Utilizing Existing Data to Measure Ecological Connectivity for Planning Southern Ontario's Urban Growth: A Case Study of the Waterloo Region

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

Urbanization is an increasing threat to global biodiversity. Urban areas are often thought to preclude native plants and animals but are capable of supporting some species if properly managed. Urban planning tends to focus on maximizing human benefits of the urban landscape; however, urban greenspaces can enhance ecological services for humans and promote natural species diversity. Habitat quantity and quality should be the top priorities when managing urban greenspaces. In urban areas, quantity and quality may be limited by the area available, so other tools are needed to make advancements. Connectivity represents a metric that could help plan urban greenspaces.

To explore the utility of connectivity tools for cities in Southern Ontario, resistance maps were developed for Kitchener, Ontario based on four animals (bats, deer, shrews and snakes) using 2019 aerial data. Scenarios were developed based on potential changes to the city by increasing either the number of habitat cells by 5% or 10% (showing potential backyard and small greenspace restorations) or the number of buildings cells to meet projected growth targets. These were created by selecting cells randomly and reassigning values based on desired fragmentation of the land type. The resulting resistance maps were analyzed using an "omnidirectional" method developed for Circuitscape that enabled landscape level analysis of connectivity.

Urban connectivity differed for the four species based on the dispersal capability of each species with bats and deer having the most connectivity with maximum resistance values of 0.53 and 0.76 respectively and shrews and snakes the least connectivity with maximum resistance values of 1.07 and 1.33. Connectivity decreased with increasing urbanization, showing a gradient of increasing current as building density increased and urban green spaces decreased. All urban greenspaces, from yards to natural areas, were important for landscape connectivity and need to be maintained if not enhanced. Buildings represented the primary barrier for all species other than bats (due to their ability to fly over them). Roads and paved areas also posed barriers to all species and represented the strongest barrier for bats. Mitigation methods should be considered for these areas, with greenspaces planned through highly built areas.

Of the three models, increased building density had the largest effect on habitat connectivity, changing the resistance values by 25-33% for deer, shrew, and snakes. Bats species only had a 5-6% increase in resistance because buildings are less of a barrier to bats. The models with increasing habitat amounts were difficult to visually differentiate from the 2019 baseline, and changes in

resistance value were less than 1%. These maps did show some benefits for urban species. This was expected due to the larger number of cells changed in the increased building density scenario. Planning mitigation efforts around densification should be the top priority for maintaining connectivity, but creating and maintaining greenspaces should not be forgotten as increasing habitat provides benefits beyond connectivity.

Overall, these results were expected, but this analysis did show the utility of connectivity mapping for Kitchener. Connectivity analysis is potentially a valuable tool for urban planners in Southern Ontario cities if habitat quantity and quality are already being maximized and with the caveat that connectivity planning should not justify the removal of existing habitat patches and care should be taken to avoid undervaluing small patches.

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Dedication

To Mom and Dad, who taught me that social and environmental justice matter and taught me to explore. I will never forget the bike rides and paddles. To my brother, for letting me get close enough to the ditch to see what he was doing. He never let me run out of clay or bugs. To my partner, for giving me the time and space to do this. Also, for being willing to explore (at least you know the difference between tadpoles and minnows now)! To RJ: you were a late addition but really helped fuel me to get this finished.

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Chapter 1 Introduction

Urbanization is a primary cause of the global threat to biodiversity, and with global biodiversity changing at unprecedented rates, there is a growing need to address the effects of urbanization (Mckinney, 2006; Sala et al., 2000). Land use change (both urban and rural) is projected to have more effect on terrestrial biodiversity than climate change (Sala et al., 2000). While agriculture covers much of the land that has been modified, urbanization is more ecologically destructive (Lin & Fuller, 2013). Urbanization is changing landscapes and species distributions, and evidence is emerging that it is causing evolutionary change (Alberti et al., 2020).

Urbanization is increasing around the world and leading to significant sustainability challenges (United Nations Department of Economic and Social Affairs, 2014). The world's largest cities are expected to keep growing, with expanding ecological footprints that extend well outside of the city limits (Grimm et al., 2008; Hoornweg & Pope, 2017). There is growing concern being expressed over the need to address the problems surrounding urbanization (Goddard et al., 2010; Müller et al., 2018). This concern is reinforced with the need for cities to grow to help gain efficiencies for resource use with an increasing population (Hoornweg & Pope, 2017; United Nations Department of Economic and Social Affairs, 2017). As cities grow, ecological planning tools are needed to make decisions on density and locations of growth. Debate continues around locations of natural spaces and whether they should be integrated into cities or preserved in areas outside of cities (Lin & Fuller, 2013).

Urbanization has a number of impacts on the landscape, for example, it can increase impervious surfaces, alter hydrological processes, decrease native vegetation and increase the amount of non-native species, decrease gene flow by providing barriers like roads and buildings, add novel pressures like noise and light pollution and increase urban temperatures (Alberti et al., 2020; Aronson et al., 2016; Fleishman & Mac Nally, 2007; Gecchele et al., 2020; Lookingbill et al., 2022; Łopucki & Kitowski, 2017; Tucker et al., 2018). Cumulatively, these impacts often reduce the resiliency of systems to change, as seen in the increasing impacts of hurricanes where coastal habitats have been removed (Fleishman & Mac Nally, 2007). These effects cause animals to change behaviors, with different species reacting in different ways (e.g. shifting when and where they hunt, changing diet, changing reproduction rates), making impacts species specific with a few species thriving and all except the most extreme generalist species being extirpated from urban areas (Able & Belthoff, 1998; Alberti et al., 2020; Moretto & Francis, 2017; Thorne et al., 2021). Urban areas are built differently depending on local needs, so impacts vary, making the effects of urbanization landscape specific as well (Alberti et al., 2020). In general, the species that exist in urban areas have different compositions than those in more natural environments and are

primarily species that can tolerate disturbance and use novel resources (Gecchele et al., 2020). This makes cities novel ecosystems that are not well understood (Aronson et al., 2016; Łopucki & Kitowski, 2017).

Urban areas are often seen as places that do not support natural habitat or biodiversity, but they provide habitat for native and non-native species just in a lowered capacity (Aronson et al., 2014; Braaker et al., 2014; Gecchele et al., 2020; Gomes et al., 2011; Ives et al., 2016; Kong et al., 2010; Lepczyk et al., 2017; Lin & Fuller, 2013; Müller et al., 2018; Soares et al., 2024). Despite having lower biodiversity than other natural areas, urban greenspaces can provide value and could be even more beneficial if properly planned and managed, especially as the urban areas intensifies (Bourgeois et al., 2024; Gallo et al., 2017; Müller et al., 2018; Rudd et al., 2002). Urban greenspaces can add value like stop over points for migration, release from landscape pressures like predators, increasing heterogeneity of the landscape (creating edge environments), and they may contain different resources or resources at different times than the surrounding natural areas (ornamental species, food waste, etc.) (Gecchele et al., 2020; Lookingbill et al., 2022). Useful urban greenspaces can include many types of land, from backyards to golf courses to natural areas (Bourgeois et al., 2024; Colding, 2007; Craig, 2022; De Ridder et al., 2004; Gallo et al., 2017; Gecchele et al., 2020; Lepczyk et al., 2017; Ossola et al., 2019; Rudd et al., 2002; Vergnes et al., 2012; Zhang et al., 2019).

To promote biodiversity within these spaces, communities must be designed with local ecology in mind (Park, 2017). Many cities have ecological goals, but these often lack detail and are not quantifiable (Nilon et al., 2017). Even if city planners try to meet these goals, barriers exist to creating and enhancing green infrastructure, so it is important that easy and accessible tools exist for optimizing these areas for ecological impact (Johns, 2019). Urban areas have historically had limited opportunity to enhance habitat quality and quantity, which are two of the main metrics that ecologists use to promote/enhance natural habitat. They have small diverse patches of landscape with increasingly isolated natural areas (Beninde et al., 2016; Braaker et al., 2014; Goddard et al., 2010; Grimm et al., 2008). As a result, researchers have started looking into whether connectivity between the remaining green space areas could be improved. Connectivity analyses are just one tool set being used to try to optimize the utility of small amounts of habitat. Connectivity metrics are increasingly utilized as a landscape management tool, but how connectivity should be quantified and the actual effects on biodiversity are still debated (Fletcher et al., 2016). The term connectivity can mean many things. This is problematic when trying to talk about the effects of connectivity on various systems (Beger et al., 2022; Martínez-Richart et al., 2024; Riva et al., 2024; Wood et al., 2022). One frequently used definition of connectivity is “the degree to which landscape facilitates or impedes movement among resource patches” (Taylor et al., 1993). This appears in many connectivity papers including more theoretical papers as well as connectivity applications

(Adriaensen et al., 2003; Bailey, 2007; Koen et al., 2014; Saura & Rubio, 2010; Tischendorf & Fahrig, 2000a; Wang et al., 2015; Xiu et al., 2017). This definition summarizes a lot of complexities. It incorporates the structure of the landscape but also how organisms move through it. These two parts of connectivity are often referred to as structural connectivity, which depends only on the shape and pattern of the landscape and functional connectivity, which incorporates how organisms respond to that landscape during movement (Baguette & Van Dyck, 2007). Functional connectivity has since been narrowed in scope to refer to impacts of the shape and pattern of the landscape that lead to gene flow (Row et al., 2018). When connectivity is modeled, the aim is often to estimate functional connectivity; however, these studies are often limited by a lack of data about gene flow of the organisms being modeled. This led Calabrese and Fagan to talk about actual versus potential connectivity where potential connectivity is a theoretical model of functional connectivity created with limited organism data (Calabrese & Fagan, 2004). Ultimately, the goal in connectivity modeling is to analyze how connections can help or hinder the conservation or restoration of sustainable populations.

These varying ideals of connectivity all rely on the idea that connectivity itself is something to be conserved or that its opposite (fragmentation) should be avoided, however whether this is true remains unclear. Fragmentation impacts many things, for example, the amount of habitat, the number of patches, the size of those patches and their isolation (Fahrig, 2003). Habitat amount is important for many species. In both simulations and real landscapes, habitat amount has been found to have dominated the effects caused by fragmentation (Jackson & Fahrig, 2014; Melo et al., 2017; Wilson et al., 2016). It is also noted that fragmentation often derives from habitat loss (Wilson et al., 2016). This makes it difficult to separate out these effects. Focus should be given to habitat area and quality, but there are some cases where habitat amount and quality cannot be increased but improvements can still be made (for example, determining which areas should be developed or conserved when some areas will be spared from development) (Hodgson et al., 2011). It is hypothesized that connectivity is important when habitat levels are below 20-30%, but these numbers are theoretical (Fahrig, 2003; Hodgson et al., 2011). It is possible that in areas with limited habitat, the ability to use small patches of land as stepping stones or narrow linear links as passages between otherwise isolated habitats could help maintain species populations (Soares et al., 2024).

A lot of connectivity modeling focuses on preventing isolation effects, but the magnitude and direction of isolation effects is uncertain. There are many papers that link the spatial configuration caused by fragmentation of the landscape to negative effects (Aguilar et al., 2019; Brudvig et al., 2009; Haddad et al., 2017). These papers look primarily at patch scale dynamics, which poses two problems. The first is that habitat loss and other effects of fragmentation are linked at a patch scale (Fahrig, 2019). These two

things being linked means that they are not independent so cannot be controlled for in the typical ways (Fletcher, Reichert, et al., 2018). The second is that the effects of fragmentation are expected to be at the landscape scale (Tischendorf & Fahrig, 2000b). Papers that have assessed the landscape scale effects show somewhat different results. Many papers had connectivity having little to no effect and those that had effects often had positive effects of fragmentation (Fahrig, 2017; Fleishman & Mac Nally, 2007). Other reviews have noted overwhelmingly positive effects of connectivity on biodiversity (Fletcher et al., 2016). Understanding of the effects of fragmentation is further complicated by time-scale. Scientific studies have limited time-scales, but recent studies suggest that the effects of fragmentation increase with time (Fletcher, Didham, et al., 2018; Haddad et al., 2017). Overall, there is a lack of understanding of the impacts of fragmentation in general when accounting for habitat loss. Focus should be on increasing habitat quantity and quality with connectivity being a secondary tool in the conservation toolbox (Fletcher et al., 2016; Hodgson et al., 2009).

The value of connectivity mapping in urban areas is even less well researched than connectivity effects in general. Theoretically, the decrease in urban habitat also leads to increased isolation of remnant patches, and areas like roads and other built landscapes can bifurcate habitats separating them from each other (Baker et al., 2003; Vergnes et al., 2012). Landscape genetics studies have mixed results, with different species showing urban features as inhibiting, facilitating or not affecting various species (Lookingbill et al., 2022). Research working on the verification of the real-world applicability of connectivity has largely been done in non-urban areas and urban areas differ enough from these cases that it is hard to assess the relevance of connectivity work for species in urban areas (Braaker et al., 2014; Lookingbill et al., 2022). Some preliminary studies in cities have found some positive responses in urban species to increased habitat connectivity. In New York City, percent canopy cover was found to correlate with the degree of genetic variation in white footed mice (Munshi-South, 2012). Patch size, quality and isolation were all found to affect squirrel presence in Brussels (Verbeylen et al., 2003). Movements for urban hedgehogs in Zurich were found to be impacted by both habitat connectivity and quality (Braaker et al., 2014). In each study, the species tested were urban adapters and already had fairly easy movement through urban spaces and more research is needed to know how applicable urban connectivity is to less well adapted urban species. In general, there is a lack of data connecting urban connectivity to effects on flora and fauna, but these areas have very low habitat to begin with, and improvements for urban fauna are necessary (Braaker et al., 2014).

Urban habitat connectivity is a growing field of research, with many turning to connectivity metrics to assess urban habitat matrices. These analyses generally focused on either how to create better habitat connectivity within cities or to look at how to develop cities with the lowest impact on urban habitat

connectivity. In Coquitlam, British Columbia, habitat connectivity of neighborhoods was measured, and it was found that backyard habitat, planted boulevards, and utility rights of way were necessary to create urban habitat connectivity (Rudd et al., 2002). A connectivity analysis in Stockholm about European toads was used to help plan where connectivity needed to be improved and where potential areas of the landscape could be used to help meet development goals (Zetterberg et al., 2010). Similarly, in Jinan City, China, habitat connectivity analysis was used to expose potential problems with the greening plan for the city, showing that the proposed plaza and roadside greenspaces were insufficient to create adequate habitat connectivity (Kong et al., 2010). Stockholm was perceived as having adequate greenspace, but researchers realized that connectivity between these areas was low and successfully utilized connectivity analysis to plan to enhance it (Xiu et al., 2017). Future scenarios were developed for Nanning City, China, showing that urban expansion would weaken the urban habitat connectivity (Chang et al., 2023). An urban area of Lyon was studied, with different species showing that private spaces are important to urban habitat connectivity and that the amount of improvement in connectivity was related to more than just the addition of habitat (Bourgeois et al., 2024). These examples use vastly different methods to work toward an overall goal of increased connectivity. They do show that there is potential for utilizing connectivity analysis to improve urban habitats, but more research is required.

Connectivity as a tool allows users to investigate a myriad of questions. This paper specifically is aimed at assessing the utility of current methods for helping to guide urban development in Southern Ontario. This project was planned around the idea that urban greenspaces may be able to promote connectivity in major urban centres within Southern Ontario, Canada. Previous studies have found urban greenspace to be necessary for creating connected habitats for urban fauna (Munshi-South, 2012; Rudd et al., 2002). Southern Ontario has already undergone intensive land use changes with much of its land cover already being agricultural and urban (Andrews, 2022). Many municipalities in Southern Ontario are in the process of densification with provincial guidance from the Places to Grow initiative (Ontario Ministry of Infrastructure, 2013). Times of infrastructure change (like densification) offer opportunity to add restoration efforts to that infrastructure work (proper planning and integrating restoration efforts into already planned work can decrease the cost of restoration and decrease the need for remediation later) (Neeson et al., 2018). As this growth occurs, the greenspace in urban Southern Ontario will become more restricted. It is important to assess the possibility of providing better, more connected habitat in the urban core while development is taking place, to ensure that these areas exist in the future and to better design them in partnership with these changes.

Ideally, connectivity maps would focus on functional connectivity, but genetic data is often lacking, limiting the use of current best practices for connectivity modeling in urban areas. Urban planners often

only have access to aerial data and limited classified landscape data (built areas are often mapped, but habitat data is frequently limited). Most urban planners can only produce estimates of structural or potential connectivity if information about species movement can be approximated, as they lack genetic data for creating functional connectivity maps (Tischendorf & Fahrig, 2000b). Data on habitat suitability is often lacking as well. Little urban movement data was available. In order to estimate habitat suitability, information from as far back as the 1920's was used. Much of this information was anecdotal, but occurrence and limited mark-recapture data were used where possible; a few studies with telemetry data were also found. Lack of high-quality movement data made this research primarily exploratory, and better urban movement data is needed in the future if city planners are to rely more heavily on these methods. The hypothesis of this thesis is that this data can produce useful estimates of connectivity in urban areas in Southern Ontario. Kitchener, Ontario is used as a case study to explore the utility of connectivity methods focused on easily available data to provide value for urban planners. Two questions were used as the focus of this study 1) What is the current state of landscape connectivity for species dispersal in downtown Kitchener for bats, deer, shrews and snakes? 2) How might changes in land use impact landscape connectivity for species dispersal in downtown Kitchener for bats, deer, shrews and snakes?

Chapter 2 Methods

2.1 Scale and Study Area

This analysis must either account for movement ability across the whole landscape or only model connections between residual patches (Tischendorf & Fahrig, 2000b). Patch to patch modeling assumes that the patches being moved from and too are known, and that the paths defined are suitably sized and the correct habitat for movement (Lookingbill et al., 2022). In urban areas, there is a lack of pristine habitat, which means that areas outside of these habitat patches are critical. This led to a focus on landscape level connectivity over patch to patch connections.

Modeling landscape level dynamics necessitated large amounts of data and needed large amounts of processing power, so it was important to choose an extent and grain size at which available computing power would suffice. Ideally connectivity would be measured for a large extent, as the smaller the area the more knowledge of the landscape and interaction with other organisms impacts movement separate from resistance (Hanks & Hooten, 2013). It was important to balance the possible extent with the ideal of having a species appropriate grain size. Area of impact is probably at the landscape granularity level for connectivity, though there are arguments for effective scale being much narrower, and this is species and process specific (Adriaensen et al., 2003; Anderson et al., 2010; Fahrig, 2003; Fleishman & Mac Nally, 2007; Keinath et al., 2017; Tischendorf & Fahrig, 2000b). The scale of effect is difficult to predict (Jackson & Fahrig, 2014). In general, the regional scale is thought to be better than the local scale for looking at populations, so broader regions were initially considered over single cities (Foltête et al., 2014).

