most of the SOLRIS classes fit easily into these 10 categories. However, since swamps could functionally be considered a forest type or wetland type, we determined that the treed swamp and thicket swamp SOLRIS classes could be classified under either the Forest or Wetland class and the ranking of them as one or the other could impact the model results. As a result, we chose to test two different land cover groupings. One placing treed and thicket swamps under the forest class and another placing them under the wetland class.

Following the consolidation of land cover classes, we ranked each class from high to low permeability separately for forest and wetland species. The rankings we chose were based on a literature review and our assumptions about how landscape structure impacts movement including the foraging, dispersal, and migration capabilities for forest and wetland species. Consistent with the assumptions used by Theobald et al. 2011, we assumed that largely intact forest ecosystems provide habitat for a broad array of forest species and that largely intact wetland ecosystems provide habitat for a broad array of wetland species. We also assumed that as vegetation characteristics depart from forest or wetland conditions, land cover types would have increasing resistance to movement (Theobald et al., 2011). These assumptions were supported by our opportunistic literature review. The focus of this research was to model structural connectivity in the Region with the objective of capturing broader patterns of connectivity. As a result, the focus of the literature review was to get a general understanding of the impacts of different land cover types on movement for a variety of species including birds, mammals, herpetofauna, and plants. We focused our literature search on review papers and prioritized the review of papers published in the last 15 years. To find relevant articles we undertook searches by species (i.e., birds, mammals, herpetofauna, plants) and land cover type, as well as a general search of land use effects on movement for forest and wetland species. We also considered the permeability rankings used by other studies.

For forest species, we assumed that: forest cover was the most permeable to movement; wetlands, grasslands, and cultivated trees and hedgerows were supportive and moderately permeable; water and parks and open space provided some permeability and natural cover that functions as stepping stones; agriculture functions as a modest barrier; and urban, infrastructure, and extraction uses provide very low permeability. The rankings for wetland species were similar, where we assumed that: wetlands and water were the most permeable; forests, grasslands, and cultivated trees and hedgerows were moderately permeable; parks and open space provided some permeability and natural cover that functions as stepping stones; agriculture functions as a modest barrier; and urban, infrastructure, and extraction uses provide very low permeability. When ranking the land cover classes from high to low permeability we determined that for wetland species the water class could be ranked either the same as wetlands or second most permeable after wetlands. Therefore, we chose to test both options. This, paired with the two options for treed and thicket swamps led to two forest land cover groupings (Forest A & B) and four wetland groupings (Wetland A, B, C, & D) being tested (refer to Tables 3 and 4).

Following permeability ranking, we then assigned the landscape resistance values. As there is no standard method for assigning landscape resistance values (Avon & Bergès, 2016; Graves et al., 2014; Zeller et al., 2012), we opted to test a range of values and land cover classes to assess the sensitivity of variation on model outputs. For each land cover grouping (Forest A & B and Wetland A, B, C, & D), we tested four landscape resistance scenarios. The first three scenarios vary the ratio between resistance values with the first scenario based on the values used by Theobald et al. (2011), the second scenario using a geometric sequence, and the third scenario using orders of magnitude inspired by the method used by Etherington et al. (2014). The fourth scenario reduces the land cover classes to two: Forest or Wetland and Non-Forest or Non-Wetland. This scenario is based on the methods of Pelletier et al. (2017). A breakdown of the scenarios is outlined in *Tables 3 & 4*.

Table 1. Land Cover Classes for Forest Group A & Wetland Groups A & C. Consolidation of the SOLRIS land cover classes into the 10 classes identified in the left column. Numbers correspond to the SOLRIS value numbers for each class.

Class	SOLRIS 2000-2002 Classes	SOLRIS 2009-2011 & 2015 Classes
Forest	22 – Tallgrass Woodland 27 – Forest 28 – Coniferous Forest 29 – Mixed Forest 30 – Deciduous Forest	83 – Tallgrass Woodland 90 – Forest 91 – Coniferous Forest 92 – Mixed Forest 93 – Deciduous Forest
Grassland	20 – Open Tallgrass Prairie	81 – Open Tallgrass Prairie
Wetland	**50 – Swamp** 55 – Fen 59 – Bog 63 – Marsh	**131 – Treed Swamp** **135 – Thicket Swamp** 140 – Fen 150 – Bog 160 - Marsh
Parks/Open Space	44 – Built-up Area Pervious	202 – Built-Up Area - Pervious
Cultivated Trees & Hedgerows	36 – Plantations – Tree Cultivated 37 – Hedge Rows	191 – Plantations – Tree Cultivated 192 – Hedge Rows
Water	66 – Open Water	170 – Open Water
Agriculture	99 – Undifferentiated	193 – Tilled 250 – Undifferentiated
Urban	45 – Built-up Area Impervious	203 – Built-Up Area - Impervious
Infrastructure	42 – Transportation	201 – Transportation
Extraction	43 – Extraction	204 – Extraction – Aggregate 205 – Extraction – Peat/Topsoil

Table 2. Land Cover Classes for Forest Group B & Wetland Groups B & D. Consolidation of the SOLRIS land cover classes into the 10 classes identified in the left column. Numbers correspond to the SOLRIS value numbers for each class.

Class	SOLRIS 2000-2002 Classes	SOLRIS 2009-2011 & 2015 Classes
Forest	22 – Tallgrass Woodland 27 – Forest 28 – Coniferous Forest 29 – Mixed Forest 30 – Deciduous Forest **50 – Swamp**	83 – Tallgrass Woodland 90 – Forest 91 – Coniferous Forest 92 – Mixed Forest 93 – Deciduous Forest **131 – Treed Swamp** **135 – Thicket Swamp**
Grassland	20 – Open Tallgrass Prairie	81 – Open Tallgrass Prairie
Wetland	55 – Fen 59 – Bog 63 – Marsh	140 – Fen 150 – Bog 160 – Marsh
Parks/Open Space	44 – Built-up Area Pervious	202 – Built-Up Area – Pervious
Cultivated Trees & Hedgerows	36 – Plantations – Tree Cultivated 37 – Hedge Rows	191 – Plantations – Tree Cultivated 192 – Hedge Rows
Water	66 – Open Water	170 – Open Water
Agriculture	99 – Undifferentiated	193 – Tilled 250 – Undifferentiated
Urban	45 – Built-up Area Impervious	203 – Built-Up Area – Impervious
Infrastructure	42 – Transportation	201 – Transportation
Extraction	43 – Extraction	204 – Extraction – Aggregate 205 – Extraction – Peat/Topsoil

Table 3. Forest Resistance Scenarios. Resistance values assigned for each Forest scenario. Notation corresponds to scenario number and land cover grouping (e.g., F1a = Forest Scenario 1, Land Cover Grouping A)

FOREST GROUP A				
Land Cover	**F1a**	**F2a**	**F3a**	**F4a**
Forest	1	1	1	1
Wetland (Includes swamp classes)	2	5	10	500
Grassland	2	5	10	500
Cultivated Trees & Hedgerows	2	5	10	500
Parks/Open Space	4	10	100	500
Water	4	10	100	500
Agriculture	10	50	1,000	500
Urban	100	100	10,000	500
Infrastructure	100	100	10,000	500
Extraction	100	100	10,000	500
FOREST GROUP B				
Land Cover	**F1b**	**F2b**	**F3b**	**F4b**
Forest (Includes swamp classes)	1	1	1	1
Wetland	2	5	10	500
Grassland	2	5	10	500
Cultivated Trees & Hedgerows	2	5	10	500
Parks/Open Space	4	10	100	500
Water	4	10	100	500
Agriculture	10	50	1,000	500
Urban	100	100	10,000	500
Infrastructure	100	100	10,000	500
Extraction	100	100	10,000	500

Table 4. Wetland Resistance Scenarios. Resistance values assigned for each Wetland scenario. Notation corresponds to scenario number and land cover grouping (e.g., W1a = Wetland Scenario 1, Land Cover Grouping A)

WETLAND GROUP A					**WETLAND GROUP B**				
Land Cover	**W1a**	**W2a**	**W3a**	**W4a**	**Land Cover**	**W1b**	**W2b**	**W3b**	**W4b**
Wetland (Includes swamp classes)	1	1	1	1	Wetland	1	1	1	1
Forest	2	5	10	500	Forest (Includes swamp classes)	2	5	10	500
Grassland	2	5	10	500	Grassland	2	5	10	500
Cultivated Trees & Hedgerows	2	5	10	500	Cultivated Trees & Hedgerows	2	5	10	500
Water	2	5	10	500	Water	2	5	10	500
Parks/Open Space	4	10	100	500	Parks/Open Space	4	10	100	500
Agriculture	10	50	1,000	500	Agriculture	10	50	1,000	500
Urban	100	100	10,000	500	Urban	100	100	10,000	500
Infrastructure	100	100	10,000	500	Infrastructure	100	100	10,000	500
Extraction	100	100	10,000	500	Extraction	100	100	10,000	500
WETLAND GROUP C					**WETLAND GROUP D**				
Land Cover	**W1c**	**W2c**	**W3c**	**W4c**	**Land Cover**	**W1d**	**W2d**	**W3d**	**W4d**
Wetland (Includes swamp classes)	1	1	1	1	Wetland	1	1	1	1
Water	1	1	1	1	Water	1	1	1	1
Forest	2	5	10	500	Forest (Includes swamp classes)	2	5	10	500
Grassland	2	5	10	500	Grassland	2	5	10	500
Cultivated Trees & Hedgerows	2	5	10	500	Cultivated Trees & Hedgerows	2	5	10	500
Parks/Open Space	4	10	100	500	Parks/Open Space	4	10	100	500
Agriculture	10	50	1,000	500	Agriculture	10	50	1,000	500
Urban	100	100	10,000	500	Urban	100	100	10,000	500
Infrastructure	100	100	10,000	500	Infrastructure	100	100	10,000	500
Extraction	100	100	10,000	500	Extraction	100	100	10,000	500

Circuitscape & Sensitivity Analysis

Each scenario presented in *Tables 3 & 4* was modelled in Circuitscape using an omnidirectional connectivity method to produce current density maps. Omnidirectional methods are an alternative to identifying focal nodes (i.e., priority/high-quality land cover patches). Focal nodes are typically used in studies that are interested in specific areas and/or specific species but the approach is more difficult to implement if the goal is to get a broader sense of connectivity across an entire landscape and the location of specific nodes may be unknown (Phillips et al., 2021). A relatively new method to get around this problem is to undertake an omnidirectional approach, which predicts the probability of movement across an entire landscape without specific source and destination nodes identified (Pelletier et al., 2014; Phillips et al., 2021). There are three common omnidirectional connectivity methods: wall-to-wall (Pelletier et al., 2017), point-based (Koen et al., 2014), and moving window (McRae et al., 2016). Phillips et al. (2021) undertook an analysis to compare these three methods and found that they all produced similar results with the wall-to-wall method being the least computationally demanding (Phillips et al., 2021). We chose the wall-to-wall method using one cell wide input/output regions on the north-south and east-west edges of the analysis area. To do this, we ran Circuitscape twice for each scenario using the pairwise setting: once for east-west and once for north-south. The current density results of these two directional runs of the model were then multiplied together to get the omnidirectional current density maps. To compare the different scenarios, we undertook a sensitivity analysis using the Spearman's rank correlation coefficient for 1000 randomly selected cells. This was undertaken in R version 4.2.0 (R Core Team, 2022) using the raster (Hijmans, 2022), corrplot (Wei & Simko, 2021), and Hmisc (Harrell Jr, 2022) packages. The scenario most correlated to the others was then selected for use for the remaining analyses. This is consistent with the approach by Pither et al. (2023) who undertook ecological connectivity analysis throughout Canada.

2.3.3 Policy Analysis

Content analysis was used to examine the trends and evolution of land use policy guiding growth and development in the Region with a particular focus on requirements to protect and enhance landscape connectivity. Content analysis relies on the independent judgement of the analyst(s) to properly code the content. As a result, it is important that the categories of analysis are mutually exclusive (Given, 2008). Inspired by the methodology undertaken by Meyfarth O'Hara (2009), the documents were analyzed based on whether they directly, indirectly, or do not include direction to protect or enhance landscape connectivity. Policies that directly address landscape connectivity had to specifically reference connectivity, corridors, linkages, or other language describing systems-based approaches to environmental protection and enhancement. Policies that qualified as indirectly addressing landscape connectivity included any policies that addressed the protection, enhancement, or restoration of features of the natural environment as well as any policies supporting general conservation of biodiversity in urban areas. The unit of analysis was based on statements. For the purposes of our research this meant a sentence or group of sentences that address the protection or enhancement of landscape connectivity. Bulleted sub-policies were considered as separate statements from one another. The policies were then further categorized by the following policy types: positive directives (e.g., shall, will), limitations (e.g., shall not, will not), and enabling language (e.g., should, encouraged to). These categories are the same as those included in the PPS 2020 ‘Part III: How to Read the Provincial Policy Statement”. The PPS forms the basis of Ontario’s top-down land use policy structure and consequently these policy types were expected to be consistent across the land use policy documents selected. In addition to identifying the number of policies that indirectly and directly address landscape connectivity we also calculated the density. To do so, we divided the number of policies by the document size (i.e., page number). For the page numbers for each policy document, we excluded the figures, schedules, and definitions section. For the Growth Plan (“GP”), the section specific to the Simcoe Sub-Area was also excluded as those policies were not relevant to Waterloo Region and thus were not reviewed. Following this, we undertook a comparative analysis of the policies that directly and indirectly address landscape connectivity across all versions of the policy documents looking for changes to original policies and the introduction of new policies as well as keywords which we subsequently organized into various themes. This allowed us to understand the evolution of the policies over time and the key policy areas where landscape connectivity is being addressed.