Waterloo Region is currently a mid-sized community (Region of Waterloo, n.d.). It includes urban, industrial, rural and conservation areas. This region is one of the fastest growing areas in Canada (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014). As of the 2016 census, it had a population of 535,154 that has grown to 617,870 and is expected to reach 923,000 by 2051 (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020; Pogrzeba & Parkin, 2020). The Region of Waterloo is within the Grand River watershed. It has historically contained source water protection areas, rivers, reservoirs, wetlands, Carolinian woods, boreal islands and various geological topography formed through glaciation, with main habitat areas being forested upland and wetland (Grand River Conservation Authority: Natural Heritage, n.d.; Grealey, 2010; Soper, 1923).Over the last 200 years, the watershed has lost many of its forests and wetlands, resulting in habitat loss and fragmentation (*Grand River Conservation Authority: Natural Heritage*, n.d.). This population growth, combined with sensitive natural

areas, makes it a prime area of focus for connectivity of urban habitats. The Grand River Conservation Authority believes urban areas like backyards and public areas can be managed to help native species (*Grand River Conservation Authority: Natural Heritage*, n.d.). Given the planned growth increase, now is the time to think about how to plan greenspace in the region. Waterloo Region contains three main growth centres: Kitchener, Cambridge and Waterloo (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020). Planning for these three cities places the bulk of this growth in the urban areas, but expansion into the undeveloped and agricultural lands is still occurring (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020). Waterloo Region includes a large land area, and due to the small perceptive range of some urban wildlife, a resolution was needed that precluded the use of all three major cities to reduce overall data processing RAM consumption. As a result, only the largest city (Kitchener) was included in the analysis (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014). Kitchener contains an urban core with rural and industrial areas on the outskirts. The largest scale square extractable that fully included the downtown core was selected, including as much of the surrounding area as could be included while maintaining the square (Figure 1). Buffering the cities with industrial and agricultural areas decreases the risk of seeing edge effects within the urban areas of the maps, so that urban areas outside the urban centre can still be used (Beier et al., 2011; Etherington, 2016; Koen et al., 2010). Unfortunately, not all sides of the square reached a buffer area due to the extent of the available data.

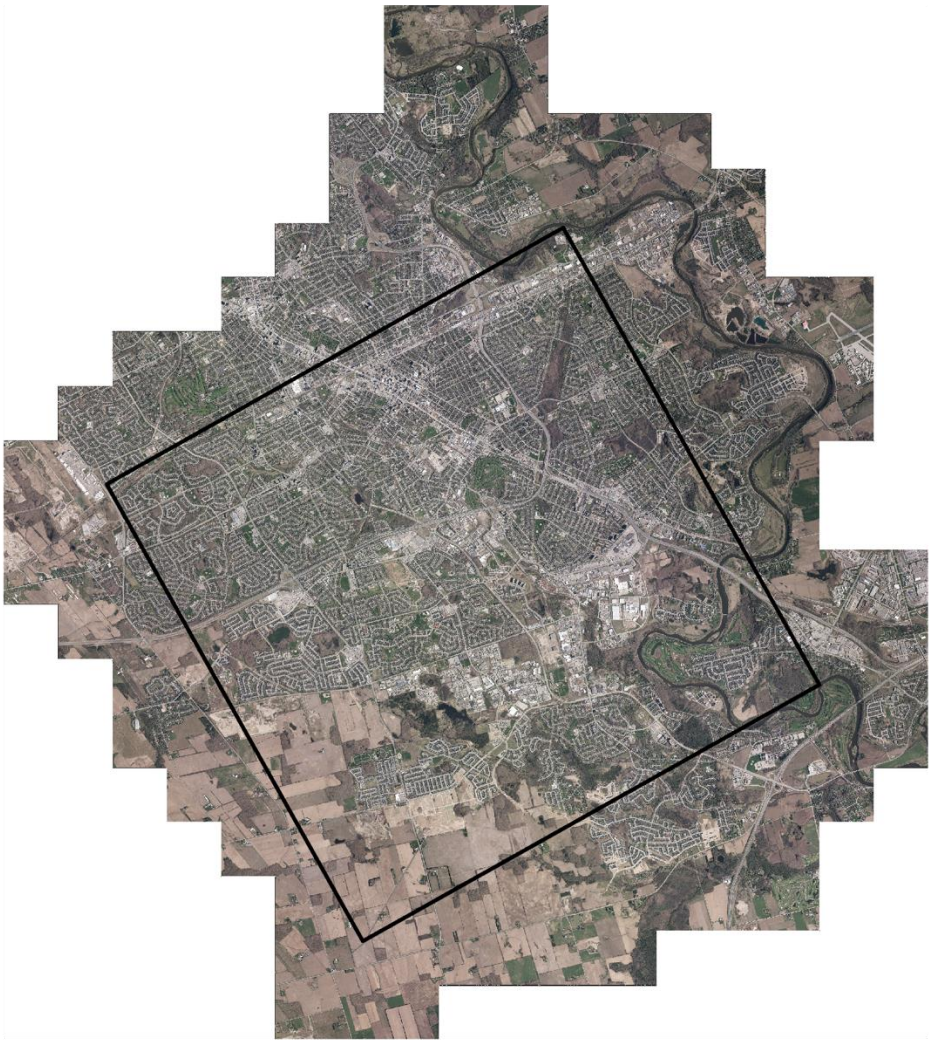


Figure 1 – Kitchener Bounding Box

Kitchener has historically been fairly dispersed due to lack of a strong downtown core, a large amount of suburban growth, the proximity of other cities and a lack of physical constraints to growth (Bunting & Filion, 1999). This form is characteristic of many cities in Southern Ontario (Bunting & Filion, 1999). As a result, Kitchener's growth can be planned mainly within the current built up area, with 50% of expected growth being required within this area (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020). By 2021 Kitchener's population had reached 256,885, up 10.1% from 2016, exceeding the provincial average increase of 5.8% (Statistics Canada, n.d.). The area is looking like it will have a

population of over 300,000 by 2031 (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014).

Discussions of land use make it imperative to acknowledge that this research takes place on the traditional territories of the Neutral, Anishinaabeg and Haudenosaunee peoples. It takes place on the unceded Haldimand Tract which encompasses six miles on either side of the Grand River that was granted to the Six Nations (Filice, 2020; *Territorial Acknowledgement*, n.d.). Much of our ecosystem knowledge lacks understanding of the roles of the peoples who traditionally live here and therefore care should be taken when discussing connections, interactions or restorations of what we think of as historic landscapes and how we reshape those ecosystems moving forward. This acknowledgment is at the end of the area discussion not to deemphasize it but to highlight that the research so far has been done with no Indigenous consultation. The use of this research moving forward should be done in consultation with local Indigenous peoples.

2.2 Species

Landscape connectivity depends both on the species that are selected, as well as the type of movement being modeled (McClure et al., 2016). There are many types of movement that contribute to the ability for a species to thrive, as well as many factors that impact this movement (Baguette & Van Dyck, 2007; Rudnick et al., 2012). Each species and even individual animals have different types of movement depending on what they need to do (e.g., foraging, migrating, dispersing), how well they can accomplish it (ease of mobility) and the resources available (Aronson et al., 2016; Fleishman & Mac Nally, 2007; McClure et al., 2016). The landscape dynamic and the fact that urban habitat patches tend to be far apart means that modeling landscape level connectivity will theoretically best represent dispersal movements (at least for smaller animals). Dispersal movements are less frequent than other types of movement but are an important indicator for gene flow which can help support species (Baguette & Van Dyck, 2007; Keeley et al., 2016). This analysis does not capture important data about other types of movement. It does not show how to protect all species, movement types or ecological processes (Beier et al., 2008).

Dispersal movement is species specific. This means that to get an idea of urban dispersal capabilities, multiple species with different dispersal needs should be represented (Beier et al., 2008; Koen et al., 2014; Krosby et al., 2015; Liu et al., 2018; Rudnick et al., 2012; Sattler et al., 2014). This suite of species should represent both short and long dispersers (even dispersal over multiple generations) (Beier et al., 2008). These species should also be umbrella species that represent a larger diversity of species than is modeled (Beier et al., 2008; Fleishman et al., 2000; Sahraoui et al., 2017). Ideally there would be 10-20

species, but due to processing power constraints, only four species were used, for more specifics on power constraints see 2.6 Processing Data (Beier et al., 2008).

The species themselves should be sensitive to fragmentation but also present within the area of concern and encompass sensitivities of other species (Fleishman et al., 2000; Leoniak et al., 2012). This could be species that have habitat or distance constrained dispersals or are reluctant to cross barriers (Beier et al., 2008). In this case, this means that the species should be present in some urban areas but sensitive to loss of habitat connectivity within the urban core in order to provide the earliest possible warning signs for connectivity loss (species that are present but not ubiquitous) (Beier et al., 2008; Fleishman et al., 2000). Choosing species that have a wide geographic range allows for comparison of results with other studies (Jones et al., 2009; Sattler et al., 2014). Each species selected needs to have information available about their movement or habitat use and be easy to study, allowing for assessment of the utility of any landscape changes made due to connectivity analysis (Fleishman et al., 2000). In order for this data to exist it is important that these species be easily monitorable. This also allows for future research to be done on the applicability of connectivity to these species in various contexts (Jones et al., 2009).

The fauna selected include the *Myotis* species of bats, white tailed deer (*Odocoileus virginianus*), *Sorex* species of shrews and eastern garter snakes (*Thamnophis sirtalis sirtalis*). Species were selected from a list of species present at rare Charitable Research Reserve (*Rare Fauna – Wildlife*, n.d.). This list was compared to iNaturalist species reports and a 1923 species list from the area to help include as many local species as possible and ensure that they were present in the area (*INaturalist Observations*, n.d.; Soper, 1923). The list was then shortened. The focus was on the movement of animals through terrestrial ecosystems, so all animals that were not primarily terrestrial were removed from the list (e.g., fish, beaver, mink, turtles, amphibians, etc.). The species chosen could not be ubiquitous (as the species needed to benefit from increases to connectivity based on relieving habitat restrictions or reluctance to cross barriers) (Beier et al., 2008). This removed animals like squirrels, chipmunks and skunks, among others. The species chosen needed to benefit from small amounts of land and connections between them, so large carnivores that are no longer present in urban areas (e.g., bears, bobcats, wolves) and birds that can easily move through urban areas without the addition of small habitat patches were removed from the list. Large carnivores are often used as flagship species in other systems as they can give early warning of problems with connectivity loss and appeal to the public, but urban areas do not have enough residual habitat to support them (Beier et al., 2008). Overall, the fauna groups chosen can survive in smaller habitat patches (or groups of patches) to reflect ability to survive in an urban environment but are not already ubiquitous in the area so are still anticipated to benefit from connectivity.

Three of the chosen species are mammals. Some larger mammals were considered, as they can use habitat fragments as part of their habitat, but the focus for finding species for this analysis was on smaller mammals, as residual habitat patches are often small. Small mammals are good bioindicators (Pearce & Venier, 2005). They are representative of the environment in which they are found, as dispersal is relatively short and they have a relatively high population turnover that causes a rapid response to environmental change (Bellocq & Smith, 2003; Cassel et al., 2020; Jackson, 1928; Laakkonen et al., 2001; Nocera & Dawe, 2008; Pearce & Venier, 2005; Ryckman, 2020). Small mammals play an important functional role in the ecosystem (they play a key role in the food web, spread seeds, mix soil, etc.) (Gomes et al., 2011; Pearce & Venier, 2005). They regulate food webs, acting both as predator and prey, they disperse seeds and fungal spores, they alter landscapes (even at the small scale as some species help aerate soil and create homes for other species) and help decompose materials (Ascensão et al., 2015; Gomes et al., 2011; Hollier et al., 2016; Millward et al., 2022; Pearce & Venier, 2005; Ryckman, 2020). This sets them up to reflect needs of other species and in some cases the entire ecosystem.

Many small mammals are present in natural areas as well as cities but do not fully adapt to the urban environment, so still reflect the negative impacts of urbanization (Hollier et al., 2016). Small mammals can respond well to disturbance, giving them a higher chance of becoming urban adapters (Larsen-Gray & Loehle, 2022). There are many factors that affect small mammal populations in urban areas. Things like introduced urban predators (like domestic cats), chemical applications, prevalence of impervious surfaces and built area, herbaceous and woody habitat removal (mowing, pruning, etc.), lower habitat quality and fragmentation all limit their populations (Baker et al., 2003; Dickman & Doncaster, 1987, 1989; Łopucki & Kitowski, 2017; Mahan & O'Connel, 2005). Effects are worst in city centres and diminish with increased distance from city cores (Łopucki & Kitowski, 2017). Habitat structure appears to play an important role in determining how urban ground dwelling vertebrates are distributed (Łopucki et al., 2013; Łopucki & Kitowski, 2017). Small mammals react to urban gradients, but some are still present. Small mammals have been found in urban areas (even in small habitats) and tend to prefer areas with more natural undergrowth so they are expected to respond well to urban restorations and connected natural areas (Baker et al., 2003; Gomes et al., 2011; Laakkonen et al., 2001; Łopucki et al., 2013; Łopucki & Kitowski, 2017; Pearce & Venier, 2005). This means that despite being present in urban areas, small mammals could benefit from enhancements to local habitats and increased connectivity. They also need relatively small habitat areas compared to larger animals, allowing them to persist in a fragmented urban environment despite a potential reduction in abundance and movement (Gomes et al., 2011; Laakkonen et al., 2001; Pearce & Venier, 2005).

An added benefit to using small mammals is that they are usually easy to track (Gomes et al., 2011). Long term data on the effects of connectivity are lacking (Fahrig, 2017). Assessing long term effects from changes based on connectivity analysis is more viable with species that are easy to monitor. Ideally these studies would be done over a long period, as connectivity effects may take time to manifest and small mammals often have strong variance in their year to year populations (Pearce & Venier, 2005).

Small mammals were too large a group to model, so were further narrowed down to bats and shrew. The ideal species for this analysis is neither an urban adapter nor an urban avoider. Urban adapters have little problem establishing populations within urban environments, and urban avoiders are unlikely to colonize urban areas even with support. This means that the ideal species for analysis is present but not abundant. Species like skunk are present, but the urban landscape provides few barriers (Brashear et al., 2015). On the other hand, mammals like mustelids tend not to be present in built areas and exist only in habitat patches. Bats and shrews offer species that are present in the built environment but can still benefit from increased connectivity.

Bats and shrews were both considered due to differences in their habitats and movements. Bats are more mobile and use a higher part of the habitat. Bats are known to be good bioindicators. Bats are sensitive to urbanization while still having populations that remain in urban areas (Hale et al., 2012; Jones et al., 2009; Moretto & Francis, 2017). Bats have a fairly high trophic level, so reflect animals beneath them, and they have an incremental response to change so even slight changes can be identified and are easily monitored (Jones et al., 2009). Bats are monitorable at both the small and large scales with specific techniques depending on scale and the research question (Jones et al., 2009). They have much broader movement capabilities compared to shrews. *Myotis* species have been known to move up to 1000km to go between summer and winter roost spaces, but everyday movement occurs at a much smaller scale with scale impacts being consistent between 25m and 500m (Langlois, 2013). There are multiple bat species in the Region of Waterloo. The two *Myotis* species are both endangered. They are present but tend to avoid urban areas so were chosen for this analysis (Hale et al., 2012). Data on specific species was lacking so multiple species were used to create the movement model present in 3.2 Methods Applicability.

Shrews (*Soricidae*) and voles (*Microtus*) were both present in and sensitive to urban environments, but voles tended to be rarer, so shrews were used (Dickman & Doncaster, 1987; Łopucki & Kitowski, 2017). Shrews are sensitive enough to fragmentation that their responses to connectivity changes can be detected (Laakkonen et al., 2001; Łopucki & Kitowski, 2017; Vergnes et al., 2013). There are multiple shrew species in the Region of Waterloo. Globally, *Sorex* species have been found to be impacted by spatial configuration, whereas *Blarina* species have been found in heavily urban areas (Brack, 2005; Dickman &

Doncaster, 1987; Vergnes et al., 2013). *Sorex* species are known associates to other organisms like certain voles, mice and other shrews (including *Blarina brevicauda*) (Whitaker, 2004). This sensitivity to habitat connections combined with a low level of presence in urban areas makes *Sorex* species good indicators for potential impacts of habitat connectivity in urban areas. In addition to being potential indicators of change, shrews occupy an intermediary position in the food chain so they can reflect some species above and below them on the food chain (Vergnes et al., 2013). Shrews have low mobility compared to the other species analyzed. Shrews tend to move no more than 500m at the extent of their long-distance movement (Dickman & Doncaster, 1989).

Sorex species are present in many areas of North America (Jackson, 1928). They are also widely distributed in the Northern hemisphere (Laakkonen et al., 2001). The large distribution of these species mean that they can be monitored if changes in connectivity are made, contributing to a larger body of work that could be developed for this genus. Any studies done will need to be longer-term studies, as *Sorex* species tend to have high population fluctuations (Laakkonen et al., 2001). These species are also fairly well researched, allowing for enough data to be found to create a habitat-based movement model describes in 5.2 Methods Applicability.

Deer are larger mammals that remain within cities. They have been included due to people's interest in them (be it for the diversity they add to urban areas and hunting opportunities, or the risks from disease spread, traffic accidents and harm to gardens) (Etter et al., 2002; Gallo et al., 2017; Storm et al., 2007; Walter et al., 2009). Deer have adapted to somewhat urban areas. They are highly mobile and tend to be habitat generalists that benefit from the heterogeneity of the urban form (Gallo et al., 2017; Locher et al., 2015). Deer habitat often exists near parks and other naturalized spaces in or near urban areas. Deer need large amounts of forage, but can find sources within urban areas, for example: bird feeders, ornamental species and surrounding agriculture/garden plants (Gallo et al., 2017; Grund et al., 2002; Magle et al., 2014). This potential for urban deer means that when planning urban restorations and connections, people are often interested in the effects on the deer population. Furthermore, coyotes are often found in similar areas to deer when in urban environments, so this analysis may reflect more than one animal that people are interested in (Magle et al., 2014). Due to the ability of deer to move large distances (with migration routes on the order of tens of kilometers if not more), landscape connections for deer may only matter at a broad scale (Etter et al., 2002; Grovenburg et al., 2009; Locher et al., 2015; Wright et al., 2020). This means that local connectivity mapping may not be the best scale at which to map deer. It is still important to map this species, as they are subject to local barriers like rivers and high traffic roads (Locher et al., 2015). This makes them an important species to include, as they are a larger animal that could benefit from this analysis, and it is important to know potential problems with human interactions and where it

might be important to mitigate them. Deer have been well studied in many areas around the world, so there is data available from many species to build habitat models (Forsyth et al., 2022). Data for the model developed for white-tailed deer can be found in 4.2 Methods Applicability. Many techniques exist for tracking deer species (from track counts to GPS transmitters to genetic testing) with varying cost and accuracy as well as size and type of habitat they work best for, so continued monitoring of deer should be possible (Forsyth et al., 2022; Hughes et al., 2024).

Species outside of mammals are important to help better cover more types of animals. Herpetofauna are often noted as good bioindicators, as they tend to be sensitive to change (Jones, 2010). This sensitivity to changes makes them good potential species for showing effects of fragmentation in an urban environment. The effects of urbanization on herpetofauna are largely negative: effects from habitat loss and fragmentation are especially prevalent, but some species persist in these environments (Cassel et al., 2019; McGregor et al., 2015). This means that some herptiles may be good indicators for this study. Many herpetofauna need aquatic habitats, so snakes were the main group considered.

Snakes have been identified in residual urban habitat, but more specifically have responded to habitat restoration initiatives within existing urban habitat, for example, in Western France (Bonnet et al., 2016). Snakes are known to be good bioindicators (Kjoss & Litvaitis, 2001). They have unique body forms that represent differences in movement from the other species selected (Lind et al., 2005). The eastern gartersnake has been found in residual patches of habitat in urban and suburban areas (Blaesing, 1979; Cassel et al., 2019; Gray, 2014; Zappalorti & Mitchell, 2008). As snake species go, they tend to adapt fairly well to human modifications to the environment and are present in at least semi urban areas (Gray & Lethaby, 2017). The species is widely distributed in urban areas, but populations in small patches have been found to be in poorer condition than those in larger habitats (Kjoss & Litvaitis, 2001). This means that though they are present, the species does face challenges from the urban environment. Eastern gartersnakes are generalists (Kjoss & Litvaitis, 2001; McCoard, 2008; Placyk et al., 2007). Eastern gartersnakes in southern Ontario already only comprise one genetic population, which means that connectivity is not thought to be hampering species reproduction (Dileo et al., 2010). They tend to have greater variation in morphology and be present in areas that other snakes are not (Kjoss & Litvaitis, 2001; McCoard, 2008). These characteristics make it hard to generalize from the eastern gartersnake to other species; however, terrestrial snakes in general tend to like open areas and forest edges, so focusing on the eastern gartersnake does give some insight into the habitat available for other species. A species that is still present but less ubiquitous would be ideal, however, habitat data, specifically urban data, is lacking for many such species and the eastern garter snake has been associated with other snake species, like

Dekay's brown snake (*Storeria dekayi*) and declines in gartersnakes have been linked to declines in their prey species, so they also represent other species (Gray, 2014; Lind et al., 2005).

The eastern gartersnake has the largest range of any reptile in North America, ranging across most of the continent (Blaesing, 1979; Placyk et al., 2007). This means that a body of data could be developed on this species and contribute to the broader question of the utility of connectivity analysis in urban planning. Gartersnakes have less movement capability than deer or bats, being able to move up to 17km between various habitats (though this is not a normal distance) with resource gathering movement limited to 500m (Dileo et al., 2010; Gigeroff & Blouin-Demers, 2023; Most, 2013). Compared to shrews, their movement differs more in their strong response to barriers than the distances they can travel. Habitat-based movement model numbers can be found in 6.2 Methods Applicability. Gartersnakes also tend to be monitorable, with different techniques having been developed (i.e. field counts, mark-recapture, radio transmission and thread tails) (Furman et al., 2011; Lind et al., 2005).

2.3 Kitchener Landscape Data

This analysis relied on two main sets of data: landscape imagery which was classified into habitat categories and information about animal habitat preferences (used to approximate movement for each species). Connectivity models are only as good as the data on which they rely, so this information is critical to the quality of the output (McClure et al., 2017).

The base data for the landscape classification was created by combining a number of different sources. Aerial imagery and maps of urban infrastructure and habitat were obtained from the Region of Waterloo's open data portal (*Region of Waterloo: Open Data*, 2016). Ecological Land Classification (ELC) data was also found for select areas within the region by contacting managers of local conservation areas. Categories were kept as simple as possible to ensure each category reflects distinct impacts on species behavior (Adriaensen et al., 2003). Ideally, categories would focus on factors that were important to animal movement like cover, potential hazards, available resources, etc., but in this case the categories were constrained by available datasets (Beier et al., 2008).

The aerial imagery was used as the basis for classification. Aerial imagery represents a specific point in time and location, in this case that imagery was for Kitchener in 2019 (Pelletier et al., 2017). The imagery was in multiresolution seamless image database format and had a resolution of 10cm by 10cm. The resolution was reduced to 50cm by 50cm. The ideal grain size theoretically changes with the species and landscape, but simulations predict that smaller is better in general, especially to avoid cracking in linear features (Anderson et al., 2010; Cushman & Landguth, 2010; Etherington, 2016; Rudnick et al., 2012).

The cell size should not be larger than half the size of the smallest barrier to prevent cracks when rasterizing and should be smaller than the average home range size, relate to the dispersal distance or be based on animal perception (Anderson et al., 2010; Baguette & Van Dyck, 2007; Jackson & Fahrig, 2012; Theobald, 2005). This size is less than half the size of the smallest roads. There are smaller potential barriers like trails, but they do not pose as significant a barrier as paved surfaces. It is also smaller than the green spaces that were proposed for restoration (backyards, cemeteries, sections of park and utility rights of way).

This cell size is appropriate for mid-size animals like raccoons, skunks and ermines (Martin & Fahrig, 2012). This cell size is large for some of the species with smaller perceptual ranges and is too fine for species like white-tailed deer but to balance maintaining barriers and decreasing total image resolution, this size was chosen. Other urban connectivity studies used pixel sizes from 2mx2m upwards, so this does represent a smaller resolution than other studies (Braaker et al., 2014, 2017; Grafius et al., 2017; Munshi-South, 2012; Rudd et al., 2002; Shimazaki et al., 2016; Xiu et al., 2017).

The aerial imagery was classified with the Support Vector Machine (SVM) classifier in ArcGIS. SVM is a supervised classification tool (data classification is based on training samples not just imagery). SVM was selected because it supports large images, is less susceptible to noise and can support training data that is of different sizes for different categories (*ArcGIS Pro: Classify*, n.d.). Comparisons of classification methods show vector models and neural nets outperform other classification schemes and neural net classifiers were not yet available in ArcGIS when the data was classified (Khatami et al., 2016). The classified raster was mostly classified based on the available base layers, but the ELC data needed to be re-classified before training (Lee et al., 1998). ELC can only be classified to the community series level from aerial data, so any points in the training dataset that were more specific than this were reclassified to community series level. Classification is a limitation of the process, as creating categories based on thresholds from continuous data does cause a loss of information (Moilanen, 2011; Pelletier et al., 2017). The original plan was to use all available data for producing the classification model, as more training points might have yielded better results for some classes, but due to processing restrictions, 1500 samples was used as a maximum number for each class (Lang et al., 2015).

The classification output was evaluated by manual inspection. Classification had acceptable accuracy, with minor variances in types of habitats (including golf and park) and categories of roads (the worst road misclassifications happened when parts of highways were classed as a less impactful category). The aquatic categories were the most miscategorized, both having some natural areas classed as open aquatic and some rivers being classified as roads. The output was not perfect, but most natural areas were

classified as some form of habitat or greenspace and built areas were mostly classified as roads and buildings.

2.4 Animal Habitat Preference Data and Transformation

Cost rasters are estimates of movement resistance that the species may face across the landscape. They often come from two types of information: landscape (classified aerial imagery) and information about the behaviour of the species (Vuilleumier & Metzger, 2006). These cost rasters are the main input for connectivity analysis and as such the quality of them directly affects the quality of the output (Keeley et al., 2016; Liu et al., 2018; Rainey, 2012; Rudnick et al., 2012; Spear et al., 2010; Trainor et al., 2013).

Assigning values to the landscape based on habitat preferences and transforming those values to produce a raster of movement costs are the steps with the largest potential to create errors, even more so than selecting the tools for modeling connectivity (Braaker et al., 2017; Rudnick et al., 2012; Spear et al., 2010; Trainor et al., 2013). Ideally these movement costs are proportional to the difficulty an organism faces when traversing a cell relative to other cells (Zeller et al., 2012). Quantifying these costs is challenging (Braaker et al., 2017). It is species and landscape specific, so these values depend strongly on the goals (Fahrig, 2007; Knaapen et al., 1992; Spear et al., 2010; Stevenson-Holt et al., 2014). Adding to the difficulty, these costs often lack units and only show a relative effort when compared between pixels and as a result costs are not comparable across analyses (Adriaensen et al., 2003; Beier et al., 2008; Etherington, 2016; Howey, 2011; Koen et al., 2012; Pelletier et al., 2014; Sawyer et al., 2011).

Connectivity outputs are sensitive to the inputs for some species and landscapes but not all (Broquet et al., 2006; Chardon et al., 2003; Epps et al., 2007; Gonzales & Gergel, 2007; Hagerty et al., 2011; Parks et al., 2013; Sawyer et al., 2011; Stevens et al., 2006). Sensitivity increases with increases in fragmentation and was highest with 20-50% of area representing hospitable area (Gonzales & Gergel, 2007; Rayfield et al., 2010). Urban areas tend to be heterogeneous, meaning that they are often more fragmented so will be sensitive to these values. The results tend to be more sensitive to the ratio between values than the magnitude of the values with differences between inhospitable cells and hospitable cells mattering more than the difference between hospitable cells and habitat (Chardon et al., 2003; Rayfield et al., 2010). Further adding to the complexity, the methods used to process the data result in different sensitivities (Koen et al., 2012).

The development of these costs is often done in two steps: the first is figuring out the movement capability or habitat suitability of different landscape types and the second is transforming this into resistance (Keeley et al., 2016). Many analyses fail to justify how they develop these costs (Zeller et al.,

2012). For best results, field data is needed to construct the costs of moving through the landscape (Beier et al., 2008; Fahrig, 2007; Lapoint et al., 2013; McClure et al., 2016; Rayfield et al., 2010; Sawyer et al., 2011).

The first step is to estimate how well an animal can move through the landscape classes. Whether movement or genetic data is preferable and how to construct the resulting information may depend on the landscape and species movement being modeled (Beier et al., 2008; Chetkiewicz & Boyce, 2009; Fahrig, 2007; Stevenson-Holt et al., 2014; Wang et al., 2009; Zeller et al., 2012; Ziolkowska et al., 2016). The technique used to go from the available data to movement estimations may change the results, so it is important to choose these methods carefully (Anderson et al., 2010). Genetic data will bias toward successful dispersal but also has a time lag between change and response making real world measurement harder, whereas movement data is preferable for most other movement types and represents immediate movements (Coulon et al., 2004; Cushman et al., 2006; Keeley et al., 2017; Rainey, 2012; Schwartz et al., 2009; Zeller et al., 2012). It is not always plausible to get movement or genetic data. There is a gradient between direct and indirect measurement, for example, presence detection data can also be used to infer movement ability in the absence of direct movement data (Zeller et al., 2012). Lack of empirical data results in subjective values and relies heavily on the knowledge of the expert (Munshi-South, 2012).

Direct genetic or movement information for the selected species was not readily available, and time and resources restrictions prohibited field studies. Due to a desire to get preliminary output without resource intensive studies indirect information was used to estimate habitat suitability for movement. This estimation was done with a literature review about types of habitats used by the selected species. Expert opinion or literature reviews are often used due to a lack of other information (Beier et al., 2008; Braaker et al., 2017; Gonzales & Gergel, 2007; Keeley et al., 2016, 2017; Lookingbill et al., 2022; Milanesi et al., 2017; Spear et al., 2010; Trainor et al., 2013; Zeller et al., 2012). The main underlying assumption is that animal movement happens similarly to habitat selection, but this connection depends on the species and landscape in question (Liu et al., 2018). Habitat selection is largely driven by resource availability. Selection of movement area is often driven by avoidance of barriers, but animals can move through areas that do not support all their resource needs. The main limitation for movement area selection is often barriers, but each species responds to these areas in different ways depending on the available paths in a given landscape and the level of need for the movement (Keeley et al., 2017; Liu et al., 2018). Animals tend to move faster through less ideal landscapes, especially for movements like dispersal or migration but tend to avoid these areas for daily movement (Brennan et al., 2018). Literature review may work for some specific species and types of movement, especially ones that are well studied and for movements for use of resources within the home range rather than dispersal movements (Keeley et al., 2016; Liu et al.,

2018; Mateo-Sánchez et al., 2015; Milanesi et al., 2017; Rainey, 2012; Stevenson-Holt et al., 2014; Zeller et al., 2012). This means the focus of this analysis will not be as applicable to dispersal movements as desired. An additional complication arose with the lack of urban habitat data. Ideally the information used to develop these rankings would be based on urban data, as animals are known to change their behaviours in the urban environment, but this was often not available (Able & Belthoff, 1998).

Overall, expert opinion and literature reviews are not reliable for establishing resistance maps. They should only be used with multiple experts, literature review and ideally empirical data to validate with, but even then, the data being used to evaluate movement is species and landscape specific so may not be applicable (Charney, 2012; Fattebert et al., 2015; Keeley et al., 2016; Lapoint et al., 2013; Pullinger & Johnson, 2010; Sawyer et al., 2011; Stevenson-Holt et al., 2014; Thiele et al., 2018; Zeller et al., 2012). This analysis is preliminary and serves to prompt more research into specific species and locations.

Papers about specific animal movements were difficult to find, so habitat suitability was used to model this. This assumes that habitat suitability is a useful proxy for resistance. The actual applicability of habitat suitability depends on the type of movement, species and landscape (Rainey, 2012; Zeller et al., 2012). Animals tend to move faster through less ideal landscapes, especially for movements like dispersal or migration but tend to avoid these areas for daily movement (Brennan et al., 2018). In the absence of field data, the assumption that habitat selection represents preferred habitat for movement was made for this analysis, but it should be noted that this means the focus of this analysis will not be as applicable to dispersal movements as desired. An additional complication arose with the lack of urban habitat data. Ideally the information used to develop these rankings would be based on urban data, as animals are known to change their behaviours in the urban environment, but this was often not available (Able & Belthoff, 1998).

Habitat categories were ranked and assigned suitability values between 0.1-1 (0.1 being the lowest suitability and 1 the highest) based on relative preference and avoidance of different habitats for each species, meanings for each value can be found in Table 1. Methods and values for each species can be found in each species' respective chapter. Each value is a discrete representation of different continuous values of habitat quality, amount of naturalness and presence of threats (Cushman et al., 2006; Ziolkowska et al., 2016). These values are used in many connectivity analyses, but there is large variation in values between different studies and the scales are often arbitrary and lack justification despite outputs being sensitive to value changes (Beier et al., 2008; Broquet et al., 2006; Chardon et al., 2003; Epps et al., 2007; Hagerty et al., 2011; Parks et al., 2013; Sawyer et al., 2011; Stevens et al., 2006; Zeller et al., 2012). Sensitivity to these values tends to change with different landscapes, with areas of higher

fragmentation being more sensitive (Gonzales & Gergel, 2007; Rayfield et al., 2010). Sensitivity is also higher in areas where good quality habitat and extremely poor habitat meet (Rayfield et al., 2010). This means that small changes in these values can have a large impact, especially in an urban area due to the increased fragmentation and the frequency with which good habitat meets low quality areas. As this research was primarily focused on exploring the utility of connectivity tools for urban habitats, this sensitivity was not addressed. Future research should account for this sensitivity as it does impact the utility of the results for use in planning for restoration and conservation.

Table 1 – Meaning of Habitat Suitability Values

Value	Habitat Represented
1.0	Natural area representing preferred habitat for the species
0.9	Natural areas with many of the resources the species needs
0.8	Natural areas with some of the resources the species needs
0.7	Human maintained areas that offer many resources the species needs
0.6	Natural areas with little of the resources the species needs
0.5	Natural areas with little of the resources the species needs as well as containing threats to the species
0.4	Minimally built areas with some natural resources and minor threats
0.3	Area that is not good habitat or has access constraints or minor threats
0.2	Areas with major threats
0.1	Areas with major barriers

The habitat suitability values were transformed into resistances, but unfortunately species specific data does not exist to help guide this transformation (Beier et al., 2008). The type of habitat may affect movement in different ways, making for non-linear relationships between habitat suitability and resistance: for example, poor habitat impacts movement more than fair to good habitat (Trainor et al., 2013). Linear relationships may work for species with less dispersal capability but for better dispersers

only the worst habitat will be avoided (Keeley et al., 2016, 2017). The use of four different animals meant that a more generic value transformation was warranted. The values were transformed from habitat suitability to resistance with the negative exponential function shown in Equation 1. The relationship between suitability and resistance is species and landscape dependent. This makes it difficult to generalize methods for transforming habitat suitability to resistance. A common transformation is a negative linear transformation, but this is often used without justification (Keeley et al., 2016; Rainey, 2012; Ziolkowska et al., 2016). Negative exponential functions have also been used and have been verified for red-cockaded woodpeckers, brown bears, kinkajous and desert bighorn sheep. Equation 1shows the function that was used in these trials and all except elk (a habitat generalist) used the strongest negative exponential function available where c was 0.25-32 (Keeley et al., 2016, 2017; Trainor et al., 2013). Non-linear functions have often been better, but it is thought that transforms will approach linear as movement is restricted and extreme generalists have resistances nearer to linear compared to other species (which exponential functions will not approximate) (Keeley et al., 2017; Trainor et al., 2013). Movement type will also affect the relationship between habitat suitability and resistance (Braaker et al., 2017). This is particularly problematic when dealing with urban species as the heterogeneous landscape provides many barriers to movement. Many of these barriers are not full restrictions to movement so use of Equation 1 should remain valid but a c value of 16 was used instead of 32 as urban species tend to be habitat generalists, but these species were selected to not be extreme generalists.

$$100 - 99\,\frac{1 - e^{-ch}}{1 - e^{-c}}$$

Equation 1 – Transformation of Habitat Suitability to Resistance (Keeley et al., 2016, 2017; Trainor et al., 2013) **- c is the transform (16 was used) and h is the habitat suitability number assigned.**

2.5 Creating Scenarios

Kitchener is densifying, but how this densification occurs will impact the amount of habitat and connectivity in the area moving forward. The plan is to intensify already built areas so that natural and rural areas can be maintained (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014). This intensification process presents a problem, because intensification of the areas around fragments of habitat could add to the effects of their isolation, but it also allows an opportunity to plan development to not only protect current green space but to add more of it and/or improve what already exists (Bailey, 2007). Based on the uncertainty of how future development will be moderated, three scenarios of change were developed. The first two scenarios model what could happen if we increased the amount or quality of habitat available in the city, adding an additional 5-10% (classified as meadow), while maintaining the

current building footprints (intensification would be solely vertical). Given that existing incentives for developers to increase green space are insufficient (cash in lieu of greenspace is available and often selected), it is anticipated that there will not be an increase in greenspace and that building footprints will grow, as a result, the third scenario solely increases the footprints of buildings to reach the projected density in the city as of 2031. These scenarios reflect the extreme ends of how the city could develop and it is expected that the densification process will leave the city somewhere in between these outcomes. However, knowing the potential benefits and drawbacks that come with how the city is planned are important for decision making.