2.4 Results

2.4.1 Spatial Analysis

<u>Sensitivity Analysis</u>

The results of the Spearman’s rank correlation coefficient analysis revealed that resistance scenarios one to three for Forest and Wetland connectivity were correlated (*see Appendix B for detailed results*). For Forest groups A and B the current density results were highly correlated with coefficients ranging from 0.83 to 0.98 for 2000-2002, 0.81 to 0.99 for 2009-2011, and 0.84 to 0.99 for 2015. The results were similar when comparing Wetland groups A, B, C, and D with coefficients ranging from 0.67 to 0.99 for 2000-2002, 0.66 to 0.99 for 2009-2011, and 0.80 to 0.99 for 2015. These results are consistent with other studies that have assessed sensitivity of their models where the model remains insensitive to moderate errors in resistance values as long as the ranking of the values is in the correct order (Beier et al., 2009; Simpkins et al., 2017). Scenario four, which reduced the land cover classes to two (Forest/Wetland, Non-Forest/Non-Wetland) was low to moderately correlated with the other three scenarios for both forest (0.25 to 0.76 for 2000-2002, 0.26 to 0.73 for 2009-2011, and 0.23 to 0.74 for 2015) and wetland (0.01 to 0.65 for 2000-2002, 0.01 to 0.55 for 2009-2011, and 0.01 to 0.62 for 2015) connectivity. This finding would suggest that the current density results of scenario four were somewhat consistent with the other scenarios but given the coarser land cover classes the results are less precise. Scenarios F3a and W3b (Table 3 and 4) were the most correlated to the other scenarios (excluding scenario four) and as a result, we focused the remainder of our spatial analysis on these results.

Omnidirectional Connectivity

The omnidirectional current density results (*Figure 2)* revealed that the connectivity corridors within and adjacent to the urban areas of the Region are similar for both forest and wetland connectivity. The following eight corridors were identified in the 2000-2002 results (*Figure 3)*: (1) Laurel Creek Conservation Area, (2) Lakeshore Village, (3) Grand River, (4, 5) South Kitchener, (6) Speed River, (7) Mill Creek, and (8) Moffat Creek. The majority of these corridors are located on the periphery of the urban area and connectivity within the urban area is very limited. The corridors identified in the 2000-2002 analysis remain largely intact in the 2009-2011 and 2015 results (99% no change; *Table 5*). *Table 5* provides an overview of corridor loss and gain between 2000 and 2015 and *Figure 4* highlights the changes that occurred to the connectivity corridors between 2000 and 2015 (*see Appendix C for 2000-2009 and 2009-2015 comparisons*). Corridor loss between 2000 and 2015 was concentrated in the Laurel Creek Conservation Area, South Kitchener, Mill Creek, and Moffat Creek corridors (*Figure 4*). Based on the Region of Waterloo aerial imagery for 2000 (Region of Waterloo, 2022b), 2009 (Region of Waterloo, 2022c), and 2015 (Region of Waterloo, 2022d), all these areas are locations where residential development occurred between 2000 and 2015 with most of the residential development occurring between 2000 and 2009.

Table 5. Corridor change between 2000-2015. Corridor area loss and gain between 2000-2002, 2009-2015, and 2000-2015 current density results.

Results Comparison	**Corridor Change**					
	Loss		**Gain**		**No Change**	
	%	Km^2	%	Km^2	%	Km^2
2000-2002 & 2015 (*Figure 4*)	0.6%	$18km^2$	0.6%	$18km^2$	98.8%	$2864km^2$
2000-2002 & 2009-2011 (*Appendix C*)	0.5%	$14km^2$	0.5%	$14km^2$	99.0%	$2872km^2$
2009-2011 & 2015 (*Appendix C*)	0.5%	$15km^2$	0.5%	$14km^2$	99.0%	$2871km^2$

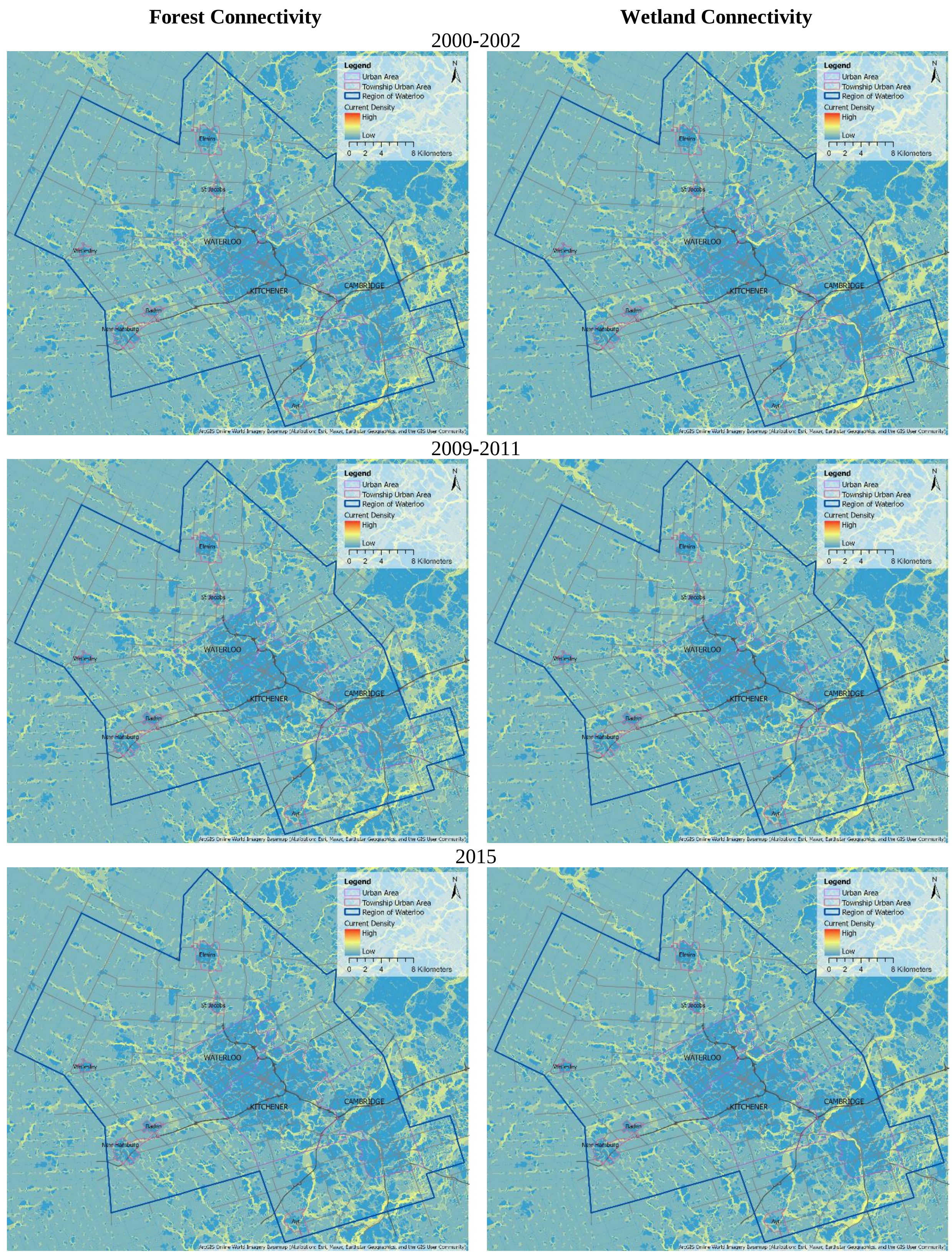

Figure 2. Omnidirectional current density results for Forest scenario F3a and Wetland scenario W3b.

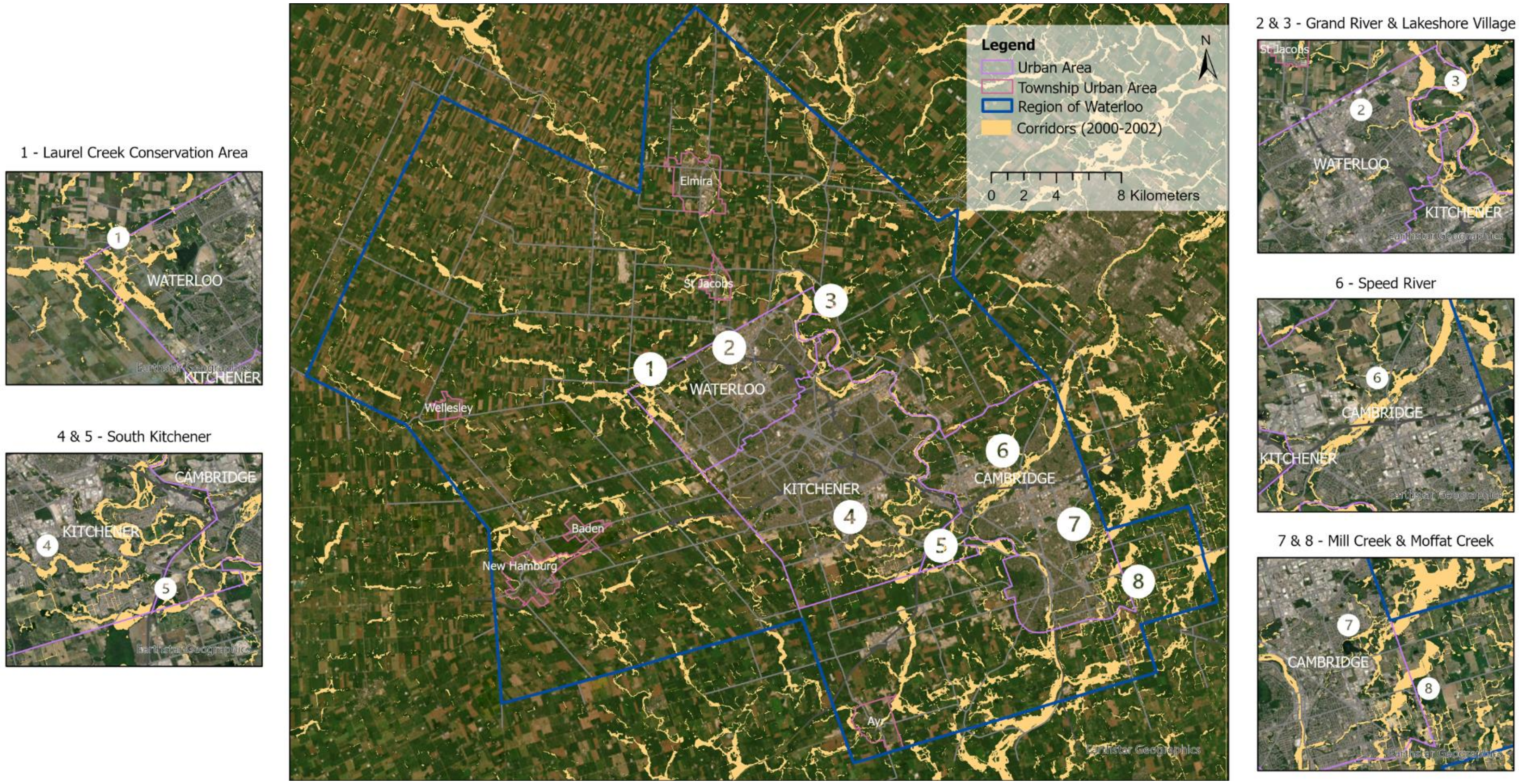

Figure 3. Combined corridors for Forest and Wetland connectivity from the 2000-2002 current density results. Eight corridors were identified: (1) Laurel Creek Conservation Area, (2) Lakeshore Village, (3) Grand River, (4, 5) South Kitchener, (6) Speed River, (7) Mill Creek, and (8) Moffat Creek.