Scenarios were created using a method developed by Tischendorf and Fahrig as it allowed for varying the number of cells changes as well as the ability to provide rules for clustering for the existing landscape (Tischendorf & Fahrig, 2000a). The scenarios had different numbers of cells to change and land classifications that could be changed/were changed to. Cell reassignment went through several steps. First, a random cell was selected for reassignment. A random number was then generated between zero and one. This number was compared to a predetermined fragmentation value. The cell type was changed for that cell if the number generated was less than the square of the fragmentation value or if at least one of the neighbouring cells was of the same type as that of the reassignment, otherwise the process was repeated until a valid location was found for reassignment. Each cell that was changed was also padded out with a block of changed cells around it for all eligible neighbouring cells (size depended on the scenario). This process was repeated until the desired number of cells were changed. Tischendorf and Fahrig did not include the blocking method, but due to a small cell size and the usual size of buildings and restorations, additional area was needed for each changed cell (Tischendorf & Fahrig, 2000a).

2.5.1 Habitat Scenario

Cities contain natural and semi natural areas. There are also many places that serve as partial habitat for species or that could offer more resources for species without detriment to other uses (areas like trails, utility rights of way, etc.). In urban areas, these spaces are necessary to create connectivity in the urban landscape (Munshi-South, 2012; Rudd et al., 2002). Times of infrastructure change (like densification) offer opportunity to add restoration efforts to infrastructure work as proper planning and integration of restoration efforts into already planned work can decrease the cost of restoration or the need for remediation (Neeson et al., 2018). Currently, the City of Kitchener owns 2000 hectares of green space, with about 60% being natural areas and 40% maintained areas (*Kitchener: Parks Master Plan*, n.d.). Creating green space is noted as a priority in city plans with a goal of at least one hectare of land for every 300 units that are built, but cash in lieu of greenspace is accepted (City of Kitchener Official Plan A

Complete and Healthy Kitchener, 2014). The option for cash in lieu of green space makes it unlikely that green space will increase with development projects. The potential to improve existing areas or for private owners to restore land still exists even if the total level of public green space stays the same or decreases. A study in nearby Waterloo found public green space and private yards had underutilized space that they proposed using for agriculture (Port & Moos, 2014). Agricultural efforts are important but another potential use for these areas is to provide urban habitat for flora and fauna.

Two scenarios were created to model the potential use of underutilized urban green space for habitat. The scenarios increased the amount of natural area by 5% and 10%, respectively. Natural areas include several landscape classification types but for best use of small areas and to make sure that habitat additions benefited all species, reassigned cells were designated meadow. Classification types available for change included park, road 1 or sidewalks. Cells were assigned in a maximum of 2.25m^2 blocks to remain small enough to represent a potential backyard restoration but also to represent a size of land that could feasibly be restored in an urban green space (like a part of a park or trail). A fragmentation value of 0.8 was used as restored areas are to be small and geographically isolated (private lands are more likely to be restored if surrounding areas have been, but overall, the parcels of land available for restoration within the urban landscape are small). This should create very isolated patches, as fragmentation values as low as 0.5 create an extreme pattern of randomness (Rayfield et al., 2010). This is an overestimate of the potential for land restoration, as the city's focus is currently on intensification rather than increasing quality and quantity of green space.

2.5.2 Buildings Scenario

The historic dispersed form of Kitchener has left room for intensification within the built-up area of the city (Bunting & Filion, 1999). Densification has already begun, and by 2019 the downtown core had about 198 residents and jobs per hectare (Coutu, 2019). The growth plan for the Greater Golden Horseshoe area states that Kitchener must reach at least 200 residents and jobs per hectare by 2031, to provide for a growing population in Southern Ontario (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020). Local plans for Kitchener's density vary with location, with the downtown core able to reach 306 residents and jobs per hectare if all areas slated for development are developed (Coutu, 2019). The planned fractional increase in density was found for each of the areas in the city plan and averaged to get an 83% increase in residents per job per hectare (Coutu, 2019). A scenario was developed to model an upper limit for building footprints with densification. It had 83% more cells classified as building. Cells eligible for change were golf course, park, roads 1, meadow, savannah or sidewalk. This was done with the same methods as the habitat scenarios but with a maximum block size

of 12.25m^2 and a fragmentation value of 0.05. A low fragmentation value was used to simulate densification of existing areas over creation of new buildings. This is an overestimate of building spread, as densification will primarily occur happen vertically.

2.6 Processing Data

Circuitscape 5.13.3 was used to analyze the cost rasters for connectivity. Circuitscape is an implementation of circuit theory. Circuitscape was developed to approximate random walks by modeling flow through an electrical circuit (Doyle & Snell, 1984; McRae, 2006; McRae et al., 2008; Shah & McRae, 2008). This analysis results in a representation of resistance/conductance that shows the probabilistic movement of individuals over the area (McRae et al., 2008). This enables identifying path redundancies that decrease resistance, as increased numbers of paths increase the chance of a random walker getting to the destination (McClure et al., 2016; McRae, 2006; McRae et al., 2008).

Circuit theory assumes that animals go through an environment with no knowledge of the landscape (McRae et al., 2008). Animals actually use a combination of systematic and random searches that rely on varying amounts of knowledge about the landscape depending on the type of movement being performed. Even when animals move “randomly” they tend to continue moving in the same direction (Bartumeus et al., 2005). How well circuit theory predicts animals' movement depends on how closely aligned with random walks a species’ movement is for a given landscape (Thiele et al., 2018). Tools like least cost path assume that animals have complete knowledge of the landscape which also is not true, though some researchers have attempted to add in some stochasticity (Baguette & Van Dyck, 2007; Liu et al., 2018; McClure et al., 2016; Palmer et al., 2011). The dichotomy created by the set of tools represents two extremes of a gradient of movement types (Bartumeus et al., 2005). These assumptions are not met, but these models can give us some insight into animal movement.

Circuit theory has performed well in comparison to other tools such as least cost path and Euclidean distance. For many species, least cost path and circuit theory are either found to be similar with different emphases (as for forest passerines and reptiles) or for circuit theory to outperform least cost path as it did for urban mice and European hedgehogs (Braaker et al., 2017; Munshi-South, 2012; St-Louis et al., 2014; Thiele et al., 2018). Species like wolverines had mixed results, where circuit theory mostly outperformed least cost path except for one scenario where movement was constrained by mountains (McRae & Beier, 2007; Rainey, 2012; Schwartz et al., 2009). It is expected that constrained movements work better with least cost path. Terrestrial migrations are another type of movement that can be constrained by repeated movements that tend to follow the same routes. Least cost path has tended to perform better for migratory movement in elk and pronghorns but even with these constraints and the species having knowledge of the

landscape, least cost path did not perform much better than circuit theory (Braaker et al., 2017; McClure et al., 2016; Poor et al., 2012; Pullinger & Johnson, 2010; Rainey, 2012).

These results support the idea proposed by McRae and Beier that circuit theory should perform better than least cost path when there are no linear constraints on movement (McRae & Beier, 2007). Based on these results and the fact that circuit theory can identify stepping stone paths and pinch points, it has been proposed that circuit theory has higher general applicability (McClure et al., 2016; Rainey, 2012). Selecting circuit theory versus least cost path does create some bias, so it is important to pick the right one for the study (Marrotte & Bowman, 2017). The two methods tend to be most similar when there is only one potential path, the more alternative paths that exist, the smaller the circuit theory total resistance values are compared to least cost path values (Avon & Berges, 2016; Marrotte & Bowman, 2017). In general, animals tend not to use a single best path, and studying alternative routes is beneficial (Sawyer et al., 2011). There are methods for extending least cost path to include multiple paths, but circuit theory does this too (Koen et al., 2014; Pinto & Keitt, 2009; Rudnick et al., 2012; Schwartz et al., 2009). This study focused on dispersal movement patterns in urban areas. Urban landscapes tend to be fragmented causing heterogenous, complex landscapes that are known for having better results with circuit theory (Braaker et al., 2014; Dickson et al., 2019; Dyer et al., 2010). Movement through urban areas is constrained, but not as constrained as migration paths and therefore less directional and more random, even for dispersal, so circuit theory was used.

This analysis has several assumptions. One of the biggest is that animals will follow or approximately follow the path of least resistance: this can be true, but reactions to environmental variables depend on the species and the exposure of the individual to the stimulus (Baguette & Van Dyck, 2007; Fahrig, 2007; Marrotte & Bowman, 2017; McClure et al., 2016). This analysis method also requires animals to successfully go from one point to another even if no real route exists (Pelletier et al., 2017). Circuit theory assumes that the populations being studied are in genetic equilibrium (McRae, 2006). Overall, assumptions for circuit theory are most easily met at a small scale, which fits well with the decreased scale of this analysis (McRae, 2006).

This analysis was aimed at looking at the landscape as a whole, rather than connecting a set number of patches. Circuit theory often works with the assumption that an animal is moving from one patch to another and though this may be true, animals do not necessarily have a planned destination (Cushman et al., 2009). Circuit theory has been expanded to analyze landscapes beyond patch to patch connections in multiple ways (Koen et al., 2014; Pelletier et al., 2014; Walpole et al., 2012) The method chosen was one used to map regions of similar connectivity level in boreal Canada (Pelletier et al., 2017). The method

allows the production of “omnidirectional” maps that can be done at fine scale resolution over large areas due to tiling of the landscape (Pelletier et al., 2014).

A one-pixel buffer was created around each side of the mapped area (Pelletier et al., 2014). Nodes were placed adjacent to the mapped area rather than within it to decrease bias in results (Koen et al., 2014). These buffers functioned as the “patches” that the animals move from and to. Circuitscape was run twice with pairwise 1 volt runs (approximately North to South and East to West). The number of runs needed has been tested in other analyses and two runs was found to produce similar results to more runs (Pelletier et al., 2014). These two runs were then multiplied together to get a single result. Other analyses have summed similar results but the analysis for the number of runs was done using multiplication between the layers so that was used here as well (Anderson et al., 2011; Pelletier et al., 2014). The results were transformed by log10 and stretched to fit via symbology to increase the visual impact (Pelletier et al., 2014).

This landscape level approach presented some limitations to the number of scenarios that could be run due to high needs for processing power (this limited the total area, the number of species and the number of scenarios that could be processed). The amount of RAM needed was initially expected to be high as Kitchener covers 136.81km^2 and the cell size was 0.5m resulting in 273,620,000 cells to connect (Statistics Canada, n.d.). The clipped square was somewhat smaller but still contained as much of this data as possible while creating a square by hand. An iterative approach was taken to determining the amount of RAM needed to process the dataset starting with a computer with 16GB of RAM and working up to a cloud computer with 512GB of RAM. Each run took about 50 minutes, and two runs were needed for each species scenario pair. With four scenarios per species, four species, and two directions, this results in 32 runs, which is over 26 hours, ignoring time taken for manual intervention.

2.7 Analyzing Results

The resulting current maps were examined to find potential connections and barriers. This was used to determine how well the current land structure of Kitchener allows for urban animals to complete dispersal movements. To evaluate whether underutilized city space can be used to increase ecosystem connectivity, maps from different scenarios were compared.

Shadow maps were also created to see the change between different scenarios. The unlogged maps were subtracted from one another to show the differences between the 2019 model and each of the scenarios, as well as the difference between the two habitat amount projections.

Interpretation can be difficult with Circuitscape (Lapoint et al., 2013). There are three outputs: voltage, current and resistance. Voltage shows successful movements whereas current represents the density of animals moving through the area and is generally the focus of analysis (Walpole et al., 2012). Effective resistance represents the total resistance between two patches, adding paths or patches causes resistance distance to decrease (McRae, 2006; McRae et al., 2008). In general, areas with lower resistance will have higher currents, however with more areas of low resistance the current will spread out over more area causing a more moderate current over the entire map (McRae et al., 2008; Nordén, 2016). High current represents an increased density of random walkers and therefore increased probability of use by moving animals (Koen et al., 2014; Rudnick et al., 2012; Walpole et al., 2012). High current may be a result of low resistance creating corridors or of funneling away from an area of higher resistance (pinch points) or because of barriers (McClure et al., 2016; Nordén, 2016; Rudnick et al., 2012). Not all current shows movement that could happen, as animals are forced to go from one point to another even if high resistance areas would actually prevent the movement (Pelletier et al., 2017).

Conclusions may be hard to draw from these metrics. Extrapolating from the results should be done with care, as different currents mean different things depending on context (Rudnick et al., 2012). Key movement areas should be protected, but conservation efforts work best in conjunction with mitigation efforts (minimizing the effects from barriers and other landscape features that might influence local fauna) (Beier et al., 2008). It is important to note which of the connections are most essential to protect and enhance (Beier et al., 2011). Ideally these results would be compared to other urban cores, but due to lack of data, incongruities in analysis, and connectivity being species and landscape specific, a lack of data prohibits this (Fleishman & Mac Nally, 2007). If the results of this analysis warrant further research, that work should include multiple sets of movement or genetic data in order to test the predictions and an uncertainty and sensitivity analyses, as well as presenting multiple options for establishing habitat suitability values and processing data (Beier et al., 2008; Etherington, 2016; Rudnick et al., 2012; Sawyer et al., 2011; Urban et al., 2009; Zeller et al., 2012).

Chapter 3 Bats

3.1 Introduction

Bats tend to be good urban indicators (Azam et al., 2018; Jones et al., 2009). Bats are sensitive to changes (both immediate and long term) and these changes in bats are easily monitored and responses to changes are predictable and graded to the amount of impact (Jones et al., 2009). They show sensitivity to increases in built area at the species, guild and community level (Hale et al., 2012). Due to the long-lived nature (can live over 30 years) and slow reproduction of bats (generally less than one pup per season) these responses tend to happen slowly with slowed reproduction rate instead of species collapse, allowing for time to measure and respond to changes (Azam et al., 2018; Jones et al., 2009). They may represent other species as they have a high trophic level and provide ecosystem services for other species (Jones et al., 2009).

Bats have a unique context for connectivity as relatively mobile small animals (due to their ability to fly) while still fitting within the scale of the analysis as opposed to many species of birds that travel distances larger than the scale of this study. This unique movement also results in use of different habitats than other small mammals. Bats interact more with higher levels of the habitat for roosting and feeding than say shrews that were also analyzed. They often need some forest cover and readily use transitional zones for feeding to gain access to open feeding areas as well as cover. Bats offer the right balance between being found in an urban environment but not being over abundant in these areas, and population levels often remain lower than in more natural areas (Moretto & Francis, 2017).

Bats are sensitive to connectivity, with populations predicted to become more stable with increased connectivity (Frey-Ehrenbold et al., 2013). Bat species are sensitive to increased urban density having overall negative reactions, but some remain in urban areas (Hale et al., 2012). The bat species selected only needed to persist in urban areas, as there are none that thrive in urban environments. There are two *Myotis* species present in the Region of Waterloo, with the little brown myotis being one of the most common bats in Canada (*Grand River Conservation Authority: Natural Heritage*, n.d.; Langlois, 2013). *Myotis* species often avoid urban areas but do occur within cities like Toronto and Calgary, as they can roost in human made structures (Coleman & Barclay, 2011; Hale et al., 2012; Thorne et al., 2021). Some urban areas have been tested to see if species are synurbic or just present. In the prairies where urban areas can increase access to roosts and other habitat elements, there was no urban benefit for bats, which suggests that urban areas are in fact a detriment and that bats are present but not flourishing (Coleman & Barclay, 2011). Specifically focusing on *Myotis lucifugus,* they are present from east to west in North

America and extend from Alaska south to Georgia (Turner, 2017). Bats species inhabit all but the most extreme habitats of the world, so are broadly applicable (Craig, 2022).

Bats are the most abundant mammal outside of rodents and represent the only mammals that can fly (Turner, 2017; Whitaker, 1996). Bats are nocturnal and lack of available roosts tends to limit their abundance, but in urban areas where roost availability increases, they may be food limited (Krauel & LeBuhn, 2016; Turner, 2017). Bats enter hibernation for portions of the winter (Turner, 2017). Bats serve as a food source for raptors, reptiles, amphibians, fish, racoons and weasels and, in more urban areas, cats (Langlois, 2013; Turner, 2017). They also reflect insects' population levels as North American bats tend to be insectivores (Azam et al., 2018; Moretto & Francis, 2017). They use echolocation for foraging and movement (Turner, 2017).

Current threats to *Myotis* species include white nose syndrome, habitat alteration (urbanization, logging, agriculture), climate change and pollution (Fabianek et al., 2011; White et al., 2016). This analysis focuses specifically on the impacts of urbanization. Bat species respond differently to different elements of the urban environment (Russo & Ancillotto, 2015). Urban effects on bats are overall negative (Jung & Threlfall, 2016). Some potential problems include light pollution (though some species use this as foraging habitat), avoidance of roads, pollution and habitat loss (Jones et al., 2009). Potential advantages include new roost and shelter spaces, open spaces for hunting and new waterways for foraging and drinking (Craig, 2022; Russo & Ancillotto, 2015). These advantages may be causing potential sinks for populations, rather than true benefit for bats living in them (Turner, 2017).

3.2 Methods Applicability

The landscape classification was the same for every species and can be found in 2.3 Kitchener Landscape Data. The 0.5m by 0.5m resolution of this analysis was designed for less agile small mammals. *Myotis* species do not have long migrations but have been known to move up to 1000km to go between summer and winter roost spaces (Langlois, 2013). In models that address different scales of surrounding habitat, effects on an area showed similar direction and magnitude of effect from 25m to 500m (Craig, 2022). Despite the undersized scale, bats are still small mammals with limited perceptive range that interact with the environment at smaller scales than these, so the scale of 0.5m will not create a large bias for bats.