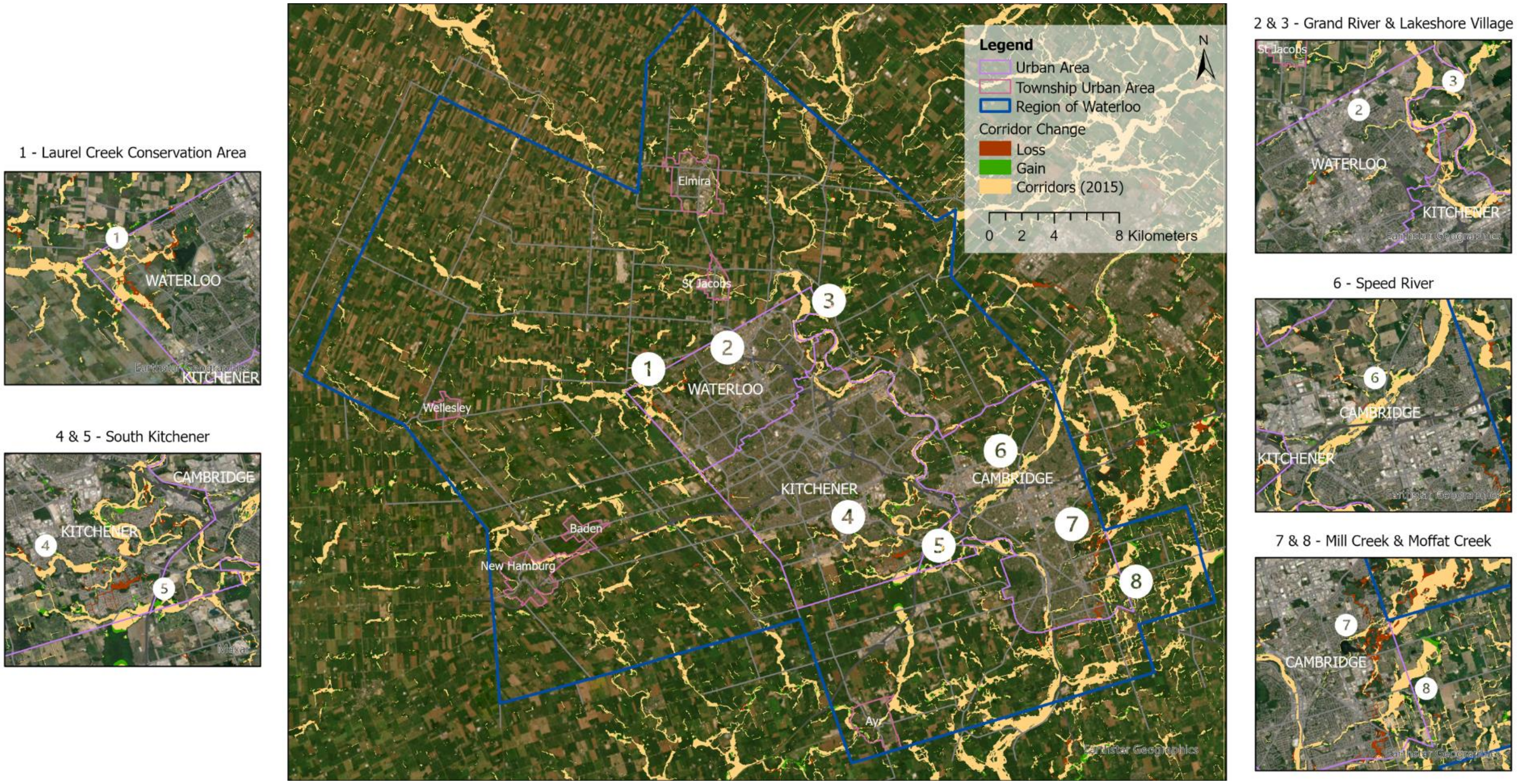

Figure 4. Corridor changes between 2000-2015. Red indicates corridor areas that appear in the 2000-2002 results but do not appear in the 2015 results. Green indicates corridor areas that did not appear in the 2000-2002 results but do appear in the 2015 results.

2.4.2 Policy Analysis

Content Analysis

All land use policy documents analyzed contained policies that address landscape connectivity with considerable increases in the number of policies over time. In most of the documents there was an increase in policies that both directly and indirectly address landscape connectivity the exceptions being the GP (Growth Plan) 2019 and 2020 Consolidation where there was a decrease in direct policies and the ROP (Regional Official Plan) 2015 where there was a decrease in indirect policies (*Table 5*). Despite this, the overall density (i.e., policies per page) increased over time for all policy documents. For policy types, there was a notable shift in the proportion of enabling policies in comparison to positive directive and limitation policies in the documents (*Table 6*). Older policy documents tended to have more enabling policies than the newer documents do (*Figure 5*). The most significant shift is found in the provincial policy documents where older policy documents tended to have a greater proportion of enabling policies (e.g., PPS 1996 – 57% enabling, 29% limitation, 14% positive directive) and newer policy documents have a greater proportion of positive directive and limitation policies (e.g., PPS 2020 – 39% positive directive, 36% limitation, 25% enabling).

Table 6. Policies that directly or indirectly address landscape connectivity in provincial and regional planning documents.

Planning Document	**Policy Class**				**Total**	
	Direct		**Indirect**			
	Count	%	Count	%	Count	Density
Provincial Policy Statement (“PPS”)						
PPS 1996 *(11 pages)*	1	14%	6	86%	7	0.6
PPS 1997 *(11 pages)*	1	14%	6	86%	7	0.6
PPS 2005 *(25 pages)*	1	5%	20	95%	21	0.8
PPS 2014 *(35 pages)*	4	13%	27	87%	31	0.9
PPS 2020 *(36 pages)*	4	12%	30	88%	34	0.9
Growth Plan for the Greater Golden Horseshoe (“GP”)						
GP 2006 *(38 pages)*	3	27%	8	73%	11	0.3
GP 2013 Consolidation *(39 pages)*	3	27%	8	73%	11	0.3
GP 2017 *(61 pages)*	17	22%	61	78%	78	1.3
GP 2019 *(60 pages)*	13	15%	74	85%	87	1.5
GP 2020 Consolidation *(60 pages)*	13	15%	74	85%	87	1.5
Waterloo Regional Official Plan (“ROP”)						
ROP 1998 Consolidation *(157 pages)*	3	2%	179	98%	182	1.2
ROP 2006 Consolidation *(166 pages)*	4	2%	227	98%	231	1.5
ROP 2015 *(158 pages)*	18	8%	213	92%	231	1.5

Table 7. Policies that address landscape connectivity (either directly or indirectly) in provincial and regional planning documents by policy type.

Planning Document	**Policy Type**						**Total**
	Positive Directive		**Enabling**		**Limitation**		
	Count	%	Count	%	Count	%	Count
Provincial Policy Statement ("PPS")							
PPS 1996	1	14%	4	57%	2	29%	7
PPS 1997	1	14%	4	57%	2	29%	7
PPS 2005	4	19%	5	24%	12	57%	21
PPS 2014	10	32%	8	26%	13	42%	31
PPS 2020	13	38%	8	24%	13	38%	34
Growth Plan for the Greater Golden Horseshoe ("GP")							
GP 2006	3	27%	8	73%	0	0%	11
GP 2013 Consolidation	3	27%	8	73%	0	0%	11
GP 2017	50	64%	13	17%	15	19%	78
GP 2019	55	63%	16	18%	16	18%	87
GP 2020 Consolidation	55	63%	16	18%	16	18%	87
Waterloo Regional Official Plan ("ROP")							
ROP 1998 Consolidation	128	70%	49	27%	5	3%	182
ROP 2006 Consolidation	148	64%	72	31%	11	5%	231
ROP 2015	137	59%	36	16%	58	25%	231

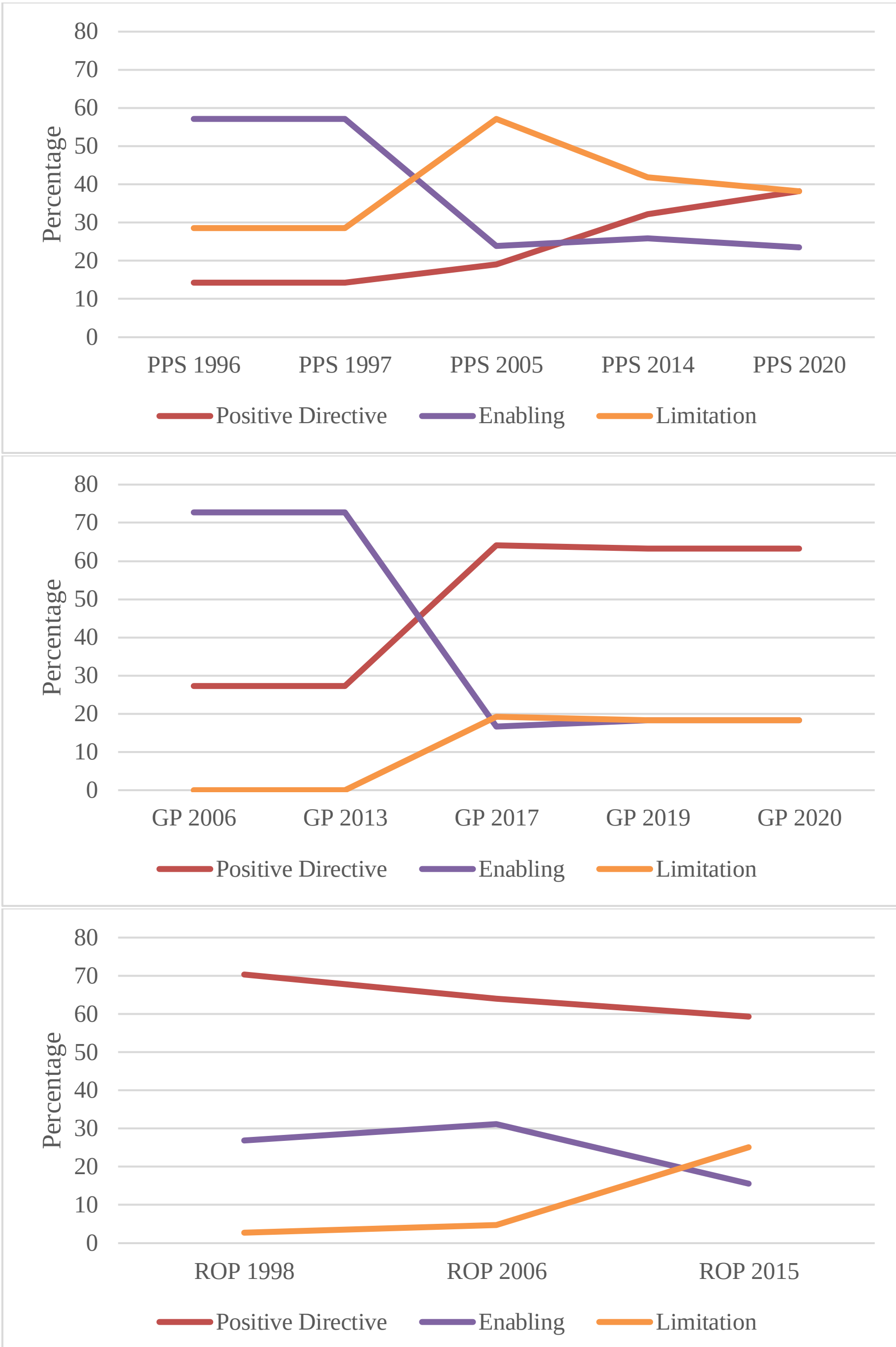

Figure 5. Percentage of provincial and regional policies that either directly or indirectly address landscape connectivity by type.

Comparative Analysis

Five themes arose from the land use policies that directly or indirectly address the protection or enhancement of landscape connectivity. These were:

- Policies for the protection of natural heritage and water resources;

- Policies providing direction on development and land use patterns;
- Policies indicating the need for a coordinated approach to land use planning across lower, single, or upper-tier municipal boundaries and with other orders of government, agencies, and boards;
- Policies for the provision of green infrastructure; and
- General policies promoting conservation and recognizing the ecological benefits provided by nature.

Natural Heritage and Water Resources

All iterations of the PPS and GP included direction for the protection of natural heritage (PPS 1996 & 1997 s.2.3, PPS 2014 & 2020 s.2.1, GP 2006 & 2013 s.4.2.1.3, GP 2017, 2019 & 2020 s.4.2.2, 4.2.3, 4.2.4). Natural heritage features and areas include significant wetlands, fish habitat, significant woodlands, significant valleylands, habitat of endangered species and threatened species, significant wildlife habitat, and significant areas of natural and scientific interest (PPS 2020 s. 6.0). Despite all provincial policy documents addressing natural heritage protection, the scope of the policies varies. For instance, the earliest versions of the PPS included direction for when development and site alteration can occur in natural heritage features and areas including requirements for demonstrating that there will be no negative impacts (PPS 1996 & 1997 s. 2.3.1, 2.3.2). These policies were carried through in later iterations of the PPS (PPS 2005 s.2.1.4, 2.1.6, PPS 2014 & 2020 s.2.1.5, 2.1.8). However, the GP 2006 and 2013 do not include specific policies for natural heritage beyond encouraging municipalities to identify natural heritage features and areas (GP 2006 & 2013 s.4.2.1.3) and an indication that the Minister would identify natural systems for the Greater Golden Horseshoe with additional policies for their protection (GP s.4.2.1.1). It was not until the GP 2017 where the natural heritage policies were substantially expanded including policies specific to development and no negative impacts (GP 2017, 2019, 2020 s.4.2.2.3).

The PPS 2014 introduced a new policy requiring the identification of natural heritage systems (PPS 2014 s.2.1.3). Natural heritage systems are defined as "a system made up of natural heritage features and areas, and linkages intended to provide connectivity (at the regional or site level) and support natural processes which are necessary to maintain biological and geological diversity, natural functions, viable populations of indigenous species, and ecosystems…" (PPS 2020 s. 6.0). The GP 2006, 2013, and 2017 promised a provincially identified natural heritage system for the Greater Golden Horseshoe and in the GP 2019 the Provincial Natural Heritage System for the Greater Golden Horseshoe which applies to lands outside settlement areas was introduced.

All iterations of the ROP also address the protection of natural heritage with emphasis on the importance of connectivity. The ROP 1998 and 2006 identify a Natural Habitat Network consisting of the following elements: Environmental Preservation Areas; Environmentally Sensitive Policy Areas;

Provincially Significant Wetlands; Significant Valleylands; Sensitive Groundwater Recharge and Discharge Areas, Head Waters and Aquifers; Significant Woodlands; Locally Significant Natural Areas; Significant Wildlife Habitat; and Fish Habitat (ROP 1998 & 2006 s. 4.1.1). The policies for the Natural Habitat Network specify the requirements for protecting the network, the restrictions to development and resource extraction within and adjacent to the network, and environmental study requirements. The ROP 2015 introduced a change in terminology from the Natural Habitat Network to the Greenlands Network comprised of: Landscape Level Systems; Core Environmental Features; Fish Habitat; Supporting Environmental Features and the linkages among these elements, and lands designated within the Provincial Greenbelt Plan as Natural Heritage System (ROP 2015 s. 7.A.1). All iterations of the ROP emphasized the importance of identifying and enhancing natural corridors (ROP 1998 & 2006) and linkages (ROP 2015) with the ROP 2015 requiring linkages to be incorporated into the design of new development (ROP 2015 s.7.E.7).

In addition to policies on natural heritage, the PPS 2005 introduced a new policy (PPS 2005 s. 2.2.1) for the protection of water resources including surface water features, ground water features, and hydrologic functions. The PPS 2014 expanded upon this policy to directly address connectivity through a new requirement to identify water resource systems and maintain linkages among natural features and areas (PPS 2014 s.2.2.1). For the GP, the GP 2017 introduced water resource system policies and policies ensuring watershed level planning including a new requirement for planning authorities to identify water resource systems (GP 2017 s. 4.2.1.1, 4.2.1.2). A water resource system is defined as "a system consisting of ground water features and areas and surface water features (including shoreline areas), and hydrologic functions, which provide the water resources necessary to sustain healthy aquatic and terrestrial ecosystems and human water consumption…" (GP 2020 s.7). While all iterations of the ROP address water resources, only the ROP 2015 addresses connectivity among groundwater and surface water features (ROP 2015 s. 7.F.4).

Development and Land Use Patterns

Provincial policies that indirectly addressed landscape connectivity through direction for development and land use patterns were included in the earliest documents reviewed where the PPS 1996 and 1997 included section 1.1.1 which stated that "development and land use patterns which may cause environmental or public health and safety concerns will be avoided." This policy was expanded in later iterations of the PPS to promote land use patterns that conserve biodiversity and consider or prepare for the impacts of a changing climate (PPS 2014 s.1.1.1 & PPS 2020 s.1.1.1, s.1.1.3.2). All iterations of the GP also include direction for development and land use patterns that indirectly address landscape connectivity. In particular, the GP provides direction on when settlement area boundary expansions may occur and require consideration of the natural heritage system and water resource system (GP 2006, 2013 s. 2.2.8, GP 2017, 2019, 2020 s. 2.2.8.3).

All iterations of the ROP also provided direction for development and land use patterns that indirectly address landscape connectivity. The ROP 1998 and 2006 provide direction for many land use designations including the City Urban Area, Township Urban Area, and Rural Settlement Area that the expansion of these designations must consider the impact on the Natural Habitat Network. The ROP 2015 has similar policies for the Greenlands Network. The ROP 2015 introduced the concept of the "Countryside Line" and the "Protected Countryside". Section 2.B.1 states that the Countryside Line "represents the long-term boundary between the existing Urban Area/Township Urban Areas and the countryside. Where the Countryside Line coincides with the Protected Countryside designation as shown on Map 7, the Countryside Line will be considered a permanent boundary." Further, section 6.B.1 describes the Protected Countryside designation as "a continuous band of environmental features and agricultural lands surrounding the north, west and south sides of the Urban Area designation that is to be permanently protected…" These policies indirectly address landscape connectivity by protecting corridors located along the periphery of the urban area from future development.

Coordinated Approach

All iterations of the PPS encouraged a coordinated approach when addressing ecosystem and watershed related issues with later iterations adding the management of natural heritage and water resources as well as policies that encourage planning authorities to coordinate environmental planning considerations (PPS 1996 & 1997 s.1.1.1, PPS 2005 s.1.2.1, and PPS 2014 & 2020 s.1.2.1, 1.2.3). Consistent with the PPS, the GP iterations also include direction for a coordinated approach however, the GP 2006 and 2013 are vague and just refer to "issues that cross municipal boundaries" (GP 2006 & 2013 s. 5.4.2.1). The GP 2017 introduced new policies to direct integrated and co-ordinated approaches to planning that directly refer to environmental protection and conservation (GP 2017 s. 2.2.1.3). The iterations of the ROP do not explicitly reference a coordinated approach to planning, however many of the policies indicate collaborating with the lower-tier municipalities, province, and conservation authorities for matters related to the Natural Habitat Network or the Greenlands Network and the identification of linkages.

Green Infrastructure

For the PPS, policies related to green infrastructure were first introduced in the PPS 2014 with section 1.6.2 stating that "planning authorities should promote green infrastructure to complement infrastructure." The PPS 2020 expanded upon by directing planning authorities to consider the mitigating effects of vegetation and green infrastructure (PPS 2020 s. 1.8.1). All iterations of the GP encouraged municipalities to establish urban open space systems including green infrastructure elements such as rooftop gardens and public parks (GP 2006, 2013, & 2017 s. 4.2.1.5). Additionally, the GP 2017 introduced new policies requiring the integration of green infrastructure to support the achievement of complete communities (GP 2017 s. 2.2.1.4, 3.2.7.1, 3.2.7.2, 4.2.10.1, 4.2.10.2). Similar policies are also included in the GP 2019 and 2020. The ROP 2015 introduced a new designation for Major Urban Greenlands which are "relatively large, publicly accessible parklands or open spaces located within urban areas that are owned and maintained by the Region, Area Municipalities or the Grand River Conservation Authority" (ROP 2015 s. 2.G.1). In support of these lands, the ROP 2015 requires lower-tier municipalities to develop an Urban Greenlands Strategy including requirements to identify a system of natural areas and open spaces as well as promotion of green roofs, community gardens, and tree planting in urban areas (ROP 2015 s. 2.G.3).

General Conservation Policies

In addition to the policies described above, many of the land use policy documents included general direction related to environmental conservation, which indirectly support the maintenance and enhancement of landscape connectivity. One example is section 1.7.1 of the PPS 2014 and 2020 which states that "long-term economic prosperity should be supported by minimizing negative impacts from a changing climate and considering the ecological benefits provided by nature." Further, the GP 2017 introduced a new policy that indicated that "applying the policies of this Plan will support the achievement of complete communities that mitigate and adapt to climate change impacts, build resilience, reduce greenhouse gas emissions, and contribute towards the achievement of low-carbon communities" (GP 2017 s. 2.2.1.4). The iterations of the ROP also contained these types of policies such as ROP 1998 and 2006 section 3.3.1 which states that "the Region will, where appropriate, encourage the conservation and enhancement of the region's native biodiversity." All iterations of the ROP also included policies encouraging private landowner stewardship and various programs to support stewardship (ROP 1998 & 2006 s. 3.4.3, 4.7.3, ROP 2015 s. 7.I.8, 7.I.9, 7.I.11, 7.I.15), as well as encouraging individuals and agencies to use native species when planting within or adjacent to the Natural Habitat Network or Greenlands Network and discouraging the use of non-native species (ROP 1998 & 2006 s. 3.3.4, 3.3.5, ROP 2015 s. 7.I.12, 7.I.13).

Provincial Natural Heritage System and ROP Greenlands Network

We compared the corridors identified in the 2015 current density results to the Provincial Natural Heritage System (*Figure 6*) and the ROP 2015 Greenlands Network (*Figure 7*). This revealed that the corridors are largely consistent with the areas already protected under provincial and regional land use policies. There was a 59% overlap between Provincial Natural Heritage System and the 2015 corridors and an 80% overlap for the ROP 2015 Greenlands Network. It is noted that the Provincial Natural Heritage System only applies outside of settlement areas and that the Greenlands Network only applies (with a few exceptions) within the Region of Waterloo boundary. There are some core features identified under the Greenlands Network that did not show up in the current density maps. This is likely because these core features are isolated from other patches and linkages.

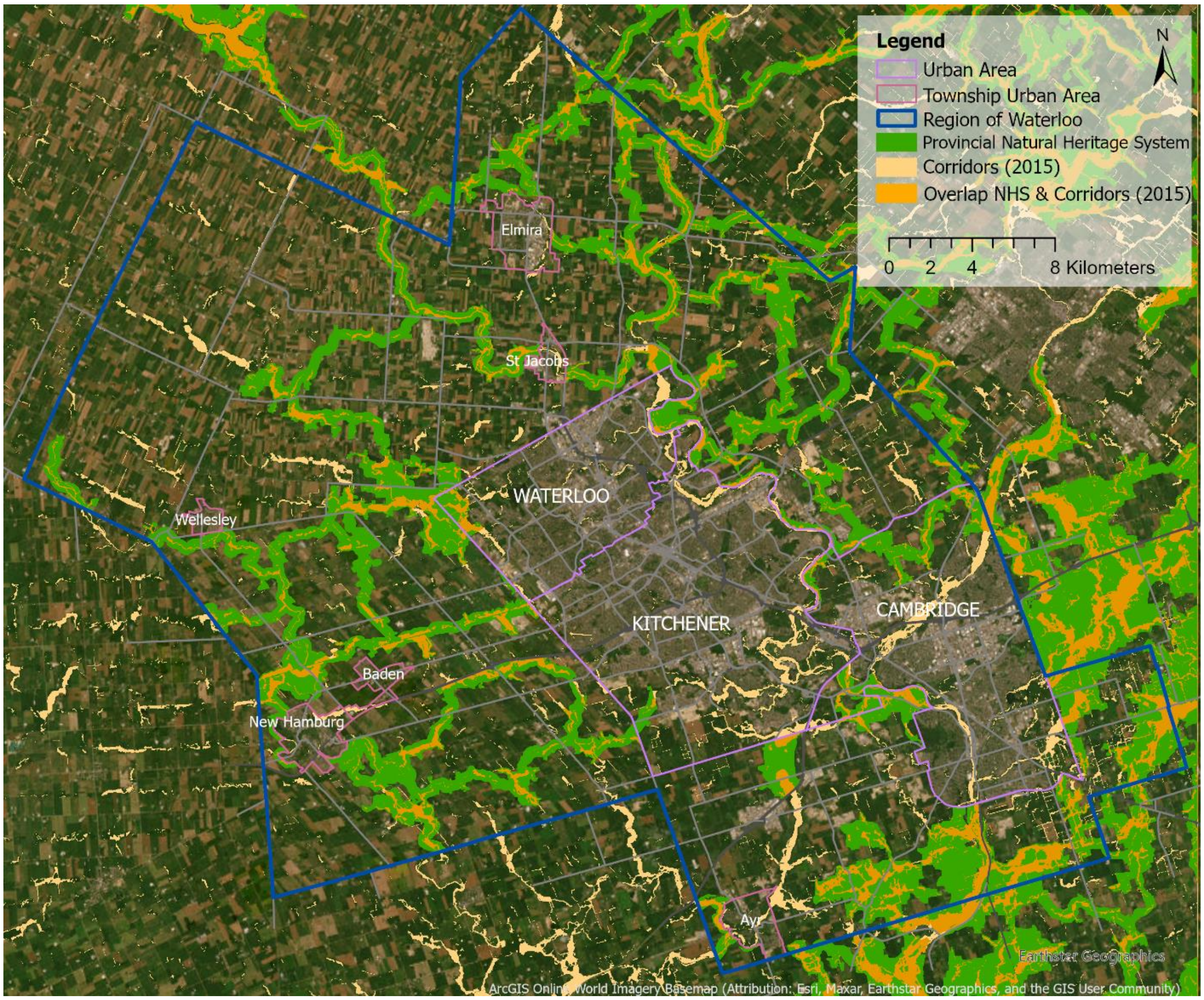

Figure 6. Comparison of corridors from 2015 current density results to the Provincial Natural Heritage System.