Habitat suitability ranks were created using research from studies on how bats use each land cover type. Land cover types were assigned a value from 0.1-1, with 0.1 being the worst land cover type for habitat and 1 being the best (Table 2), meanings of these values can be found in 2.4 Animal Habitat Preference Data and Transformation.

Table 2 - Myotis Bats Habitat Values - Bats were assigned habitat values from 0.1-1.0 based on desirability of the habitat for the species according to the rubric 2.4 Animal Habitat Preference Data and Transformation.

Habitat	Suitability Value	Rationale
Roads - Category 4 Roads - Category 3	0.2	• Can fly over roads • Roads decrease abundance and diversity of bats (Moretto & Francis, 2017) • Bats (specifically high-frequency bats like *Myotis* species) tend to avoid roads, being less active than in the surrounding areas (Bhardwaj et al., 2017; Craig, 2022; Pauli et al., 2017) • Roads pose a barrier but do not prevent all movement for bats (Bhardwaj et al., 2017) • Bats mainly avoid large highly trafficked roads but small roads have little effect (Moretto & Francis, 2017)
Buildings	0.3	• Can fly over buildings • Bats have a negative relationship with urban areas (Craig, 2022) • *Eptesicus* bats will forage in developed areas or use tall objects to avoid wind (Talbot et al., 2017) • Developed land has been seen to increase genetic distance in *Eptesicus* bats (Talbot et al., 2017) • These papers were not building specific, but buildings are part of the built area that causes these impacts
Open Aquatic	0.3	• Bats use aquatic areas for foraging and can fly over significant parts of them (Fabianek et al., 2011; Pauli et al., 2017) • Open aquatic areas lack roosting habitat • Lack of differentiation between small and large waterbodies led to a lower score
Roads - Category 2 Roads - Category 1	0.4	• See Roads - Category 4; Roads - Category 3
Railways Sidewalks	0.6	• Lack of available data suggests lack of impact, but these are still built areas
Golf Courses Parks	0.7	• Golf courses and parks are mainly open areas that lack tree cover needed by bats or are too small to provide all habitat types needed • Open green spaces add foraging space for bats (Craig, 2022) • Wooded links provide connections between foraging habitats (Azam et al., 2018; Pauli et al., 2017)
Shallow Aquatic Wetland	0.9	• Open areas like wetlands are often used for foraging (Fabianek et al., 2011; Moretto & Francis, 2017; Pauli et al., 2017; Talbot et al., 2017; White et al., 2016) • Shallow aquatic areas lack roosting habitat
Meadow	0.9	• Meadows are open areas that lack roost spaces but provide foraging habitat (Fabianek et al., 2011; Moretto & Francis, 2017; Pauli et al., 2017; Talbot et al., 2017; White et al., 2016)
Forest Savana	1.0	• Forest cover increases bat activity, but bats need a diversity in landscape, so areas like savannah with some trees and some open

		area for foraging would be ideal (Fabianek et al., 2011; Pauli et al., 2017; Talbot et al., 2017) • *Myotis* species preferentially move along forest edges (Talbot et al., 2017)

A habitat value of 0.2 was given to the two largest road categories that feature the heaviest traffic. Bats can fly over roads, but traffic levels, distance and light pollution may play a role in whether they do. In general, bats avoid roads, especially major roads, and bats show less effect from smaller roads, leading to the division in value between larger and smaller roads (these road reactions specifically represent *Myotis* species, because reaction to streetlights, traffic and other effects of roads are species dependent) (Craig, 2022; Pauli et al., 2017). As a result of differences between road size and type, smaller, less heavily trafficked roads were assigned a 0.4.

Buildings and open aquatic areas were assigned a value of 0.3. Bats can fly over both buildings and open aquatic areas, but height of buildings and distance across an open aquatic area may make some of these areas inaccessible to them. Bats have negative relationships with urban areas, including industrial and residential land uses, though this cannot be linked directly with the buildings that are present and may have more to do with urban form (Craig, 2022). Buildings were given a low score due to the impact from urbanization. Bats do use aquatic areas for foraging and can fly over significant parts of them, however open aquatic is a broad category featuring larger and smaller water bodies, leading to a need to address them as a whole and giving a lower score as they may provide foraging habitat but are devoid of roosting locations needed for rest (Fabianek et al., 2011).

A value of 0.6 was used for railways and sidewalks. Railways and sidewalks are not viewed as large problems for bats, so research on them is hard to find. They were assigned a middle value based on the lack of impact, but also the fact that these are more developed areas.

Urban green spaces that are more manicured but still open space, like golf courses and parks, received a value of 0.7. Bats do well with a diversity of habitat, so open urban green spaces can add foraging space for them (Craig, 2022). Wooded links provide connections between foraging habitat, making green spaces pivotal to promote urban bat populations (Azam et al., 2018; Pauli et al., 2017). Despite the benefits of urban green spaces over other urban areas, it still is not the ideal habitat for bats, so these spaces were valued above other urban land uses but lower than other more natural areas.

Natural areas that were not the top habitat preference for bats, like shallow aquatic, meadow and wetland, were issued a 0.9. Bats use a diversity of habitats, more open areas like these wetlands are often used for foraging but lack roost spaces (Fabianek et al., 2011; Moretto & Francis, 2017; Pauli et al., 2017;

Talbot et al., 2017; White et al., 2016). As these areas are beneficial but not sufficient for bats, they were given a high value but differentiated from areas that have roost availability.

Forest and savannah were deemed to be the best habitat for bats so were put in the top category of 1.0. *Myotis* species tend to be forest dwelling. Increasing area of forest cover increases their activity, though diversity in the landscape is desirable, so areas like savannah with some trees and some open area would be good too (Fabianek et al., 2011; Pauli et al., 2017; Talbot et al., 2017).

Suitability values were used to create resistance values based on the transformation equation in 2.4 Animal Habitat Preference Data and Transformation. The resulting resistance matrices were then used in Circuitscape with buffers outside the maps to define to and from patches for movement. This was run twice, once from top to bottom and once from left to right and the two current results were then multiplied and logged to make a single output raster.

3.3 Results and Discussion

The current map (Figure 2) for bats featured very few hard barriers to habitat connectivity and many options for potential travel routes. Due to the ability of bats to fly, very few things pose true barriers. This means that the distance between suitable roosts, rest areas and forage/water areas are probably the limiting factors in travel for bats (Fabianek et al., 2011; Johnson et al., 2008; Lintott et al., 2015; Moretto & Francis, 2017; Pauli et al., 2017). The strongest barriers on the map were roads and paved areas. These are not hard barriers, as bats can and do cross roads, but due to avoidance of paved areas they may limit habitat connectivity, especially large, highly trafficked roads. Road planning should avoid areas that are commonly used by bats and future planning for existing roads with nearby bat populations should include underpasses to help increase potential habitat connections for bats (Turner, 2017). Houses also represented barriers to potential connectivity for bats but less so than roads. These two land use types caused areas like the downtown core to show restricted connectivity potential compared to the surrounding less built-up or naturalized areas. Outside of paved areas and houses, the overall landscape supported potential connections between bat habitats.

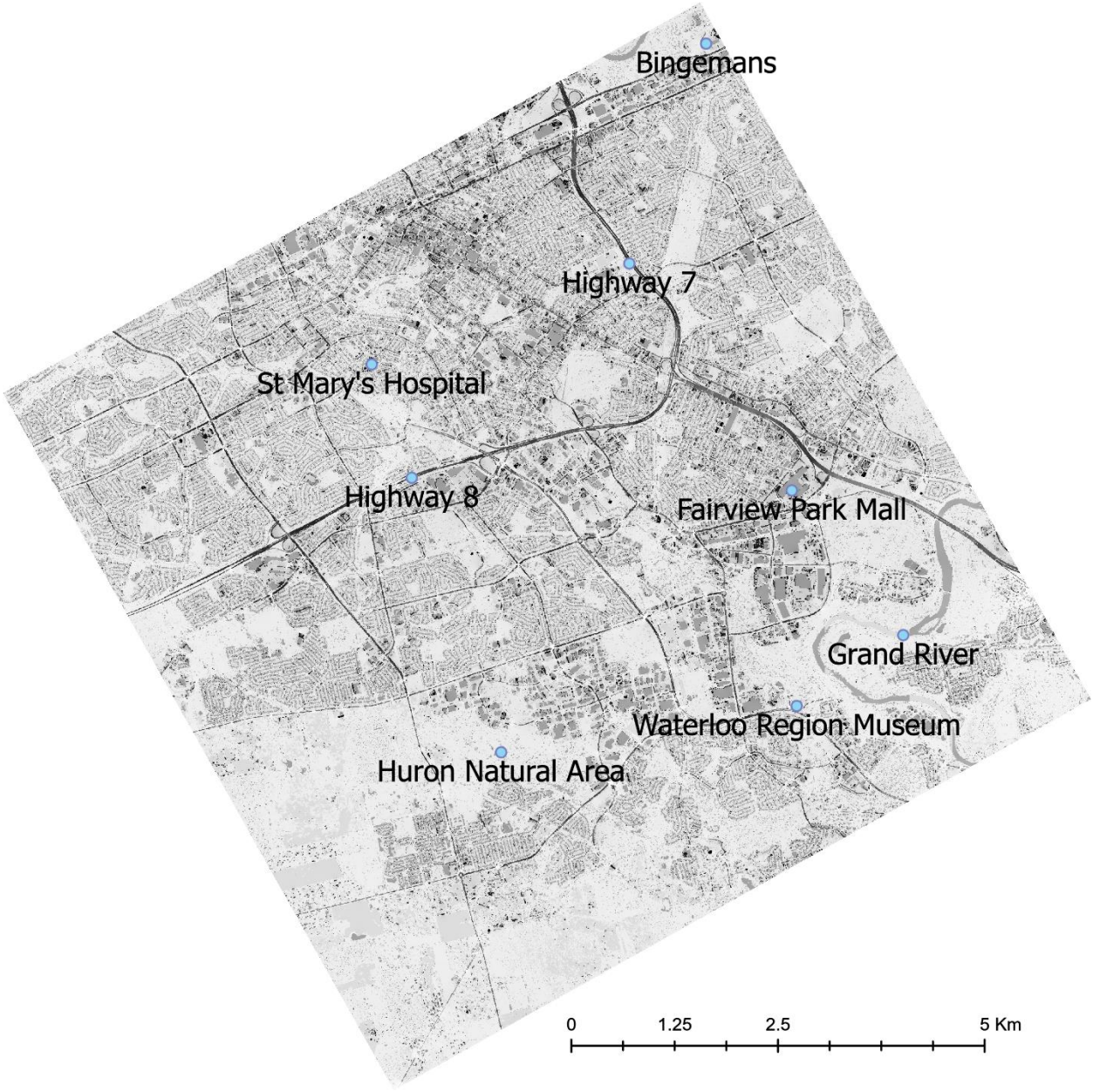


Figure 2 – Kitchener Bat Current Map 2019 - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

The lack of hard barriers should not be mistaken for the presence of high-quality habitat. Bats need multiple habitat types to meet their needs. These include open areas and waterways for forage and water and roost locations like forests for rest and reproduction. Bats reside within the urban landscape with lower abundance and diversity and mainly in or near more naturalized areas (Moretto & Francis, 2017). The urban landscape appears to connect bat habitat within Kitchener but the actual distances between habitat patches and urban trees that can be used as rest stops was not evaluated. This makes it hard to

draw conclusions about the real-world applicability of these potential habitat connections. This disconnect from real-world applicability means that urban plans for bats should focus on enhancing, maintaining and creating high quality linear link habitat and urban park habitat, whether this be adding trees in areas that lack rest areas, providing open forage space near forested areas or revitalizing parts of parks to provide for the needs of bats in addition to open foraging space.

The size of habitat that matters for bats is bigger than most backyards, with reported home ranges of bats varying between 30-2000ha (Habrich, 2018; Henry et al., 2002). Bats often fly 2km between roost and forage and have habitat preferences within these areas, so small areas may be used as part of the required habitat (Drake et al., 2023; Habrich, 2018). In order to enhance the utility of these spaces the addition of trees and or bat boxes could provide rest/living space for bats in areas they may travel through, or, if possible, neighbors could work together to provide larger spaces or linear links in backyards which could be used at a broader scale than localized restorations (Azam et al., 2018; Craig, 2022; Dietz et al., 2020).

3.3.1 Greenways and Green Spaces

Linear links like greenways and walking paths showed high amounts of habitat connectivity. In urban areas, these spaces even enhanced the connectivity of the surrounding urban area. Natural areas along waterways like the Grand River or Henry Strum creek showed similar connectivity but had less of an effect on surrounding urban areas. Roads created barriers even through these linear greenspaces. These links enhanced the habitat connectivity within the urban landscape, but when planning urban greenspace, habitat type matters for bats as well. The most important links contain wooded or even tree lined or hedged areas which can provide corridors for bats to move between necessary land cover types (Azam et al., 2018; Pauli et al., 2017; Russo & Ancillotto, 2015). These areas also provide some edge habitat which can be good for linking water access, open areas for foraging and wooded areas for roosting and have also been known to promote bug activity within these edges (Krauel & LeBuhn, 2016). These links can contribute to maintaining bat populations in urban areas where many habitats have been disconnected. Tree networks in these areas may even help to increase resilience of bats to impacts of urbanization (Jung & Threlfall, 2016).

These linear links work well to connect larger spaces, but bats rely heavily on the larger habitat blocks they connect. Green spaces like cemeteries, golf courses and sports fields may offer a refuge from some urban threats. Cemeteries, golf courses and sports fields showed more habitat connectivity than the surrounding urban area but differed in the barriers they contained. Cemeteries had paths, buildings and some misclassified areas as barriers. Golf courses had moderate barriers for waterways and sand traps and

harder barriers where roads crossed. Barriers in sports fields included fences and sometimes infields of baseball diamonds. Cemeteries and golf courses offer beneficial areas for bats as they have lower levels of disturbance and offer foraging space, resting spots and water. Bats use these areas more heavily in more developed areas, but they do not replace the large woodlot patches that many bats need (Craig, 2022; Drake et al., 2023). These large less urbanized areas represent potential habitat connections and forage locations for bats but may not provide for all bat needs due to lightning, maintenance and human use.

Urban parks and naturalized areas represent the best urban habitat for bats as they are larger and can fulfil more of their habitat needs. Parks that were more developed with fewer naturalized areas showed greater habitat connectivity than the surrounding urban area but still posed a small barrier to connectivity and contained buildings that posed a stronger barrier. Parks in less urban spaces were often more naturalized, and these areas had more habitat connectivity except for some minor patches that were harder to traverse and barriers where roads ran through them. This difference in bat usage is similar to other papers (Johnson et al., 2008). Many of these less urban areas feature different landcover types, with forests, waterbodies, more open areas and edge habitats between them. The diversity in land cover in these areas makes them good habitat for bats as they can provide for multiple life needs like roosts, foraging areas and water. In general, bat species do need heterogenous habitat, so diversity is important (with edge habitat and freshwater being important habitats as well) despite being forest dependent (Craig, 2022; Pauli et al., 2017). *Myotis* species need large forest patches, so these naturalized areas with woodlots are key habitat (Fabianek et al., 2011; Johnson et al., 2008; Thorne et al., 2021). Preservation and expansion of these urban habitats are crucial for helping urban bat populations as these are the only areas that provide the full range of landscape types needed by bats. Especially important to bats are older forest patches to promote some of the more specialized species that may have a harder time in urban areas (Dietz et al., 2020).

3.3.2 Urban Gradient

This mapped area of Kitchener includes a gradient of land uses from agriculture to suburbs to the downtown core. The current map showed bats having little habitat connectivity in the downtown core. Higher concentrations of barriers like buildings and roads limited connectivity. Larger green spaces had more potential for providing habitat connectivity than the surrounding built environment but less than the similar greenspaces that were less urbanized. Small urban open spaces (like yards and parkettes) showed similar habitat connectivity to their counterparts further from downtown. In the agricultural areas habitat connectivity increases a lot with only small amounts of variation in connectivity. The difference between

urban and agricultural areas may be overstated as agricultural areas were not modeled directly, which frequently resulted in them being classified as green spaces that are better than the agricultural land would be in practice. Overall, as urbanization decreased habitat connectivity increased, and this happened for various land use types, even golf courses that would have similar sizes and naturalness had greater potential for habitat connectivity in areas with less dense urbanization. The increase in habitat connectivity appears to be based more on lack of built space than increased greenspaces as these areas showed greater change.

Increases in connectivity with decreasing urbanization were expected. Other studies have found that few species of bat exist in urban environments and that even adapted species decline with increasing urban cover (Dietz et al., 2020). Buildings specifically have caused many species of bat to decrease their activity, though some bats are known to roost in buildings (Fabianek et al., 2011). Some *Myotis* species are known to use human made roosts but still need other key land cover types around to flourish that are often not present in dense urban areas (Craig, 2022; Johnson et al., 2008). Bat activity and species richness decrease in urban areas compared to their rural counterparts (Fabianek et al., 2011; Krauel & LeBuhn, 2016; Russo & Ancillotto, 2015; Turner, 2017). Some bats have been known to do well in the transition zone between urban and rural areas, possibly due to the increase in edge habitat in this area, but other intermediate zones have lower levels of bats in urban areas then natural areas (Coleman & Barclay, 2011; Jung & Threlfall, 2016). In general, bats tend to fare better in less urban areas, but seeing as urban areas can support various bat species and it appears that in Kitchener, at least small sections of higher habitat connectivity exist throughout the city bats may be able to move through the area if some improvements are made. The potential for urban bats means that it is important to consider bat movement when designing urban areas. One key way to improve these corridors through more urban areas is with better tree networks between residual habitat spaces (Jung & Threlfall, 2016).

3.3.3 Buildings and Yards

Buildings were moderate barriers for habitat connectivity with better potential for connectivity in the yards and greenspaces around them. Urban gardens and trees are known to facilitate movement through urban areas, some species even being associated with urban gardens (Dietz et al., 2020; Hale et al., 2012). Buildings pose some challenges to bats, but they can fly near or over them depending on the height of the building. The urban to rural gradient seems to have more of an effect and focus should remain on lessening those impacts over worrying about the impact of buildings. Yards can still play an important role in mitigating urban impacts but more for urban movement than habitat itself.