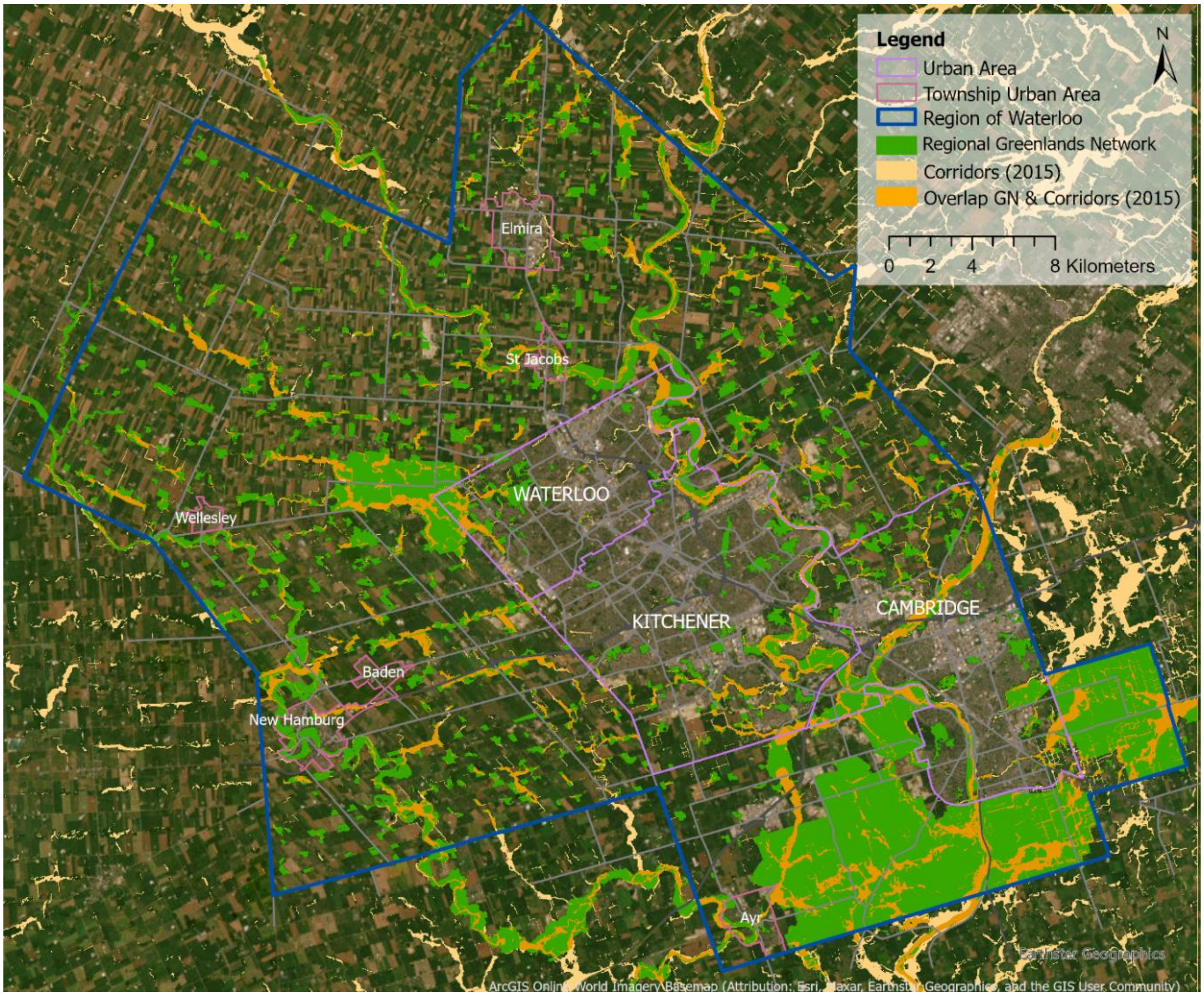

Figure 7. Comparison of corridors from 2015 current density results to the ROP 2015 Greenlands Network

2.5 Discussion

Our study found that corridors in the Region have remained largely intact over the last couple of decades. Many of the corridors are located along bodies of water (e.g. Grand River, Speed River, Laurel Creek) where development potential is limited and have been protected under various natural heritage protections over the last two decades including the Regional Natural Habitat Network, Regional Greenlands Network, and the Provincial Natural Heritage System. Our study also found that the majority of the corridors are concentrated on the periphery of the urban areas with very few linkages and habitat patches located within the urban area. There have been very few changes to landscape connectivity in the Region over the last couple of decades and the changes that did occur were mostly located in areas where residential development occurred. However, it is noted that some changes may be a result of variation in data quality across the timeframes.

Other studies on the impact of urbanization on landscape connectivity have found that existing corridors along the periphery of urban areas are often at risk of being fragmented from future settlement boundary expansions and development (Dupras et al., 2016; Park, 2015). It is encouraging that over the last couple of decades the provincial and regional land use policies applicable to the Region have incorporated long-term protections for natural heritage and to varying degrees for connectivity. The inclusion of the Countryside Line and Protected Countryside land use designation in the ROP 2015 is a useful tool to discourage future expansions and encourage intensification within the existing urban area which indirectly supports the long-term protection of the corridors along the periphery. However, it is too early in its implementation to comment conclusively on its effectiveness. For instance, even with the intent to have the Countryside Line and the Protected Countryside be permanent, maintaining its permanency relies on continued political support and resilience in the face of socioeconomic pressures. This challenge is currently being demonstrated in Ontario as pressures to build more housing in southern Ontario have led to some political support to open up parts of the Provincial Greenbelt for development (Province of Ontario, 2022b, 2022c). The PPS and the GP for the Greater Golden Horseshoe also provide limitations on boundary expansions and encourage intensification. However, little emphasis has been placed on enhancing landscape connectivity within the urban area in both provincial and regional policies. Our comparison of the Regional Greenlands Network to our current density results (*Figure 7*) revealed that there are some isolated core features of the Greenlands Network within the urban area. Greater focus should be placed on providing connections to the broader network in these areas and restoring existing features to enhance connectivity. While it can be challenging to establish new corridors, habitat, and stepping stones within urban areas due in part to piecemeal redevelopment and intensification of private lands, new developments can incorporate landscape connectivity into development plans by including ecologically-based design solutions like green infrastructure and enhancing the quality of existing habitat patches, stepping stones, and corridors.

Our study found that the number of policies indirectly and directly addressing landscape connectivity increased by 386% (7 to 34) for the PPS, 690% (11 to 87) for the GP, and 27% (182 to 231) for the ROP between 1996 and 2020. Further, policies that directly address landscape connectivity increased in amount by 300% (1 to 4) for the PPS, 333% (3 to 13) for the GP, and 500% (3 to 18) for the ROP. There was also a shift in the types of policies. While older policy documents tended to have more enabling policies (e.g., should, encourage to), newer documents tended to have more positive directive (e.g., shall, will) and limitation (e.g., shall not, will not) policies. This finding suggests a move toward stronger language that is less open for interpretation and prevents decision-makers from opting not to implement the policies. In addition, the density of policies by document size increased over time indicating an increasing emphasis being placed on landscape connectivity.

The introduction of the term “natural heritage systems” in the PPS 2005 and the indication of provincially identified natural systems in the GP 2006 mark a notable shift in the number of provincial policies directly and indirectly addressing landscape connectivity. Suggesting that landscape connectivity was increasingly being recognized for its benefits in mitigating the negative effects of urbanization and agricultural operations. It is noted that the Regional Natural Habitat Network and Greenlands Network are similar concepts to the Provincial Natural Heritage System though the provincial system only applies outside of settlement areas. Water resource systems have been given less attention over the last couple decades of provincial and regional land use policy. The protection, enhancement, and restoration of water resources was first addressed in the PPS 2005. However, mentions of connectivity did not appear until the PPS 2014 and the GP 2017, with the PPS 2014 and GP 2017 introducing the requirement for planning authorities to identify water resource systems for “the ecological and hydrological integrity of the watershed” (PPS 2014 s. 2.2.1) and “for the long-term protection of key hydrologic features, key hydrologic areas, and their functions” (GP 2017 s. 4.2.1.2). The introduction of these policies suggests further attention being placed on the importance of connectivity for water resources such as ground water and surface water features and areas. The implementation of systems-based approaches to environmental protection is consistent with the literature where ecological networks (also referred to as greenways) are recognized as important for protecting and enhancing biodiversity and facilitating movement across the landscape in urban environments (Lookingbill et al., 2022; Lynch, 2019; Park, 2015).

The increasing popularity of green infrastructure is also represented in the evolution of the policies with the term first introduced into policies in the PPS 2014. This new focus on green infrastructure is a welcome inclusion in land use policy documents given the potential for green infrastructure to assist in the enhancement of landscape connectivity in urban areas by providing additional habitat, stepping stones, and linkages that increase vegetation cover and biodiversity and improve overall ecosystem function in urban areas (Beaujean et al., 2021; Ignatieva et al., 2011). Additionally, patch size and quality can impact urban biodiversity and ecosystem function (Lepczyk et al., 2017; Park et al., 2014) and restoring habitat quality of existing green infrastructure can also support the enhancement of landscape connectivity. However, current policy language around green infrastructure is predominately under the enabling policy type and a shift to stronger language such as positive directives that require its incorporation and restoration could support the enhancement of landscape connectivity within urban areas. Further, the emphasis that all iterations of the ROP have placed on supporting private stewardship within the Natural Habitat Network or Greenlands Network is something other jurisdictions in southern Ontario should consider implementing. However, these policies can be improved by encouraging good stewardship and the use of native plants on private residential yards and gardens. Although our research did not consider private yards, gardens, and trees in our modelling, they can also contribute to landscape connectivity and urban biodiversity. Incorporating greater vegetation cover on residential yards and gardens can be particularly helpful for this (Goddard et al., 2010; Ossola et al., 2019). In a study by Ossola et al. (2019), the researchers found that yards are an integral component of the urban tree canopy in the Greater Boston Area contributing important habitat patches, stepping stones, and corridors in urban environments.

Overall, landscape connectivity has been increasingly recognized in provincial and regional land use policy as an important consideration for mitigating the negative impacts of urbanization including landscape fragmentation and habitat loss. Despite this finding, corridors in the Region have remained stable over the last two decades and there have been no improvements or enhancements to the connectivity network. While policy language has been strengthened overtime to include more positive directive and limitation policies for the identification and protection of natural heritage systems, strong policy direction for improvements and enhancements to these systems is lacking. Stronger policy language (i.e., positive directives and limitation policies) should be implemented that require the incorporation of landscape connectivity enhancements into development planning and design including the integration of new and restoration of existing green infrastructure. Further, the potential for residential yards and gardens to contribute to landscape connectivity should be recognized in private stewardship programs recognizing the benefits that transforming lawns from cultivated grass to habitat for native plants and wildlife can have on movement and overall ecosystem function. These findings are relevant to other southern Ontario urban areas especially those located within the Greater Golden Horseshoe as they are also subject to the GP and have similar social, ecological, and economic contexts to Waterloo Region.

As highlighted previously, since the completion of this research the Province of Ontario has proposed a new Provincial Planning Statement that would substantially change growth management planning in Ontario including the removal of growth and intensification targets and less stringent limitations on urban boundary expansions (Province of Ontario, 2023). Further, new policies for natural heritage protection are expected but have not yet been shared for this proposed new document and the full impact of these changes on landscape connectivity will not be known for several years.

Chapter 3 : The Role of Urban Areas in Supporting Climate Connectivity

3.1 Introduction

In response to climate warming, many species must either adapt to new climate conditions or shift their ranges to track suitable habitat and climate (Brito-Morales et al., 2018; Molinos et al., 2016; Sonntag & Fourcade, 2022). This applies to both animals and plants. While some species may be able to adapt to changes in habitat and climate conditions and maintain their current ranges, many species are shifting their ranges poleward and to higher elevations to track suitable habitat and climate for survival (McGuire et al., 2016; Senior et al., 2019; Sonntag & Fourcade, 2022). To support these range shifts, climate connectivity – "the ability of a landscape to promote or hinder species movement when responding to a changing climate" (Parks et al., 2020), is critical. Landscape fragmentation impacts both the resilience of species to adapt to climate change within their current ranges as well as the ability for others to shift their geographic range (Costanza & Terando, 2019). Both land use change and climate change negatively impact species diversity and abundance and are both significant drivers of habitat loss (Costanza & Terando, 2019). Climate corridors provide connectivity between habitat patches that support species movement from current to future habitat locations (Marrotte et al., 2020; Sonntag & Fourcade, 2022). However, climate corridors alone cannot guarantee that species will be able to keep pace with changing climatic conditions (Han & Keeffe, 2019; McGuire et al., 2016). Climate corridors may provide structural connectivity, but functional connectivity and successful range-shifts will also be dependent on habitat availability including size and distance between patches, as well as whether conditions within the corridors meet a species niche requirements (Marrotte et al., 2020; McGuire et al., 2016). Additionally, ecosystem dynamics can be impacted by range shifts as species shift at different paces and others do not shift and instead adapt to changing conditions resulting in new interactions (Sonntag & Fourcade, 2022).

Climate connectivity analyses are typically applied at large spatial scales. For example, analyses have been done for the United States (McGuire et al., 2016), the Great Lakes Region in North America (Marrotte et al., 2020), North America (Carroll et al., 2018; Parks et al., 2020), and across 43 European countries (Han et al., 2021). To model climate connectivity, it is common to use the rate and direction of movement needed for a species to track suitable climate conditions (Brito-Morales et al., 2018), called climate velocity. Climate velocity values are often calculated by incorporating landscape resistance and climate data into least-cost path analysis (Brito-Morales et al., 2018; Carroll et al., 2018; Parks et al., 2020). The types of data used for landscape resistance and climate data will vary based on the approach taken. Coarse-filter approaches to modelling climate connectivity assess connectivity for several species

(Zhang et al., 2019) and may use climate analogs, temperature gradients, and land cover data to predict movement across a landscape (Choe et al., 2021; Sonntag & Fourcade, 2022). Fine-filter approaches may also use this data but since they are focused on an individual species or a small selection of focal species, they often also incorporate species-specific data such as habitat and species distribution models (Costanza & Terando, 2019; Zhang et al., 2019). In addition, a climate exposure metric that determines how much variation in climate is expected to be experienced as species migrate (Parks et al., 2020) can be incorporated into landscape resistance assumptions. In general, climate connectivity analyses are similar to those undertaken for landscape connectivity analysis with the addition of climate change considerations. However, it is important to highlight that protecting and enhancing landscape connectivity in general will still support the ability of ecosystems and species to adapt to climate change as such strategies still increase the degree to which the landscape facilitates movement (Littlefield et al., 2019).

Urban areas can negatively impact climate connectivity and climate change-induced range shifts. Landscape fragmentation, biodiversity loss, and habitat degradation in urban areas negatively impacts the ability of the landscape to facilitate movement for many species (Beninde et al., 2015; Costanza & Terando, 2019; Park, 2015; Rudnick et al., 2012). As highlighted in Chapter 2, landscape connectivity research focused on urban areas has been growing steadily over the past 40 years and has become a conservation priority (LaPoint et al., 2015; Lookingbill et al., 2022). Although landscape connectivity in urban areas has garnered significant attention, less attention has been placed on considering climate change-induced range shifts. In this chapter we explore the importance of considering the role of urban areas in protecting and enhancing climate connectivity.

3.2 The Contribution of Urban Areas

Urban areas are particularly susceptible to the impacts of climate change. Land conversion to impervious surfaces from development, infrastructure, and other urban uses results in conditions that make urban areas more vulnerable to negative impacts from extreme weather events such as droughts, heat waves, and flooding (Hobbie & Grimm, 2020; McPhearson et al., 2016; Pickett et al., 2013). The social, ecological, and economic dimensions of urban systems are all impacted by climate change (Hobbie & Grimm, 2020). Urbanization is a major driver affecting ecological integrity including habitat degradation, biodiversity loss, and increased landscape fragmentation (Beninde et al., 2015; Park, 2015). The breakdown of ecological integrity in urban areas can negatively impact the resilience of urban systems to withstand the impacts of climate change. This is because the ecosystem services provided by nature provide important climate change mitigation benefits such as carbon sequestration and heat mitigation as well as improve adaptation capacity by reducing the impact of disturbances (Bush & Doyon, 2019). At the same time, the impacts of urbanization such as the urban heat island effect can exacerbate climate change (Grimm et al., 2008; Hobbie & Grimm, 2020). Despite the negative impacts of urbanization, urban areas are still incredibly important for climate change mitigation and adaptation including significant reductions in greenhouse gas emissions and overall progress towards climate resilience and sustainability (Intergovernmental Panel on Climate Change, 2023; McPhearson et al., 2015). For example, limiting urban sprawl through compact built form is often recommended for improving resource efficiency and reducing emissions (Hamin & Gurran, 2009), as well as spatially constraining the impact of urbanization on biodiversity and habitat quality (Sushinsky et al., 2013). These costs and benefits make urban areas both part of the problem and part of the solution to climate resilience and sustainability and emphasizes the importance of urban systems to foster resilience by being low-emission and resource efficient. Ecosystem-based approaches such as green infrastructure support overall ecological integrity and ecosystem function which in turn improves the resiliency of urban systems to withstand the impacts of climate change (Bush & Doyon, 2019). Green infrastructure is particularly effective at alleviating flood risks and the urban heat island effect as well as supporting carbon sequestration (Hobbie & Grimm, 2020; Intergovernmental Panel on Climate Change, 2023). At the same time, green infrastructure can improve ecological integrity in urban areas by providing additional habitat patches, stepping stones, and linkages that increase vegetation cover, biodiversity, and landscape connectivity (Beaujean et al., 2021; Ignatieva et al., 2011; McPhearson et al., 2016). Given the importance already being placed on ecosystem-based approaches in urban areas as a mechanism to support climate change mitigation and adaptation as well as improve landscape connectivity, we argue that urban areas have the potential to also support climate change-induced range shifts as part of these existing approaches.

When reviewing the literature on climate connectivity we found that when urban areas are referenced they are often discussed as barriers to movement (Carroll et al., 2018; Choe et al., 2021; Coristine et al., 2016; Hannah, 2011; Marrotte et al., 2020; Nuñez et al., 2013; Robillard et al., 2015) and causes of significant landscape fragmentation (Coristine et al., 2016; Fartmann et al., 2021; Honnay et al., 2002; McGuire et al., 2016; Su et al., 2021), biodiversity loss (Hamilton et al., 2018), and habitat degradation (Bandara et al., 2022; Fartmann et al., 2021) with pressure for urban development and expansion cited as a major cause of fragmentation of important climate corridors (Allen et al., 2016; Carroll et al., 2018; Fartmann et al., 2021; Han & Keeffe, 2021). While these negative impacts do exist and cannot be entirely offset, as highlighted previously, urban areas can be planned and managed to conserve biodiversity, protect ecological integrity, and contribute to climate change mitigation and adaptation (Beninde et al., 2015; LaPoint et al., 2015; McDonnell & Hahs, 2013). Despite the limited coverage of urban areas in climate connectivity literature, research by Han & Keeffe (2021) did identify opportunities for urban areas to support climate change-induced range shifts of forests through urban afforestation (Han & Keeffe, 2021). The researchers found that increasing urban tree canopy through planting trees on streets, in private gardens, and on public lands can increase climate connectivity. They also found that because urban environments are warmer than rural areas as a result of the urban heat island effect, urban areas can also provide suitable climate conditions for species moving beyond their native range limit (Han & Keeffe, 2021). Locating species beyond their native limit can potentially serve to accelerate species movement towards higher latitudes as the climate warms (Han & Keeffe, 2021; Woodall et al., 2010).

Maintaining and enhancing connectivity in urban areas will generally support the ability of ecosystems and species to adapt to climate change by increasing the degree to which the landscape facilitates species' movement (Littlefield et al., 2019). However, maintaining and enhancing landscape connectivity alone does not consider shifts in habitat suitability and the viability of movement corridors over time as species shift their ranges in response to climate change (Costanza & Terando, 2019; Littlefield et al., 2019). Adaptive approaches to landscape connectivity protection and enhancement can allow us to continue to learn in the face of uncertainty presented by ongoing climate change. Adaptive approaches incorporate monitoring and evaluation of management interventions that then inform future refinements and conservation decisions (Gillson et al., 2019; Zeller et al., 2020). Similar to scenario building and forecasting done for growth management, there is potential to project future climate conditions, range shifts, and changes in habitat suitability that can be used to inform the protection and enhancement of landscape connectivity within urban areas as well as adapt existing interventions over time. These projections could help inform decisions related to vegetation used for green infrastructure and restoration projects, as well as priority areas for protection and enhancement. However, considering climate connectivity in urban areas could be challenging as range shifts driven by climate change affect larger spatial scales than a single urban area (Nuñez et al., 2013). Any analysis done to predict changes over time would require regional or strategic-level consideration to capture movement beyond current species distributions. This information could then be used to inform local level interventions to protect and enhance climate corridors within individual urban areas. As a result, we argue that more research is needed on the role of urban areas in supporting climate connectivity across broad spatial and temporal scales. Instead of considering urban areas as solely barriers to successful climate change-induced range shifts, researchers should consider opportunities to enhance connectivity and climate corridors within urban areas and not just around them. Further, a greater understanding of the role of urban areas in supporting climate connectivity could provide insight into whether existing strategies to protect and enhance landscape connectivity within urban areas are sufficient to support climate change-induced range shifts or if additional management strategies are needed.

In regions like southern Ontario, where the landscape can be characterized by a mix of rural and urban land uses, there may be limited opportunities for climate corridors to be located solely outside of urban areas. This is because land conversion to both urban and agricultural uses can result in biodiversity loss, habitat degradation, and landscape fragmentation (Rudnick et al., 2012). In these cases, some reliance on urban areas to provide climate connectivity may be required to provide additional habitat patches, stepping stones, and corridors for movement. As highlighted in Chapter 2, corridors have remained stable within the Region over the last decades and landscape connectivity has been increasingly recognized in provincial and regional land use policy. Despite this, enhancement of landscape connectivity within urban areas has been lacking. In addition to the need for stronger requirements for enhancement within urban areas, there is an opportunity for provincial level analysis and guidance on implementing adaptive approaches to landscape connectivity protection and enhancement that considers future climate conditions, range shifts, and changes in habitat suitability over time.

3.3 Conclusion

Climate connectivity is an emerging field of research that incorporates climate change considerations including range shifts into landscape connectivity analyses. Overall, climate connectivity research has not yet explored the potential role of urban areas in supporting climate connectivity. Existing literature generally refers to urban areas as barriers to movement that negatively impact climate change-induced range shifts. While these impacts do exist and cannot be entirely offset, we argue that the existing emphasis on protecting and enhancing landscape connectivity in urban areas to reduce fragmentation, biodiversity loss, and habitat degradation could be leveraged to also support climate change-induced range shifts through adaptive approaches to landscape connectivity protection and enhancement. As the field of climate connectivity science continues to evolve, we are of the opinion that future research should address not solely the negative impacts of urban areas but explore how they can support climate connectivity across broad temporal and spatial scales. Supporting climate connectivity within urban areas is particularly important to explore in rapidly growing regions such as southern Ontario. In these regions, the rural-urban landscape can limit the availability of habitat patches and connectivity corridors and maintaining climate connectivity may require relying, to some degree, on corridors that can be maintained and enhanced within urban boundaries to ensure successful range shifts.

Chapter 4 : Conclusion and Future Directions

The objective of my research was to assess the effectiveness of current approaches to protecting and enhancing landscape connectivity in southern Ontario as well as to examine ways urban areas can support species movement under climate change. Understanding the effectiveness of current approaches is important because it provides an opportunity to evaluate the successes and failures of current practices, develop strategies for improving existing conditions, and to incorporate new information and priorities. In densely populated, rapidly growing regions like southern Ontario the protection of landscape connectivity is particularly important in part due to land conversion to urban uses that places pressure on existing corridors and ecosystem functions and makes enhancing corridors more challenging. At the same time, globally climate change is driving shifts in the ranges of some species as a result of changes in the suitability of habitat and climate conditions (Costanza & Terando, 2019; Littlefield et al., 2019). Over the past 40 years, urban-focused landscape connectivity research has steadily increased (LaPoint et al., 2015; Lookingbill et al., 2022). However, climate connectivity is an emerging field and the effects of climate change on species movement has received less attention. Landscape connectivity and climate connectivity are two related concepts. While landscape connectivity can be defined as "the degree to which the landscape facilitates or impedes movement among resource patches" (Taylor et al., 1993), climate connectivity can be defined as "the ability of a landscape to promote or hinder species movement when responding to a changing climate" (Parks et al., 2020). In general, protecting and enhancing landscape connectivity supports climate connectivity by increasing the degree to which the landscape facilitates movement (Littlefield et al., 2019). However, incorporating climate velocity and climate exposure metrics into existing landscape connectivity analyses provides the opportunity to incorporate adaptive approaches to connectivity protection and enhancement that considers future climate conditions, range shifts, and changes in habitat suitability over time.

My research explored connectivity at two different scales. Finer-scale analysis was undertaken through a case study of Waterloo Region ("the Region") to understand changes in landscape connectivity over the last two decades and the evolution of land use policies guiding growth and development in the Region with respect to requirements to maintain and enhance landscape connectivity. Together the spatial and policy analysis components provide foundational knowledge on the successes and failures of current approaches to protecting and enhancing landscape connectivity in southern Ontario. Coarser-scale analysis was undertaken to analyze existing climate connectivity literature to understand the potential role of urban areas in supporting broad scale ecosystem function and range shifts under climate change.