3.3.4 Roads

Bats had some of their lowest habitat connectivity on and around roads. Major roads were the hardest barriers and showed some funneling beside them. Smaller roads still had low habitat connectivity but were better than major roads; these were mainly in suburban areas where small, low traffic roads exist. Paved areas like parking lots also showed low habitat connectivity. Low connectivity was expected in these areas, as many bat species are less active around roads or avoid them entirely but not all (Bhardwaj et al., 2017; Dietz et al., 2020; Pauli et al., 2017; Russo & Ancillotto, 2015; Turner, 2017). Abundance of *Myotis* bats near major roads is generally less than in nearby habitat due to noise and light pollution and increased predation risk, causing bats to avoid the area, but some fatalities occur as well (Craig, 2022; Moretto & Francis, 2017). In general bat species avoid areas with impervious surface. Some of the effects of roads and other paved areas may be mediated with animal bridges, culverts or trees that span the road and reduced lighting along the road (with different types being preferred by different bat species) (Bhardwaj et al., 2017; Dietz et al., 2020; Turner, 2017). The effectiveness of these harm reduction techniques varies, so ideally major roads should avoid critical bat areas (Dietz et al., 2020; Turner, 2017).

3.3.5 Waterways

Waterways showed poor habitat connectivity, some being hard barriers for crossing. Small sections of the waterways showed more connectivity. These areas of high current on the map may be funnelling bats through areas of poor connectivity. Despite potentially being difficult to cross, waterways provide preferred foraging space, drinking water and potential corridors for movement along the riparian zone (Drake et al., 2023; Fabianek et al., 2011; Krauel & LeBuhn, 2016; Lintott et al., 2015; Pauli et al., 2017; White et al., 2016). Waterways are important resources for bats, so they should be incorporated into habitat plans with emphasis on water quality and promoting an abundance of prey in riparian areas (Craig, 2022; Lintott et al., 2015).

3.4 Summary

Bats in Kitchener had high habitat connectivity; if habitats are close enough together with few barriers (roads) they could feasibly be connected. The high connectivity is useful only in so far as it connects close together habitats as the landscape as a whole lacks quality habitat, so bats need to be able to traverse the entire distance without stopping points that provide roosting opportunity. Connectivity can be made better by improving the quality of the corridors that bats might use. Bats also may roost in urban areas. Potential movement areas and habitat in urban areas need to offer as many of the resources needed by bats as possible to prevent these areas from becoming population sinks.

The methods in this study have a major bat specific limitation. This study only looked at single habitat types and did not explicitly factor in the surrounding landscape at any given point. Compared to the other animals used in this study, bats rely on multiple habitat types, often needing forest, edge habitat and waterways to meet their needs (Fabianek et al., 2011). The impacts of urbanization are also affected by the surrounding landscape (Drake et al., 2023). The surrounding landscape limits selection of habitat more than selection of movement paths so though the methods impact the potential reliability of movement results these effects should be minimal.

Enhancing corridors and habitat for bats involves thinking about several potential anthropogenic effects like road density/traffic, noise and light pollution, pollution, roost availability and water quality (Jones et al., 2009; Moretto & Francis, 2017). Roads were the largest barrier, so it is important to alleviate impacts by increasing tree coverage, decreasing noise and light pollution and minimizing number and size of roads (Moretto & Francis, 2017). In areas where large roads are present, bat crossings might help, these include enhanced tree cover over roads, bridges, underpasses or culverts designed to facilitate bat crossings (Dietz et al., 2020; Moretto & Francis, 2017; Turner, 2017). Roost and rest stop availability can also be limiting factors for bats and their movement. Providing more forest habitat is best, but the addition of trees, hedge rows, green roofs, bat houses or leaving dead wood standing between habitats can help (Azam et al., 2018; Moretto & Francis, 2017; Pauli et al., 2017; Russo & Ancillotto, 2015). Freshwater is also pivotal to supporting bats, so ponds or other water sources should be integrated into these areas (Craig, 2022). Lighting should be avoided within 50m of these habitats and corridors as *Myotis* species tend to avoid artificial lighting due to a perceived increased risk of predation (Azam et al., 2018).

Chapter 4 Deer

4.1 Introduction

Large mammals generally move more easily and further across landscapes than small mammals. Bats represent higher movement capability as well, but large mammals show land-based movement, so have a different set of restrictions. Larger mammals can also be used to pique public interest in research. Larger mammals are often scarce in cities, but deer are prevalent in suburban areas and many people care about how they move through urban and suburban areas for various reasons (added urban diversity, hunting opportunities nearer the city, risk of disease spread, potential for traffic accidents or harm to urban gardens) (Etter et al., 2002; Gallo et al., 2017; Storm et al., 2007; Walter et al., 2009). This makes deer a species of interest for information dissemination as well as for data gathering.

White-tailed deer cover a wide area from potentially as far north as the tree line into northern South America (though with sparse populations at these extremes) and tend to be numerous compared to other large mammals in North America (Laurent et al., 2021; VerCauteren, 2003). They can be found almost coast to coast along the northern United States and southern Canada (Chen et al., 2015). They are habitat generalists, though forest is often preferred habitat, and highly mobile (Grovenburg et al., 2009; Locher et al., 2015). White-tailed deer habitat preference may also be analogous to the needs of other large mammals like coyotes who have been found in similar urban environments, so a focus on deer may help other species as well (Magle et al., 2014).

Presence of deer can dramatically change species compositions. They support the animals that predate them, like wolves, large cats, bears and coyotes and provide carrion for scavengers (*INaturalist Observations*, n.d.). White-tailed deer also pose a risk to some species, with the increase in range of white-tailed deer causing increased predation pressure on animals like caribou as predator concentrations in these areas can increase when deer are plentiful (Laurent et al., 2021). Overpopulation of white-tailed deer due to lack of natural predators can also cause overgrazing of some plants, unless populations are managed, which can even lead to decreased health in the deer population and other forest animals (McShea, 2012; Wright et al., 2020). Deer are keystone herbivores that can use up specific resources as they require large amounts of browse (Magle et al., 2014; McShea, 2012; Potratz et al., 2019; Urbanek & Nielsen, 2013). Deer tend to be grazers in the summer and browsers in the winter (McShea, 2012; Whitaker, 1996). The amount of browse taken can alter succession by changing distributions of species as well as sizes of trees, providing good conditions for exotics to come in (Loeb & Garner, 2022; McShea, 2012; Waller & Alverson, 1997). This level of herbivory can also deplete resources for other animals,

such as acorns for small mammals and plant biomass for insects (Holley, 2023; McShea, 2012). White-tailed deer may also cause problems for people in cities by hurting crops and ornamentals, causing car accidents or providing a vector for Lyme disease (McShea et al., 2008; Potratz et al., 2019; Storm et al., 2007; Waller & Alverson, 1997; Walter et al., 2009). At lower densities, deer can provide an intermediate impact that can promote plant diversity, but without predators, deer levels need to be managed (McShea, 2012).

White-tailed deer are present in urban areas, using patches as small as 0.0014km^2 as part of their range (Kilpatrick & Spohr, 2000a). Urban areas often provide supplemental resource areas for deer, allowing them to escape predators, find shelter and find food in gardens (Blanchong et al., 2013; Edelblutte et al., 2022; Grund et al., 2002; Locher et al., 2015; Potratz et al., 2019; Wright et al., 2020). It even appears that herd size being unmanaged from lack of predators provides more problems to deer populations than the urban environment does (Potratz et al., 2019). Deer are often more abundant than would be ideal, as increasing agriculture and urban areas have expanded deer habitat unlike other species that have been constrained by it (Waller & Alverson, 1997). Deer have even reached overabundance in some metropolitan areas (Etter et al., 2002; Magle et al., 2014). Overabundance of deer tends to happen at the edges of urban areas where they have heterogenous habitat, and they do still avoid urban centres (Gallo et al., 2017). They are present in suburban areas and at least nearby to urban areas and are not overabundant within the urban core.

4.2 Methods Applicability

The landscape classification used for deer was the same as for the other three species and can be found in 2.3 Kitchener Landscape Data. This means that a cell size of 0.5m by 0.5m squares was used. Deer can perceive the landscape at even greater scales than their home range sizes (Kie et al., 2002). Reports of home range sizes vary greatly: they range from less than a 0.01km^2 to about 10km^2 (Etter et al., 2002; Grovenburg et al., 2009; Kie et al., 2002; Kilpatrick & Spohr, 2000a; Locher et al., 2015; Munro et al., 2012; Urbanek & Nielsen, 2013; Walter et al., 2011; Wright et al., 2020). There are a number of factors affecting these sizes, for example, season, with home range sizes growing in the winter to access more resources or cover type, with agricultural areas having increased home ranges and urban areas having decreased range (Etter et al., 2002; Grovenburg et al., 2009; Grund et al., 2002; Munro et al., 2012; Urbanek & Nielsen, 2013; Wright et al., 2020). This variation makes predicting the scale at which white-tailed deer interact with the landscape difficult. The variation in home ranges is in response to resource use not perception, but detangling these factors is difficult. One study found that a scale of 2000m was better than smaller scales for explaining variances in home range size, so the scale used in this study is too

small (Kie et al., 2002). Migration routes and dispersal distances are similarly on the order of tens of kilometers (Etter et al., 2002; Grovenburg et al., 2009; Locher et al., 2015; Wright et al., 2020). Landscape connections for deer only become relevant at larger scales than what was developed for other species (broader than the city limits) (Locher et al., 2015). This is an important species to map to promote awareness of urban landscapes using a perceived public asset/problem, but it is important to recognize that the resolution is too small.

The landscape classification raster was used to assign habitat suitability ranks. Suitability ranks ranged from 0.1-1 (Table 3), where 0.1 was the worst habitat for white-tailed deer and 1 was the best. These values were transformed to resistance using the formula in 2.4 Animal Habitat Preference Data and Transformation.

Table 3 - White-tailed Deer Habitat Values - Deer were assigned habitat values from 0.1-1.0 based on desirability of the habitat for the species according to the rubric in 2.4 Animal Habitat Preference Data and Transformation.

Habitat	Suitability Value	Rationale
Roads - Category 4	0.1	• Deer avoid roads, and fatalities from auto collisions have a greater effect on large mammals due to slower generation times (Etter et al., 2002; Magle et al., 2014; Munro et al., 2012; Rytwinski & Fahrig, 2012; Walter et al., 2009) • Reports exist of high traffic highways increasing genetic distance for white-tailed deer (Locher et al., 2015) • The focus of prior research being on large roads and the fact that they do not create hard barriers meant that only the largest roads received the lowest score
Buildings	0.1	• Buildings are impermeable to white-tailed deer • Deer tend to avoid buildings even in exurban areas (Magle et al., 2014) • Buildings can provide shelter, and the areas around them often have supplementary resources for deer that may be used when other resources are short (Potratz et al., 2019; Urbanek & Nielsen, 2013)
Roads - Category 3	0.2	• See Roads - Category 4 • With decreasing size of road, avoidance and collision risk decrease
Open Aquatic	0.2	• Water resources are an asset for white-tailed deer as they need daily access to water (Chen et al., 2015; Magle et al., 2014) • Large water bodies and rivers are known to create genetic and home range boundaries (Kilpatrick & Spohr, 2000a; Locher et al., 2015; Magle et al., 2014) • White-tailed deer are good swimmers, but better paths exist around these waterbodies (Whitaker, 1996)

Roads - Category 2	0.3	• See Roads - Category 4 • With decreasing size of road chance avoidance and collision risk decrease
Roads - Category 1	0.4	• See Roads - Category 4 • With decreasing size of road chance avoidance and collision risk decrease
Railways Sidewalks	0.5	• Railways and sidewalks are built areas but have a small footprint • Railways have been reported to create home range boundaries for white-tailed deer, but this may have been based on highly active tracks (Kilpatrick & Spohr, 2000a)
Golf Courses	0.6	• Golf courses offer supplementary resources for deer but lack forage (Gallo et al., 2017; Grund et al., 2002) • Deer may use open areas in spring and fall and to a lesser degree in winter (Grund et al., 2002)
Shallow Aquatic Wetland	0.6	• Deer need daily access to water (Chen et al., 2015; Magle et al., 2014) • Deer rarely use wetlands (Grund et al., 2002) • Overall, these aquatic areas represent an important resource for deer but lack others
Parks	0.7	• Open urban areas may be used in spring and fall and to a lesser extent in winter (Grund et al., 2002) o Often after sunset (Walter et al., 2009) • Parks have some resources but less than denser more natural areas
Forest Meadow Savana	1.0	• Deer are forest dependent but need heterogenous habitat as they tend to use more open areas in the spring and fall (Grovenburg et al., 2009; Grund et al., 2002; Kie et al., 2002; Walter et al., 2009) • Landscape classification did not include heterogeneity of landscape and deer do not need all types for movement, so they were individually considered good habitat for movement

The largest roads and buildings were given the lowest suitability rank of 0.1. Road density has mixed effects on deer populations, but deer avoid roads, and fatalities from auto collisions have a greater effect on large mammals due to slower generation times (Etter et al., 2002; Munro et al., 2012; Rytwinski & Fahrig, 2012). Reports also exist of high traffic highways creating genetic barriers for white-tailed deer (Locher et al., 2015). Due to the mixed nature of these results, only the largest roads were included in the lowest suitability rank. Buildings, on the other hand, are impermeable to white-tailed deer. They can provide shelter, and the areas around them often have supplementary resources for deer. White-tailed deer rely on these areas less when quality habitat exists nearby and though buildings may exist in areas that offer resources they cannot be moved through (Potratz et al., 2019; Urbanek & Nielsen, 2013).

The second largest category of roads and open aquatic areas received a suitability value of 0.2. Decreasing road size results in movement effects that are less clear, but these roads are still relatively large so, a low score was given. Open aquatic areas varied in size but were the largest water bodies in the

area and included small lakes and rivers. Water resources are an asset for white-tailed deer, but large water bodies and rivers are known to create genetic and home range boundaries (Kilpatrick & Spohr, 2000a; Locher et al., 2015; Magle et al., 2014). Despite white-tailed deer being good swimmers, there are better ways around these water bodies, so they were given a relatively low score (Whitaker, 1996).

The smallest two categories of road were given suitability values of 0.3 (second smallest) and 0.4 (smallest). They both represent built areas with little habitat value, but the risk of deer-vehicle collisions is reduced on them, so they received a better ranking than the other road categories.

Railways and sidewalks have a suitability ranking of 0.5. Railways have been reported to create home range boundaries for white-tailed deer, but this may have been based on highly active tracks, so Kitchener's railways will have less impact (Kilpatrick & Spohr, 2000a). Railways are built areas that can cause harm to white-tailed deer but pose only a small reduction in overall connectivity. Sidewalks are also a built area but are small and easily crossed.

A value of 0.6 was assigned to golf courses, shallow aquatic areas and wetlands. Deer do not generally select golf courses as habitat, as they often lack forage, but the areas themselves do not provide much resistance. Deer may move freely through these areas depending on the level of human use (Gallo et al., 2017). Shallow aquatic areas and wetlands are areas with low water levels that are relatively small and often mixed with other land cover types. Water resources are important for white-tailed deer, so these areas are beneficial, but pose a small resistance to white-tailed deer connectivity over less aquatic landscape types (Magle et al., 2014).

Parks tended to be more urban than natural. There are resources present, but they tend to be less dense than more natural areas, so parks offer less for habitat suitability than forests and less manicured open areas. As a result, parks have a suitability value of 0.7.

Forests, meadows and savannahs were given a suitability rank of 1. White-tailed deer need heterogeneous habitat using more open areas in the spring and fall but need forest cover as well (Grovenburg et al., 2009; Grund et al., 2002; Kie et al., 2002). Landscape classifications did not include impacts from nearby habitat, so heterogeneity was not included. Because of this, all three habitat types were ranked the same.

The values assigned for each habitat were used to create a resistance map to approximate the cost of movement through each cell. The equation used to transform habitat suitability to resistance can be found in 2.4 Animal Habitat Preference Data and Transformation. The resistance raster was then run through Circuitscape from patch to patch using single pixel buffers. Two runs were done for each scenario map

(one from top to bottom and another from left to right). Output was then multiplied and logged to form a single raster.

4.3 Results and Discussion

The Kitchener 2019 current map for deer (Figure 3) showed high levels of habitat connectivity. Not all the areas that showed good habitat connectivity are highly connected in reality; some are too small and contain hard barriers that would restrict habitat connectivity. These areas depict habitat connectivity but only because the model forces movement through the entire landscape. Areas that can provide habitat and connectivity opportunities remain small, especially in more densely urbanized areas. The areas that showed high habitat connectivity in the urban core are small enough that they do not show real connections for deer. Buildings represented the hardest barriers while paved areas restricted habitat connectivity but did not prevent it (which may pose a risk to deer and drivers). Barriers affected habitat connectivity most in the densest urban areas. Overall, habitat connectivity was modeled to be good in all but the most urbanized areas.

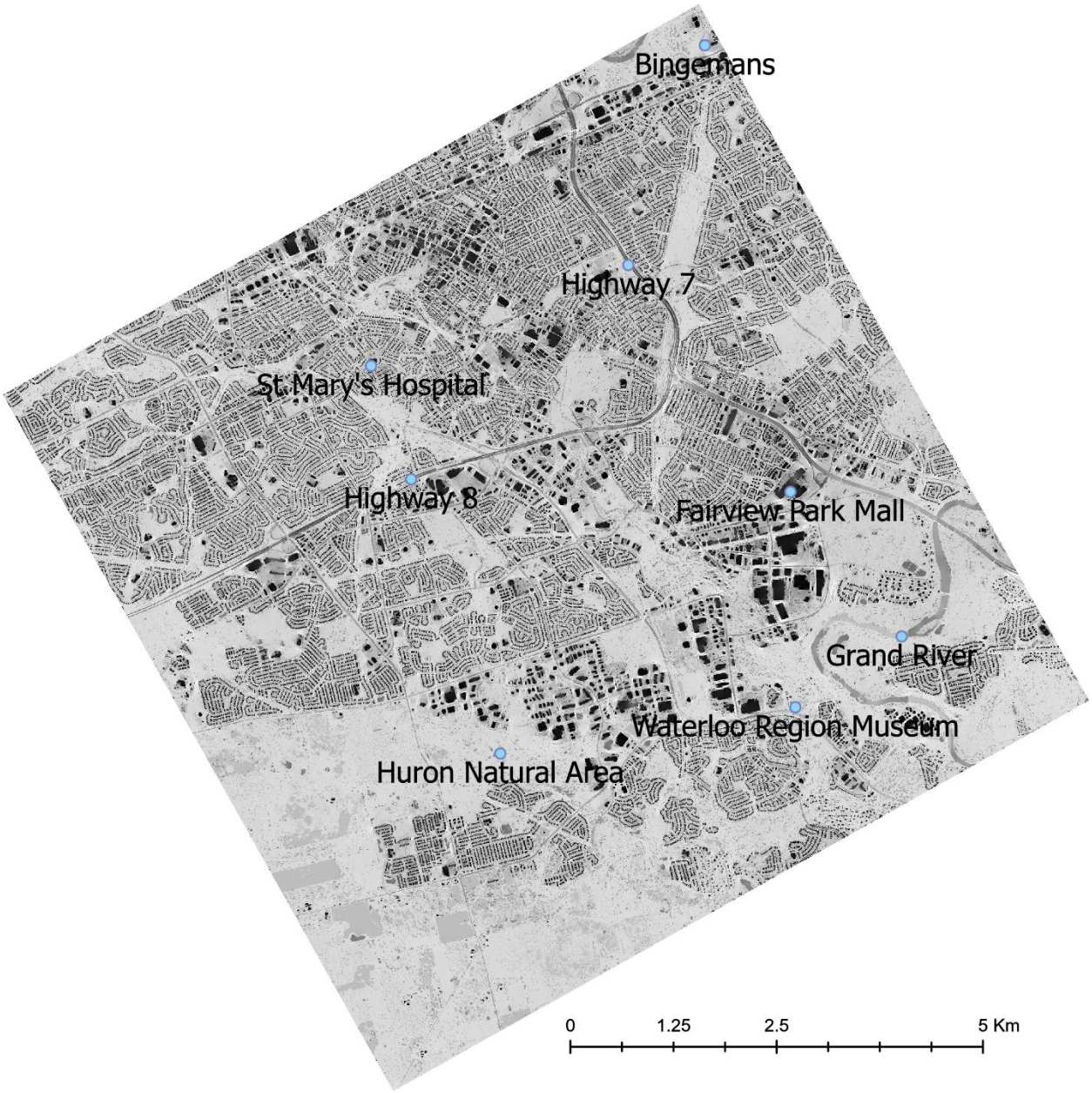


Figure 3 – Kitchener Deer Current Map 2019 - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

4.3.1 Greenways and Green Spaces

Linear links like greenways, walkways and riparian zones may benefit habitat connectivity for urban deer. Linear links offered more habitat connectivity than the surrounding suburban and urban areas with a few small areas of slightly reduced habitat connectivity within them. Walking paths within these areas did not

inhibit connectivity, and roads even showed greater connectivity in these areas than others (increased habitat connectivity on the road may increase deer crossings here if deer are present in the area). Linear links had similar habitat connectivity across the urban gradient, suggesting a stronger preference for habitat type than for the degree of urbanization. In general, deer choose heterogeneous habitat areas with edges or recent disturbances, because of an increase in shrubs and grasses for food (Chen et al., 2015; Gallo et al., 2017; Grund et al., 2002; Kie et al., 2002). Linear links are often narrow and subject to human disturbance, keeping shrubs and grasses plentiful, so linear links would be good supplementary habitat for white-tailed deer. White-tailed deer need more forest cover than these linear links contain, but these areas provide other resources so could provide real world habitat connectivity (Grovenburg et al., 2009; Urbanek & Nielsen, 2013).

Urban areas also offer largish, more manicured greenspace like golf courses, cemeteries and playing fields. Golf courses showed more connectivity than linear links but still had a few small areas of reduced habitat connectivity. Golf courses contained some mild barriers from waterways and harder barriers from sand traps. Golf courses may provide real world habitat connectivity for deer, especially since potential barriers were small, though this will be golf course dependent as heterogeneous habitat with forage must be available for deer to use these areas (Chen et al., 2015; Gallo et al., 2017; Grund et al., 2002; Kie et al., 2002). Cemeteries offered less habitat connectivity than golf courses but still offered some habitat connectivity, with paths as mild barriers and buildings as hard barriers. These areas were smaller than golf courses, so with the small decrease in habitat connectivity these areas are less important land uses but may still offer some benefit to habitat connectivity. Playing fields offered habitat connectivity closer to that of golf courses than cemeteries. Areas like baseball diamond infields had slightly less connectivity. Habitat connectivity in playing fields is limited by the size of the area and how heavily it is used, as the presence of people will deter deer. Playing fields show the potential for creating real world habitat connectivity but issues with size, resource availability and heavy use must be addressed for them to have a meaningful impact.

Kitchener also features larger green spaces, both in a more manicured park style, as well as more naturalized areas. The more manicured areas showed habitat connectivity that was similar to linear links but not as good as golf courses and playing fields. Paved paths occasionally inhibited connectivity but not all of them showed less connectivity than the surrounding areas. Buildings created a hard barrier. Larger greenspaces offer some habitat heterogeneity and spaces with frequent human disturbance, allowing for good forage of early successional plants, however they provide only temporary movement and habitat space while forage is high, as deer tend to move out of small patches during times of year when forage

decreases (Chen et al., 2015; Gallo et al., 2017; Grund et al., 2002; Kie et al., 2002; Waller & Alverson, 1997; Walter et al., 2009).

Large, naturalized areas had better connectivity than surrounding open spaces (yards, industrial areas, etc.). Paved paths decreased connectivity but only with large, paved paths so posed minimal barriers. Roads running through these areas were barriers but often had higher connectivity where they bordered natural areas. This may mean increased deer movement across roads in these areas which needs to be adequately addressed when planning cities (slower roads, signage about deer, etc.). Naturalized area having high habitat connectivity was expected, as though deer are habitat generalists they do need forest cover that is mainly provided by these areas, and these areas sometimes provide water resources as well (Chen et al., 2015; Grovenburg et al., 2009; Grund et al., 2002; Magle et al., 2014; Urbanek & Nielsen, 2013; Walter et al., 2009).

Overall, these urban green spaces allowed for better habitat connectivity for white-tailed deer than the surrounding areas. Some barriers remained, but they had minimal impact. Many of these areas are, however, small and will not support long term occupancy by deer populations, so will function to provide habitat connections not habitat. Hazards from nearby roads also need to be addressed, as many of the best areas for habitat connectivity for deer still intersect with roads.

4.3.2 Urban Gradient

Habitat connectivity in downtown Kitchener was restricted compared to the surrounding suburban areas. Paved areas limited connectivity some, and large roads and buildings were hard barriers. Small patches of green space offered areas of high connectivity. The downtown core is mainly built environment with paved areas and buildings and few small patches of green space leading to low habitat connectivity in downtown with the small areas of high connectivity being too small to be used. Habitat connectivity increased moving out from the urban core into suburban areas as green spaces increased in size, while restrictions from paved area and buildings remained. Increasing habitat connectivity continued from the suburbs into agricultural areas. Habitat connectivity is overestimated in agricultural areas, as they were classified as various habitat types as agricultural area was not a type that was mapped. Overall, habitat connectivity for deer increased with decreasing urbanization.

The strong decrease in habitat connectivity from the urban core to the suburbs is expected as deer health is not strongly tied to degree of urbanization but rather to resource availability, so size of larger green spaces improves habitat connectivity for deer (Blanchong et al., 2013; Potratz et al., 2019).

Suburban areas are often used as a supplemental resource, especially when other areas have deep snow and food is limited (Grund et al., 2002; Kilpatrick & Spohr, 2000b). They provide deer with shelter (houses may provide some cover), food (shrubs, gardens, lawns and more, such as bird feed) and decreased numbers of predators (Kilpatrick & Spohr, 2000b, 2000a; McShea, 2012; Potratz et al., 2019). Gene flow through urban landscapes is less than for other land cover types, and deer may preferentially select for better habitat than urban areas, so habitat connectivity is limited but high (Blanchong et al., 2013; Urbanek & Nielsen, 2013). The use of urban areas declines as housing density increases so the decreased connectivity in the urban core is fitting (Urbanek & Nielsen, 2013). The overall trends of this research support the idea that areas closer to the edge of the city will be used more and that use of urban areas will decrease as urbanization increases, but these effects are mild compared to effects of things like presence of habitat which supports the urban-rural gradient. There was also an increase in deer movement as agricultural areas were reached. This makes sense, as deer use agricultural areas for forage (Locher et al., 2015; Urbanek & Nielsen, 2013).

4.3.3 Buildings and Yards

Buildings were barriers to habitat connectivity. They may provide cover in residential areas, however, deer cannot move through them, so buildings were expected to be a barrier (Potratz et al., 2019). Yards featured lawns, gardens and some trees. In the urban core, yards were the areas of highest connectivity between landscapes with many barriers (buildings and paved areas). Yards provided area that funneled current through areas with many barriers (especially major roads) creating pinch points. In more suburban areas, yards had higher habitat connectivity, with connectivity spread more evenly over the landscape creating fewer pinch points. Yards being a large source of urban connectivity was expected as yards do provide feed for deer (lawns, shrubs, gardens and even other sources like bird feeders) (Blanchong et al., 2013; Kilpatrick & Spohr, 2000b, 2000a; Potratz et al., 2019).

4.3.4 Roads

Roads provided barriers to habitat connectivity for deer to varying degrees. Small roads did not hinder habitat connectivity much, but larger more urban roads were strong barriers. Pinch points were present in some areas where habitat connectivity was created across roads that were strong barriers. Many of these areas were misclassified, creating false areas of higher connectivity. Roads being barriers is to be expected, as in general roads provide negative effects for large mammals, like the potential for collisions with cars (Etter et al., 2002; Fahrig & Rytwinski, 2009; McShea et al., 2008; Potratz et al., 2019). In general, deer avoid major roads, but may cross minor roads (Etter et al., 2002; Underhill, 2002). Large roads like highways have even been noted as decreasing genetic movement so restricted habitat

connectivity along larger roads is supported (Locher et al., 2015). The effects of smaller roads are less well known, as noted effects from road density have varied, so evaluating the accuracy of the barrier effect small roads have, is not doable (Munro et al., 2012). Overall, roads provided barriers to movement, but the magnitude of that barrier depended on the size of the road.

4.3.5 Waterways

Small lakes tended to have similar connectivity to the surrounding habitat with small patches of more limited connectivity, whereas the Grand River had less connectivity than the surrounding areas. Waterways providing areas of similar habitat connectivity to the surrounding land was unexpected. Large water bodies and rivers are known to create home range boundaries or even genetic barriers for white-tailed deer (Kilpatrick & Spohr, 2000a; Locher et al., 2015). This data is based on fast moving or large bodies of water and deer can swim so since the Grand River did inhibit connectivity and other waterbodies tend to be small; these results may be accurate. Actual connections being created through the waterways will probably only happen if there is not an easier way around but even without crossing, deer do benefit from water access (Magle et al., 2014; Whitaker, 1996).

4.4 Cross Species Comparison

Deer current maps showed lower habitat connectivity than bat maps. Similarly to bats, habitat connectivity remained higher in natural spaces and yards than surrounding areas. Both species had increased connectivity moving from the urban core to more rural areas. Barriers in these areas were more noticeable for deer than bats. Barriers differed between the two species. Buildings provided a hard barrier for deer but not bats, as deer could not pass through them, whereas roads posed a hard barrier for bats but not deer.

4.5 Summary

Connectivity was high for white-tailed deer in Kitchener, except in the most developed areas. The strongest barriers were buildings, but deer can easily move around them whereas roads posed a potential hazard and had low connectivity but did not prevent it. Habitat connectivity along roads was highest in areas with large amounts of adjacent habitat, which allows for the risk of deer-vehicle collisions in these areas. Despite these barriers deer had high overall connectivity. They are also urban adapters so most suburban and agricultural areas are usable for them; however, care needs to be taken to avoid creating urban population sinks. Deer mobility is high so they are unlikely to become trapped in an urban setting, but urban resources may allow populations to exceed sustainable levels (which is an existing problem with urban deer populations in many places) (McShea, 2012; Wright et al., 2020).

The modeling methods used in this analysis have certain deer specific limitations. The size of the landscape and pixel size of the map are smaller than would be ideal for deer but were designed to balance applicability to various species. Also, deer prefer heterogeneous habitat, and surrounding land types were not considered, as a result key factors in landscape selection were missing for this species (Grovenburg et al., 2009; Grund et al., 2002; Kie et al., 2002). These are limitations that restrict real world accuracy, but this research attempts only to draw broad conclusions about potential problems and assets for urban deer and the applicability of these methodologies to urban animals, so they will not impact any of the conclusions drawn here.

There are three parts to helping habitat connectivity for deer, mitigating barriers, controlling populations and improving habitat connections. The main barriers for mitigation are road and buildings. It is best to minimize roads and buildings or place them where they will interfere least with habitat. Deer tend to be a highly mobile species and will more easily avoid these areas than other species so protections made for other species should be the focus as they will protect deer as well (Grovenburg et al., 2009; Grund et al., 2002; Kie et al., 2002). Mitigating risks from barriers, like exposure to car accidents and citizen backlash to the species from Lyme disease, can also come from population control (Etter et al., 2002; Gallo et al., 2017; Storm et al., 2007; Walter et al., 2009). Urban population levels of deer can exceed sustainable levels due to a lack of predators which causes deer to interact more with people when resources grow short (McShea, 2012; Wright et al., 2020). This makes controlling population sizes important. Lastly improving habitat connections can help deer. Deer often depend on forest habitats so these areas should be the focus for supporting deer. Deer also use heterogenous habitat and are less restricted than other species so focusing on other species would also benefit deer.

Chapter 5 Shrews

5.1 Introduction

Shrews are sensitive enough to fragmentation that their responses to connectivity changes can be detected (Laakkonen et al., 2001; Łopucki & Kitowski, 2017; Vergnes et al., 2013). Shrews do not disperse well, so urban barriers are impactful (Laakkonen et al., 2001).

Shrews have species that fall between urban adapters and urban avoiders. There are multiple shrew species in the Region of Waterloo, specifically *Blarina* species and *Sorex* species. Globally, *Sorex* species have been found to be impacted by spatial configuration whereas *Blarina* species have been found in heavily urban areas (Brack, 2005; Dickman & Doncaster, 1987; Vergnes et al., 2013). *Sorex* species are known associates to other organisms like certain voles, mice and other shrews (including *Blarina brevicauda*) so may be able to represent habitat preferences for other species as well (Munshi-South, 2012; Whitaker, 2004). *Sorex* species are also known to exist in urban areas like the suburbs of Paris so it can be assumed that they could exist in the suburbs of Kitchener (Vergnes et al., 2013).

Sorex species are present in large numbers around the world and exist over most of the northern hemisphere (Laakkonen et al., 2001; Ryckman, 2020). They are often ecological generalists, allowing them to exist in areas outside of their natural habitats (like urban areas) (Brunet et al., 2001). Specifically, *Sorex cinereus* covers more of North America than any other shrew, occupying most terrestrial ecosystems in the continent (Hope et al., 2012; Merritt, 1995; Moore, 1949; Naughton, 2012; Whitaker, 1996). They exist throughout most of Canada and Alaska and even into the northern United States (Moore, 1949). They are also the most adaptable shrews in North America making them a prime candidate for being present in urban areas (Naughton, 2012). At the same time, these small mammals tend to be nervous and are easily frightened to death (Whitaker, 1996), which can make studying them more difficult, but modern handling techniques minimize adverse effects. Shrews often have small local populations and because of this tend to show the impacts of a disturbance (Laakkonen et al., 2001).

Shrews serve as a food source to raptors, larger mammals, fish, snakes and even larger shrews, and they keep control of invertebrate populations with their voracious appetites (Bunch & Ford, 2005; Getz, 1961; Jackson, 1928; Ryckman, 2020; Whitaker, 2004). In an urban environment, they may also fall prey to introduced species like domestic cats (Jackson, 1928). *Sorex cinereus* is often nocturnal but has active periods during the day as well and is active throughout the year (Jackson, 1928; Moore, 1949; Teferi & Herman, 1995; Whitaker, 1996). These mammals may be small, but they are quite quick and often run as a primary mode of locomotion (Jackson, 1928).

5.2 Methods Applicability

The landscape classification was the same for every species and can be found in 2.3 Kitchener Landscape Data. The scale of 0.5m by 0.5m cells was designed specifically for small animals. For shrews, 500m is the upper range of long-distance movement (Dickman & Doncaster, 1989). The average perceptive range is much lower. Shrews may have some knowledge of their home range beyond what they can immediately perceive, however, for dispersal, landscape knowledge does not exist. This scale is too big for shrews but given processing time and the inclusion of larger and more mobile animals like deer, 0.5m was as small as could be used.

Habitat suitability ranks were created based on research into how shrews respond to that landscape classification. Each land cover type was assigned a value from 0.1-1, 0.1 being the worst type for habitat and one being the best (Table 4) based on the table in 2.4 Animal Habitat Preference Data and Transformation.

Table 4 - Shrews Habitat Values - Shrews were assigned habitat values from 0.1-1 based on desirability of the habitat for the species according to the rubric in 2.4 Animal Habitat Preference Data and Transformation.

Habitat	Suitability Value	Rationale
Buildings	0.1	• Buildings are impenetrable for shrews • Many buildings are small and offer some habitat around them, so they are not considered hard barriers
Roads - Category 4	0.1	• Roads prevent some species of shrews from crossing (e.g. *Sorex araneus*, *Blarina brevicauda*) (Brant & Ortí, 2003; Rico et al., 2007) • Roads have been found to prevent most small mammals from crossing (or at least reduced the frequency of moving through that area) but effects are lower with smaller roads (Ascensão et al., 2015; Oxley et al., 1974; Rico et al., 2007; Ryckman, 2020; Underhill, 2002) • Small mammals are known to return to the side in which they started when translocated, so despite being a barrier, roads are not an impenetrable barrier (Underhill, 2002) • Road impacts are localized and natural areas around them are still used as habitat (Ascensão et al., 2015; Meunier et al., 1999)
Open Aquatic	0.1	• *Sorex cinereus* do not avoid standing water but other shrews do (Getz, 1961) • *Sorex cinereus* like riparian zones (Nocera & Dawe, 2008) • Streams have been found to be barriers for *Blarina brevicauda* (Brant & Ortí, 2003) • Open aquatic areas would be difficult for shrews to cross due to their small size

Roads - Category 3 Roads - Category 2 Roads - Category 1	0.2	• See Roads - Category 4
Shallow Aquatic	0.2	• See Open Aquatic • Shallower waters make these areas somewhat easier to traverse but these areas are still likely to be avoided
Railways	0.3	• Railways are built environment and have risk of train collisions but are often narrower and have more cover than roads so were assigned a higher value
Sidewalks	0.4	• Sidewalks represent a similar risk to railways, but the risk of collision is lower, so they were assigned a higher value
Golf Courses Parks	0.7	• *Sorex cinereus* can occupy open exposed areas, though it is not a preferred habitat (Berger, 2004; Brunet et al., 2001) • *Sorex cinereus* tend to be limited more by the presence of sufficient vegetative cover and moisture than the type of cover (Bunch & Ford, 2005; Getz, 1961; Jackson, 1928; McCay & Storm, 1997; Pearce & Venier, 2005; Whitaker, 2004) • Golf courses and parks offer some resources to shrews but lack cover
Forest Savana Meadow	1.0	• *Sorex cinereus* tends to be a habitat generalist (Clayton, 2003) • *Sorex cinereus* tend to be limited more by the presence of sufficient vegetative cover and moisture than the type of cover (Bunch & Ford, 2005; Getz, 1961; Jackson, 1928; McCay & Storm, 1997; Pearce & Venier, 2005; Whitaker, 2004) • *Sorex cinereus* range from very moist environments like wetlands to wooded areas to more grassy areas and beyond (Getz, 1961; Whitaker, 2004)
Wetland	1.0	• *Sorex cinereus* like moist habitats like marshes, bogs and swamps (Innes et al., 1990) • *Sorex cinereus* does not avoid standing water like some other shrews (Getz, 1961) • *Sorex cinereus* like riparian zones (Nocera & Dawe, 2008)

Areas that shrews are unlikely to cross were given a habitat suitability value of 0.1. This includes buildings, category four roads and open aquatic areas. These areas are almost impenetrable to shrews. Buildings are impenetrable, but their size and the presence of better habitat around means that treating them as almost impenetrable should not be a problem and worked better with the methods used. Category four roads are the roads that are the widest and have the heaviest traffic. The strength of the barrier for roads increases with the width of the road so smaller roads were given higher values (Rico et al., 2007; Underhill, 2002). Open aquatic areas would be difficult for shrews to cross, but *Sorex cinereus* do not avoid standing water so there is a small chance of crossing (Getz, 1961).