Results of the finer-scale landscape connectivity analysis showed that corridors in the Region have remained largely intact over the last couple decades with most corridors being protected by provincial and regional land use policy (59% overlap of corridors with Provincial Natural Heritage System and 80% overlap with the Regional Greenlands Network). In addition, we found that there has been an increase in the number of policies that indirectly and directly address landscape connectivity (386% (7 to 34) for the PPS, 690% (11 to 87) for the GP, and 27% (182 to 231) for the ROP between 1996 and 2020). There was also a shift to stronger policy language with older documents having more enabling policies (e.g. should, encourage to) and newer documents having more positive directive (e.g. shall, will) and limitation (e.g., shall not, will not) policies. Our study provides valuable insight into the effectiveness of current approaches to protecting and enhancing landscape connectivity in urban environments of southern Ontario. These results suggest that, in order to mitigate the negative effects of landscape fragmentation and habitat loss, provincial and regional land use policies have increasingly taken landscape connectivity into account. Further, the results confirm that while land use policy for the protection of landscape connectivity has been strengthened over the last two decades, corridors have remained stable with no improvements or enhancements within the urban areas. These results highlight the need for greater emphasis on enhancing landscape connectivity. The negative impacts of urbanization on biodiversity, habitat degradation, and species movement are well documented (Beninde et al., 2015; Park, 2015; Ruas et al., 2022; Rudnick et al., 2012) and protecting and enhancing landscape connectivity has been shown to reduce these negative impacts (Gilbert-Norton et al., 2010; Resasco, 2019). Incorporating green infrastructure into developments, restoring degraded habitat, and implementing private stewardship programs to encourage the transformation of private yards and gardens to incorporate habitat for native plants and wildlife can all serve to improve connectivity and overall ecosystem function within urban areas.

There are a few limitations to this research. Lack of data availability as well as time and resource constraints to collect primary data limited the feasibility of a species-specific approach. Consequently, the spatial analysis component of our research focused on structural connectivity using generic assumptions of species movement based on land cover type. This means that we did not incorporate biological data on behavioural responses of species to landscape structure and our assumptions of landscape resistance do not capture nuances in species behaviour. Additionally, the SOLRIS land cover data does not capture street trees or private gardens and yards however, these features can also contribute to landscape connectivity in urban areas (Goddard et al., 2010; Ossola et al., 2019). Other variables such as traffic, noise, and light can also impact species movement (LaPoint et al., 2015) and were not considered in our assumptions due to lack of data availability and that they are more difficult to generalize. This research also did not address corridor effectiveness. How well a corridor facilitates movement between habitat patches depends on species niche requirements including corridor length and width (Tischendorf & Fahrig, 2000). While this research focused on structural connectivity, the functional connectivity of the corridors identified will vary from species to species. Further, although landscape resistance is a fundamental component of the modelling process there is no standard method for assigning resistance values (Avon & Bergès, 2016; Graves et al., 2014; Zeller et al., 2012). While the values chosen were based on a literature review there will always be some level of uncertainty of the ecological realism of these values. Despite these limitations, the outcomes of this research do provide foundational knowledge on the current state of landscape connectivity in Waterloo Region and provides insight into the potential conditions of other regions in southern Ontario with similar social, ecological, and economic contexts. This research can also be used to inform future finer-grain analyses that may address specific areas and species of concern.

Our coarser-scale analysis of climate connectivity found very few discussions on the potential role of urban areas in supporting climate connectivity and successful climate change-induced range shifts. In response, we argued that opportunities for climate corridors solely outside of urban areas may not be feasible in densely populated, rapidly growing regions where land is limited. In response, regional and/or strategic-level analysis of climate connectivity and implementation of adaptive approaches to landscape connectivity protection and enhancement that considers future climate conditions, range shifts, and changes in habitat suitability over time is needed. Our review of the climate connectivity literature has confirmed that, as an emerging area of research, there are opportunities for future research to consider urban contexts. For example, we believe that as climate connectivity research continues to evolve, future research should consider not only the negative effects of urban areas but also their crucial contributions to global climate resilience and sustainability by examining how they can support climate connectivity over broad temporal and spatial scales. As emphasis on climate change mitigation and adaptation continues to increase, combining climate change considerations into existing approaches to protecting and enhancing landscape connectivity could become the norm. For example, adaptive approaches to corridor protection and enhancement would allow us to continue to learn and adjust in the face of uncertainty presented by ongoing climate change. Future research is needed on whether current measures to protect and enhance landscape connectivity within urban areas are adequate to accommodate climate change-induced range shifts, or whether new approaches are required.

In addition to those mentioned above, there are a few key areas where future research could be undertaken. The first is expanding the analysis to other southern Ontario jurisdictions to explore the effectiveness of other provincial land use plans that protect key natural heritage features and areas such as the Niagara Escarpment Plan, Greenbelt Plan, and Oak Ridges Moraine Conservation Plan. Second, if there are specific species of interest, a functional connectivity approach could be undertaken. Such an approach could incorporate biological data as well as additional variables into the landscape resistance assumptions targeted to species of interest such as traffic, noise, light, street trees, private yards and/or gardens. There is also an opportunity through a functional connectivity approach to address corridor effectiveness. Third, future research to identify corridors critical to climate connectivity across southern Ontario could be used to inform strategic and regional-scale land use guidance to facilitate climate change-induced range shifts within urban areas. Lastly, while this research looked at the effectiveness of provincial and regional land use policies between 1996 and 2020, there have been substantial changes to Ontario’s land use policy and legislative context over the last five years (*see Appendix D*). These changes impact land use planning in Ontario including built form, growth management including urban expansion, community infrastructure including parks and open space, and environmental protection. The full impact of these changes on landscape connectivity will not be known for several years and may be an interesting area for research in the more distant future.

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Appendix A

Land Cover in Case Study Area

Land Cover (SOLRIS 2015)	Percentage
Forests (excluding swamps)	5.54%
Wetlands (excluding swamps)	0.97%
Treed & Thicket Swamps	8.50%
Grasslands	0.00% (0.002%)
Parks & Open Space	1.64%
Cultivated Trees & Hedgerows	1.50%
Water	0.89%
Agriculture (includes undifferentiated)	68.90%
Urban	7.01%
Infrastructure	4.49%
Extraction	0.57%

Appendix B

Sensitivity Analysis

Forest Connectivity

<u>Spearman's Rank Correlation Coefficient – 1000 Random Cells</u>

Forest 2000-2002

	F1a	F2a	F3a	F4a	F1b	F2b	F3b	F4b
F1a	1.00	0.87	0.87	0.29	0.98	0.83	0.83	0.53
F2a	0.87	1.00	0.89	0.44	0.87	0.95	0.84	0.65
F3a	0.87	0.89	1.00	0.30	0.88	0.89	0.97	0.64
F4a	0.29	0.44	0.30	1.00	0.25	0.35	0.26	0.44
F1b	0.98	0.87	0.88	0.25	1.00	0.87	0.85	0.57
F2b	0.83	0.95	0.89	0.35	0.87	1.00	0.88	0.76
F3b	0.83	0.84	0.97	0.26	0.85	0.88	1.00	0.69
F4b	0.53	0.65	0.64	0.44	0.57	0.76	0.69	1.00

Forest 2009-2011

	F1a	F2a	F3a	F4a	F1b	F2b	F3b	F4b
F1a	1.00	0.88	0.86	0.29	0.99	0.84	0.81	0.50
F2a	0.88	1.00	0.88	0.46	0.87	0.95	0.82	0.62
F3a	0.86	0.88	1.00	0.35	0.87	0.90	0.96	0.64
F4a	0.29	0.46	0.35	1.00	0.26	0.37	0.31	0.48
F1b	0.99	0.87	0.87	0.26	1.00	0.87	0.83	0.54
F2b	0.84	0.95	0.90	0.37	0.87	1.00	0.87	0.73
F3b	0.81	0.82	0.96	0.31	0.83	0.87	1.00	0.68
F4b	0.50	0.62	0.64	0.48	0.54	0.73	0.68	1.00

Forest 2015

	F1a	F2a	F3a	F4a	F1b	F2b	F3b	F4b
F1a	1.00	0.88	0.89	0.26	0.99	0.84	0.84	0.50
F2a	0.88	1.00	0.89	0.41	0.88	0.95	0.84	0.63
F3a	0.89	0.89	1.00	0.27	0.90	0.89	0.97	0.61
F4a	0.26	0.41	0.27	1.00	0.23	0.32	0.23	0.43
F1b	0.99	0.88	0.90	0.23	1.00	0.87	0.86	0.55
F2b	0.84	0.95	0.89	0.32	0.87	1.00	0.89	0.74
F3b	0.84	0.84	0.97	0.23	0.86	0.89	1.00	0.67
F4b	0.50	0.63	0.61	0.43	0.55	0.74	0.67	1.00

Wetland Connectivity

Spearman's Rank Correlation Coefficient – 1000 Random Cells

Wetland 2000-2002

	W1a	W2a	W3a	W4a	W1b	W2b	W3b	W4b	W1c	W2c	W3c	W4c	W1d	W2d	W3d	W4d
W1a	1.00	0.87	0.85	0.42	0.98	0.88	0.89	0.06	1.00	0.86	0.82	0.47	0.69	0.87	0.86	0.13
W2a	0.87	1.00	0.89	0.59	0.83	0.95	0.90	0.11	0.87	0.99	0.86	0.62	0.87	0.94	0.86	0.14
W3a	0.85	0.89	1.00	0.53	0.82	0.85	0.96	[illegible]	0.85	0.89	0.98	0.61	0.80	0.85	0.94	0.15
W4a	0.42	0.59	0.53	1.00	0.35	0.44	0.45	0.14	0.42	0.57	0.51	0.82	0.52	0.43	0.43	0.14
W1b	0.98	0.83	0.82	0.35	1.00	0.87	0.87	0.07	0.98	0.82	0.79	0.41	0.67	0.86	0.84	0.14
W2b	0.88	0.95	0.85	0.44	0.87	1.00	0.90	0.16	0.89	0.95	0.83	0.51	0.85	0.99	0.87	0.17
W3b	0.89	0.90	0.96	0.45	0.87	0.90	1.00	0.07	0.89	0.90	0.94	0.54	0.82	0.90	0.97	0.18
W4b	0.06	0.11	[illegible]	0.14	0.07	0.16	0.07	1.00	0.05	0.11	[illegible]	0.11	0.15	0.16	0.07	0.38
W1c	1.00	0.87	0.85	0.42	0.98	0.89	0.89	0.05	1.00	0.87	0.83	0.48	0.70	0.88	0.87	0.15
W2c	0.86	0.99	0.89	0.57	0.82	0.95	0.90	0.11	0.87	1.00	0.88	0.65	0.88	0.95	0.89	0.19
W3c	0.82	0.86	0.98	0.51	0.79	0.83	0.94	[illegible]	0.83	0.88	1.00	0.65	0.80	0.85	0.96	0.22
W4c	0.47	0.62	0.61	0.82	0.41	0.51	0.54	0.11	0.48	0.65	0.65	1.00	0.62	0.54	0.57	0.39
W1d	0.69	0.87	0.80	0.52	0.67	0.85	0.82	0.15	0.70	0.88	0.80	0.62	1.00	0.87	0.81	0.21
W2d	0.87	0.94	0.85	0.43	0.86	0.99	0.90	0.16	0.88	0.95	0.85	0.54	0.87	1.00	0.89	0.24
W3d	0.86	0.86	0.94	0.43	0.84	0.87	0.97	0.07	0.87	0.89	0.96	0.57	0.81	0.89	1.00	0.26
W4d	0.13	0.14	0.15	0.14	0.14	0.17	0.18	0.38	0.15	0.19	0.22	0.39	0.21	0.24	0.26	1.00

Wetland 2009-2011

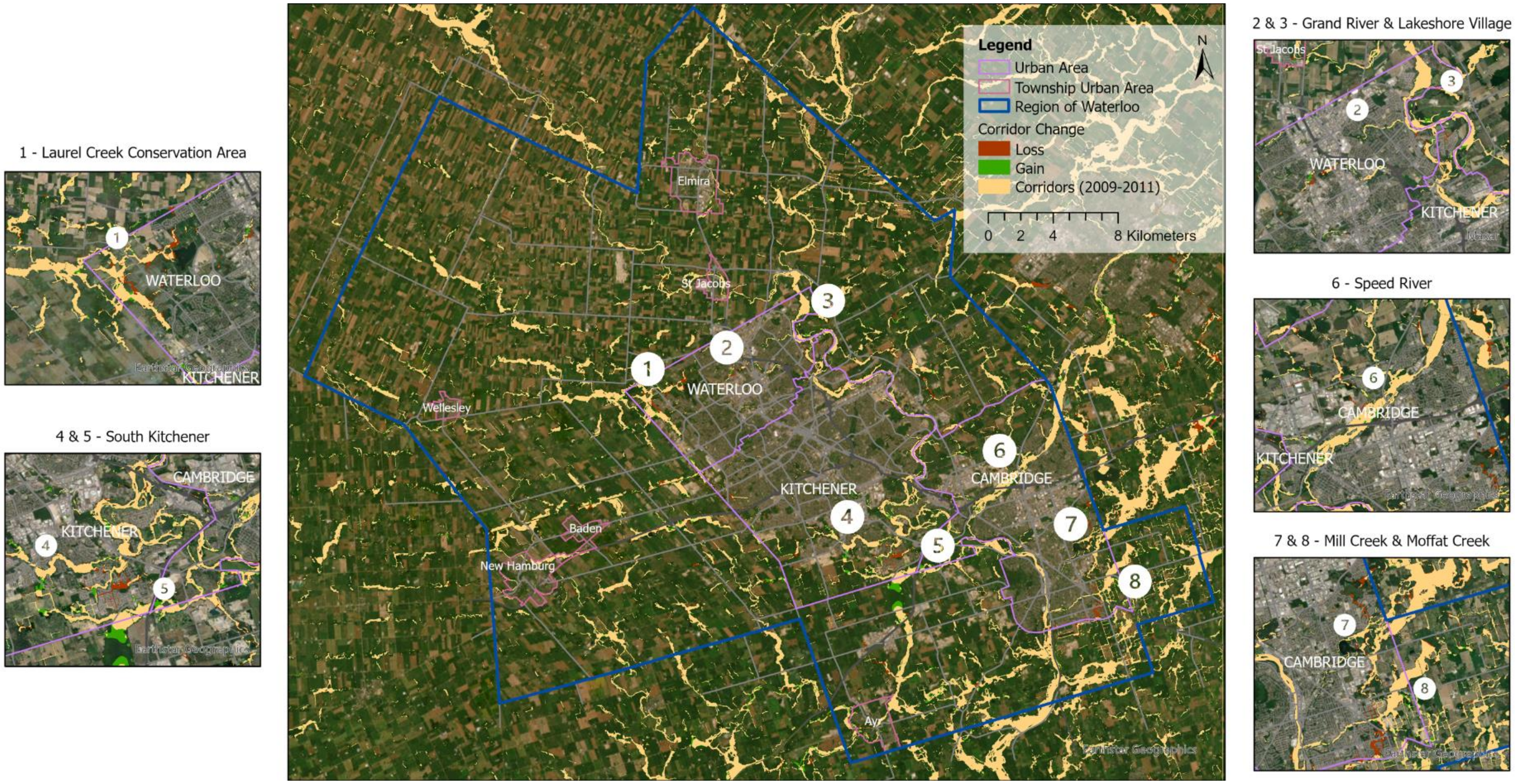
	W1a	W2a	W3a	W4a	W1b	W2b	W3b	W4b	W1c	W2c	W3c	W4c	W1d	W2d	W3d	W4d
W1a	1.00	0.88	0.84	0.23	0.77	0.90	0.89		1.00	0.88	0.83	0.39	0.98	0.90	0.87	0.10
W2a	0.88	1.00	0.88	0.33	0.66	0.96	0.91	0.09	0.88	0.99	0.85	0.52	0.85	0.95	0.88	0.11
W3a	0.84	0.88	1.00	0.29	0.68	0.85	0.96		0.85	0.88	0.98	0.53	0.82	0.85	0.95	0.15
W4a	0.23	0.33	0.29	1.00	0.25	0.25	0.23	0.13	0.23	0.31	0.27	0.50	0.19	0.24	0.21	
W1b	0.77	0.66	0.68	0.25	1.00	0.70	0.72		0.77	0.66	0.68	0.24	0.78	0.71	0.71	0.13
W2b	0.90	0.96	0.85	0.25	0.70	1.00	0.90	0.11	0.90	0.96	0.83	0.42	0.89	0.99	0.88	0.13
W3b	0.89	0.91	0.96	0.23	0.72	0.90	1.00	0.05	0.90	0.91	0.95	0.47	0.88	0.90	0.98	0.17
W4b		0.09		0.13		0.11	0.05	1.00		0.09		0.19		0.10	0.05	0.37
W1c	1.00	0.88	0.85	0.23	0.77	0.90	0.90		1.00	0.88	0.83	0.41	0.99	0.91	0.88	0.12
W2c	0.88	0.99	0.88	0.31	0.66	0.96	0.91	0.09	0.88	1.00	0.87	0.55	0.85	0.96	0.90	0.16
W3c	0.83	0.85	0.98	0.27	0.68	0.83	0.95		0.83	0.87	1.00	0.54	0.81	0.85	0.96	0.20
W4c	0.39	0.52	0.53	0.50	0.24	0.42	0.47	0.19	0.41	0.55	0.54	1.00	0.36	0.45	0.48	0.40
W1d	0.98	0.85	0.82	0.19	0.78	0.89	0.88		0.99	0.85	0.81	0.36	1.00	0.89	0.86	0.13
W2d	0.90	0.95	0.85	0.24	0.71	0.99	0.90	0.10	0.91	0.96	0.85	0.45	0.89	1.00	0.90	0.19
W3d	0.87	0.88	0.95	0.21	0.71	0.88	0.98	0.05	0.88	0.90	0.96	0.48	0.86	0.90	1.00	0.23
W4d	0.10	0.11	0.15		0.13	0.13	0.17	0.37	0.12	0.16	0.20	0.40	0.13	0.19	0.23	1.00

Wetland 2015

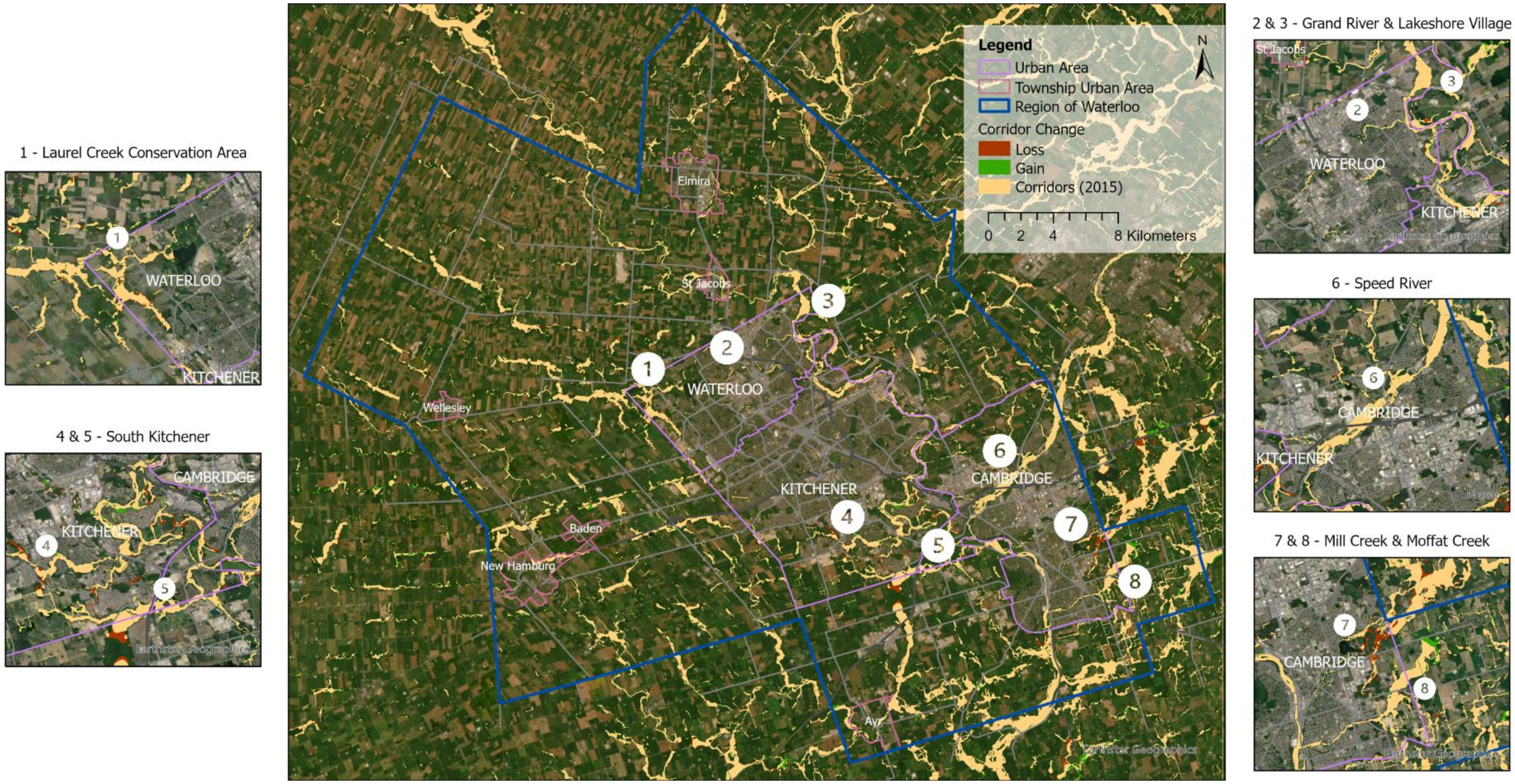
	W1a	W2a	W3a	W4a	W1b	W2b	W3b	W4b	W1c	W2c	W3c	W4c	W1d	W2d	W3d	W4d
W1a	1.00	0.86	0.83	0.38	0.99	0.89	0.89		1.00	0.86	0.82	0.42	0.98	0.87	0.86	0.17
W2a	0.86	1.00	0.87	0.58	0.82	0.95	0.90	0.05	0.86	0.99	0.84	0.59	0.82	0.92	0.87	0.19
W3a	0.83	0.87	1.00	0.53	0.81	0.84	0.96		0.84	0.87	0.97	0.59	0.81	0.83	0.94	0.20
W4a	0.38	0.58	0.53	1.00	0.31	0.41	0.44	0.12	0.38	0.56	0.49	0.84	0.31	0.39	0.41	0.11
W1b	0.99	0.82	0.81	0.31	1.00	0.88	0.87		0.99	0.82	0.80	0.37	1.00	0.87	0.85	0.18
W2b	0.89	0.95	0.84	0.41	0.88	1.00	0.90	0.06	0.89	0.95	0.82	0.46	0.88	0.98	0.87	0.22
W3b	0.89	0.90	0.96	0.44	0.87	0.90	1.00		0.89	0.91	0.95	0.52	0.87	0.90	0.98	0.23
W4b		0.06		0.12		0.06		1.00		0.05		0.12		0.05		0.37
W1c	1.00	0.86	0.84	0.38	0.99	0.89	0.89		1.00	0.86	0.82	0.43	0.99	0.88	0.87	0.19
W2c	0.86	0.99	0.87	0.56	0.82	0.95	0.91	0.05	0.86	1.00	0.86	0.62	0.83	0.95	0.89	0.24
W3c	0.82	0.84	0.97	0.49	0.80	0.82	0.95		0.82	0.86	1.00	0.62	0.80	0.83	0.96	0.26
W4c	0.42	0.59	0.59	0.84	0.37	0.46	0.52	0.12	0.43	0.62	0.62	1.00	0.38	0.49	0.54	0.36
W1d	0.98	0.82	0.81	0.31	1.00	0.88	0.87		0.99	0.83	0.80	0.38	1.00	0.88	0.85	0.20
W2d	0.87	0.92	0.83	0.39	0.87	0.98	0.90	0.06	0.88	0.95	0.83	0.49	0.88	1.00	0.89	0.29
W3d	0.86	0.87	0.94	0.41	0.85	0.87	0.98		0.87	0.89	0.96	0.54	0.85	0.89	1.00	0.30
W4d	0.17	0.19	0.20	0.11	0.18	0.22	0.23	0.37	0.19	0.24	0.26	0.36	0.20	0.29	0.30	1.00

Appendix C

Corridor change: 2000-2002 and 2009-2011; 2009-2011 and 2015



Corridor change between 2000-2002 and 2009-2011 results.



Corridor change between 2009-2011 and 2015 results.

Appendix D

Provincial changes to land use planning legislation and policies in last five years (2019-2023)

Legislative Changes

Bill	Land use planning related Acts impacted
Bill 108, More Homes, More Choice Act, 2019	Conservation Authorities Act Development Charges Act Local Planning Appeal Tribunal Act Ontario Heritage Act Planning Act
Bill 109, More Homes for Everyone Act, 2022	Development Charges Act Planning Act
Bill 23, More Homes Built Faster Act, 2022	Conservation Authorities Act Development Charges Act Ontario Heritage Act Ontario Land Tribunal Act Planning Act

Policy Changes

Policy Document	Relevant Environmental Registry of Ontario (ERO) posting number(s)
A Place to Grow: Growth Plan for the Greater Golden Horseshoe 2019 (including 2020 amendment)	ERO 4504, 0018, 1680, 1679
Provincial Policy Statement 2020	ERO 0279
Provincial Planning Statement 2023 (proposed)	ERO 6177, 6813