A value of 0.2 was given to areas that posed major threats but did not constitute major barriers. These were areas that could be crossed, but due to lack of resource availability are unlikely to be. Road categories 1-3 were included here because roads have been found to prevent most small mammals from crossing (or at least reduced the frequency of moving through that area) but effects are lower with smaller roads (Ascensão et al., 2015; Oxley et al., 1974; Rico et al., 2007; Ryckman, 2020; Underhill, 2002). Small mammals are known to return to the side in which they started when translocated, so despite being a barrier, roads are not an impenetrable (Underhill, 2002). Road impacts are localized and natural areas around them are still used as habitat, so only the road surface itself was used in this category (Ascensão et al., 2015; Meunier et al., 1999). Shallow aquatic areas may have dry areas or have low enough water levels at points that shrews are able to traverse the area, but despite being able to swim, large areas of water regardless of depth do pose a barrier to such a small mammal.

Railways pose some of the same hazards as roads but are often narrower and with more cover, so it was assigned a value of 0.3. Sidewalks are also similar but lack the hazards posed by cars and trains so were given a value of 0.4.

There were no natural areas that shrews would tend to avoid because the categories were too broad, so dry and wet habitats were treated equivalently and natural areas with few resources and/or threats were not differentiated and as such the values of 0.5 or 0.6 were not represented.

Golf courses and parks (sports fields, grassy areas, cemeteries, etc.) are areas that are maintained but less built than many of the previous categories. These areas offer some flora and access to soil over the built areas of the previous categories but are not the natural habitat and cover that would be ideal. *Sorex cinereus* is known to live in some open exposed areas, though it is not necessarily preferred habitat (Berger, 2004; Brunet et al., 2001). These categories were given a value of 0.7 due to their increase in naturalness while still being heavily maintained.

Forests, savannas, meadows and wetlands were all given a value of one. These are all natural areas that serve as habitat. *Sorex cinereus* tends to be a habitat generalist and is not confined by cover type (Clayton, 2003). They do have habitat preferences but tend to react more to the presence of sufficient vegetative cover and moisture than to the type of cover present (Bunch & Ford, 2005; Getz, 1961; Jackson, 1928; McCay & Storm, 1997; Pearce & Venier, 2005; Whitaker, 2004). They can range from very moist environments like wetlands to wooded areas to more grassy areas and beyond (Getz, 1961; Whitaker, 2004). Wetland being a value of one could be debated depending on how much of the area was underwater but given that both shallow aquatic and open aquatic exist, areas that were designated wetland likely contain large amounts of above water plant life and/or only have transient water levels. Shrews tend

to prioritize areas that provide sufficient moisture and have been noted in wetlands elsewhere (Innes et al., 1990).

Habitat suitability values were transformed into resistance values using a nonlinear equation as shrews tend to have localized but unrestricted movement, for more detail on this transformation see 2.4 Animal Habitat Preference Data and Transformation (Keeley et al., 2017; Trainor et al., 2013). The resulting raster was passed to Circuitscape with a buffer layer for start and end patches on the top and bottom of the raster and again with a buffer on the left and right. The two resulting current maps were then multiplied together, and the results were logged for ease of analysis.

5.3 Results and Discussion

The Kitchener 2019 current map for shrews varied from strong barriers to potentially plausible pathways (Figure 4). The model for shrews resulted in habitat connectivity that was better than reality. Circuitscape models potential paths through the landscape and does not account for how likely or unlikely successful dispersal is in general. Many of the areas that showed potential connectivity for shrews contained areas that would not actually allow for it. Some areas that showed potential habitat connectivity contain large areas of short grass or bare soil and though *Sorex cinereus* are habitat generalists they do require moisture and vegetation or leaf litter cover which these areas do not provide (Bunch & Ford, 2005; Getz, 1961; Jackson, 1928). Other areas showed potential habitat connectivity over the Grand River. The Grand River was also crossed in misclassified areas where water was reported as category one road. Shrews can swim, but the Grand River is a large amount of water for a small mammal to cross (Jackson, 1928). Another crossing resulted from a Highway 8 bridge that crossed the Grand River. Some small mammals use habitat near roads to move, but roads themselves are barriers and shrews would struggle to cross a bridge that spans an entire river (Adams & Geis, 1983; Dickman & Doncaster, 1987). Shrews being modeled with more potential habitat connectivity than really exists may be due to a lack of quality habitat. A lack of habitat for shrews is also supported by the lack of shadows or funnels around barriers as there are no good areas for shrews to move to. The multidirectionality of the analysis helped reduce shadows but even accounting for that, one would expect to see changes in habitat connectivity near barriers. Some habitat preferences were present in larger greenspaces as these areas provide enough area for shrews to be discerning about habitat type, but most areas do not offer enough high-quality habitat for this. The downtown core showed some areas of higher potential habitat connectivity near barriers, but these areas are not large enough or high enough quality to be used. Overall, the current map showed some habitat connectivity but more than would be expected in reality and quite a few barriers existed throughout the area. Lack of habitat connectivity may isolate urban shrew populations. Addressing this is challenging as

shrews have relatively short dispersals so, for the distances needed to travel between residual habitats, shrews would need any connections between to be habitat itself, or to have close together stepping stone patches with the necessary resources.

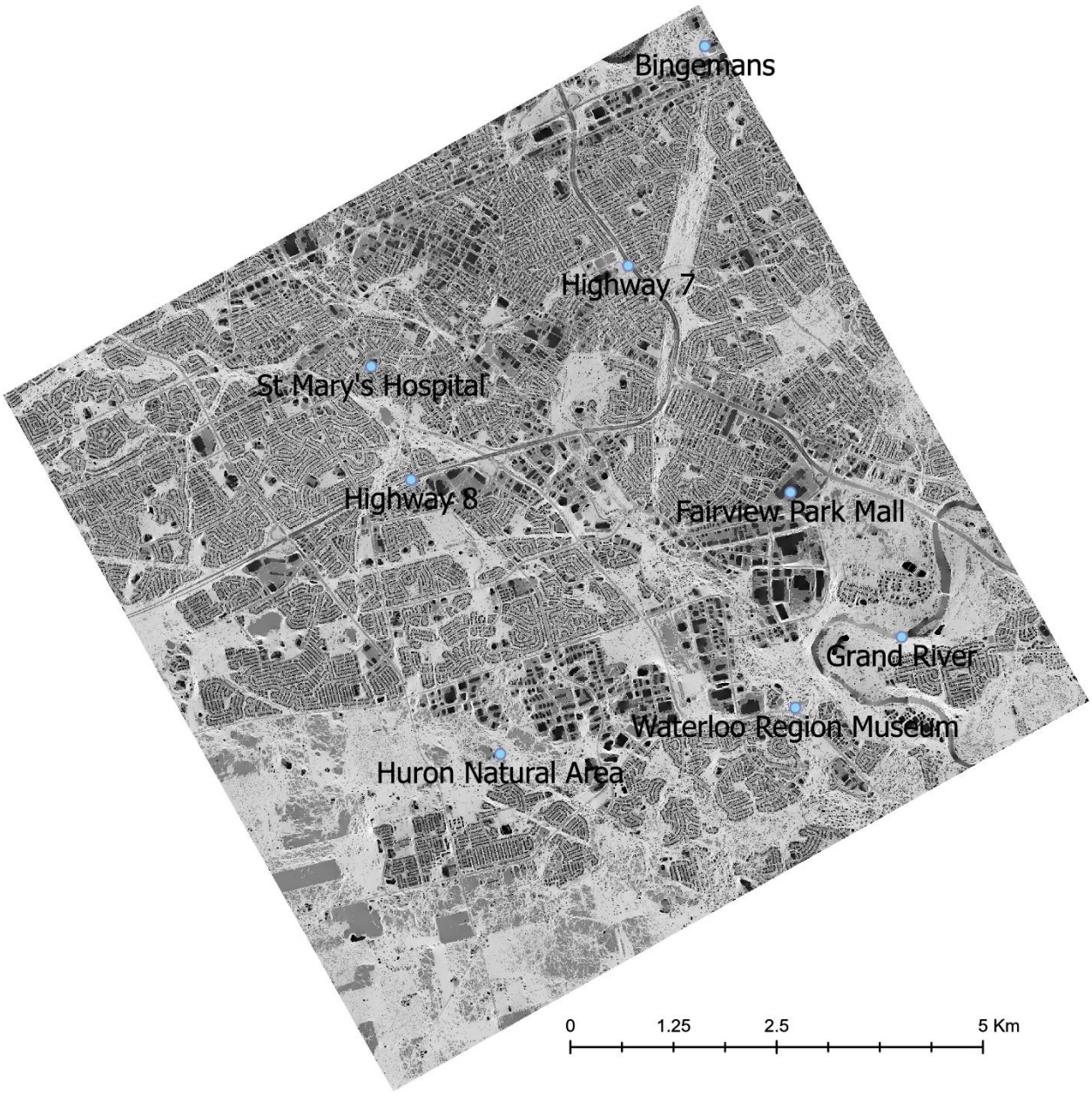


Figure 4 – Kitchener Shrew Current Map 2019 - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

5.3.1 Greenways and Green Spaces

Linear links like greenways and walking paths showed moderate levels of habitat connectivity for shrews. In the densest urban areas these linear links had higher connectivity and appeared as pinch points where they juxtapose the connectivity of the densely built environment. In highly urbanized areas this can serve as the only habitat available to shrews so is important for providing connections between habitat areas. The links did have hard barriers though, where things like paths or waterways posed areas of low connectivity within the higher connectivity links. The habitat available in linear links varies in quality. Some areas have mostly paved path with little vegetative cover while others have large vegetative buffers (like waterways or broader walking paths) and may even connect to larger habitat areas. The variation in quality of these areas makes it hard to evaluate the potential for real world connectivity from these results but these areas did show potential. Efforts for protecting shrews should focus on restoring and maintaining quality habitat for shrews but if these efforts are done within these areas some habitat connectivity benefits could be gained as well. Naturalization of these corridors may help facilitate movement and may be important factors in stopping extinctions of urban small mammal populations (Dickman & Doncaster, 1989; Mahan & O'Connel, 2005). This corridor structure is prevalent in urban greenspaces, so though greenways and trails were the focus, it is possible that this increased connectivity could be developed in other corridors like railways (Vergnes et al., 2013).

Linear links can help with shrew habitat connectivity, but they lack larger habitat areas. Larger green spaces within urban areas include cemeteries, golf courses and parks. These areas showed more habitat connectivity than the surrounding areas and featured some avoidance of barriers as well. Though these areas seemed to offer habitat connectivity, actual use of these areas for longer timeline movement or as habitat may be more difficult as many of these areas are low in resources and do not provide for all the lifecycle needs of the species. This limits the utility of this connectivity to short distance travel. Kitchener also features some naturalized areas. These areas showed marginally more habitat connectivity for shrews than non-naturalized areas and linear links. These areas offer better habitat connectivity than the other areas as they contain larger amounts of higher quality habitat making it possible for larger scale dispersal. Similarly to linear links, barriers were present within the larger greenspaces as well.

Urban greenspaces offered the best areas for shrew habitat connectivity within the city, but some adjustments are needed to provide enough high-quality habitat that these connections have real world value. Lack of urban habitat makes urban natural areas important in the survival of urban small mammals (Mahan & O'Connel, 2005). Small mammals tend to be impacted more by the vegetation in their local environment than the urban surroundings so small increases in habitat amount and connectivity could

have large impacts on the overall health of small mammal populations (Dickman & Doncaster, 1987). To help shrews and other small mammals access these areas, it is important to have large, vegetated patches especially near water sources (Mahan & O'Connel, 2005). In spaces with less vegetated area, it may help to increase total tree cover and diversity, and to limit human disturbance (e.g., light, noise, presence of pet predators, etc.) (Thaweepworadej & Evans, 2022). Though these processes do not remove the risks from urbanization, they may help small mammals adapt and move between potential habitat sites.

5.3.2 Urban Gradient

Habitat connectivity for shrews increased with distance from the urban centre. The urban centre showed relatively little habitat connectivity that was concentrated in the small amounts of residual green spaces. Large urban parks like Victoria Park showed increasing connectivity from the more urban side to the more suburban side even within the same park. Habitat connectivity continued to increase through suburban areas and into agricultural lands. The gradient from the dense urban core to the suburbs was expected due to increasing pressures in urban areas like increased domestic predators, high levels of pollutants and modification of the habitat like mowing or removal of shelter materials (Baker et al., 2003). A similar result was found in both small and large cities in Poland where species richness and diversity of small mammals decreased with increasing urbanization with the greatest effect in urban cores (Łopucki et al., 2013; Łopucki & Kitowski, 2017). Species richness and relative abundance also had negative effects from urbanization in a metropolitan area of Portugal (Gomes et al., 2011). The suburban portion of the map is not without barriers though, for example, the lack of density allows for large, paved areas or single-story malls (e.g. malls like the Sunrise Centre or 730 Ottawa St S). These sprawling areas still provide a built barrier and there was lower connectivity within them. The increase in connectivity from the suburbs to agricultural areas was expected but was overemphasized as agricultural land was not a classification and these areas were classified as green space or some form of habitat, which may provide better habitat for shrews than large areas of agricultural land. Further research into this transition is necessary to draw any conclusions.

5.3.3 Buildings and Yards

Buildings posed a strong barrier to shrews limiting habitat connectivity. Buildings were expected to be barriers as they are impermeable to movement and are often co-located with other stressors like paved areas. Yards around these areas showed high connectivity as shrews were funneled away from buildings and paved areas. Funneling was especially prevalent near large roads. Yards near open spaces or habitat areas tended to offer similar levels of habitat connectivity as the areas they bordered. Yards vary in size and habitat is often made up of gardens and mown lawn. In general, gardens in yards increase the

resources available for shrews, making yards with gardens better for providing habitat connectivity. As funneling was modeled regardless of the type of yard present, supporting habitat connectivity for shrews in these areas must focus on increasing and enhancing naturalized lawns and gardens to support shrew movement (Baker et al., 2003; Gomes et al., 2011; Vergnes et al., 2013). Utilization of yards as habitat or movement corridors comes with the caveat that fences may be barriers. Shrews and other small mammals can often fit through links of fences or underneath fences which can allow them to move between yards with all but the most extreme fences that create a complete vertical barrier all the way down to the ground.

5.3.4 Roads

Roads provided barriers to shrew habitat connectivity to varying degrees, depending on the road size and traffic levels. Major roadways like highways 7 and 8 prevented habitat connectivity for routes that crossed them. In reality, these roads should create hard barriers but because Circuitscape models connectivity across the landscape regardless of plausibility there was some shrew habitat connectivity through these areas (usually at small sections of misclassified road). Large, highly trafficked roads also resulted in the surrounding areas having higher habitat connectivity relative to them as animals avoided these areas. In general, the larger the road the more impact it tends to have on small mammals with crossing smaller roads and others treating roads as strong barriers (Galantinho et al., 2022; Rico et al., 2007). Regardless of road size, the more roads small mammals must cross to return, the less likely they are to return to their original location McGregor et al., 2008). Habitat destruction by roads may be especially important for small mammals, as they have limited mobility and small home ranges. This means that a small mammal could have its entire habitat destroyed when a single road is added and would have trouble relocating (Ascensão et al., 2015). Reducing impacts of roads is important through proper planning and maintenance. This could include locating new roads away from shrew habitat, creating road crossing points for shrews and preventing shrew crossings in highly trafficked areas.

The low habitat connectivity of roads was juxtaposed by higher connectivity along the roadsides except in areas that had been misclassified where connectivity increased for small stretches on the road. Green spaces along the roadside occasionally had higher habitat connectivity then similar green spaces not along the roadside. This shows the importance of green spaces in built environment, as they support habitat connectivity in areas with overall low connectivity. Papers studying small mammals report similar results, where small mammals will preferentially utilize the habitat near roads even over nearby habitat if there is a vegetated swath near the road providing herbaceous habitat (Adams & Geis, 1983; Galantinho et al., 2022; Meunier et al., 1999). Roadside areas create connections between otherwise disconnected areas

(Ascensão et al., 2015; Holderegger & Di Giulio, 2010). These areas can provide opportunities to create more greenway style links if properly restored and maintained (Underhill, 2002). This is not ideal land for habitat, as there are hazards present from the road like salt, oils and lead, but may provide area for movement (Oxley et al., 1974). Oxley et al, 1974 recommended using roadside plants other than grasses, like ground-cover shrubs, to reduce mowing costs and increase utility for small mammals.

5.3.5 Waterways

Open aquatic areas reduced habitat connectivity drastically. Some areas of higher habitat connectivity existed across waterways, but these were in misclassified areas. Areas that were not misclassified did show some habitat connectivity as well (like the Grand River), but these waterbodies are too large for shrews to cross. Some potential areas of habitat connectivity across the Grand River existed but none were promising crossing points, for example the Highway 8 bridge is large and highly trafficked, and dams would be difficult to traverse. Overall, waterways were fairly hard barriers. Areas beside waterbodies had high habitat connectivity. Riparian zones were not modeled separately from other potential habitat types, but the focused movement around waterways make riparian zones a potential place to consider fostering habitat for connectivity. The wider the area of riparian protection the better, as narrower buffers create edge environments that can be easily colonized by non-natives and do not provide habitat for less edge relevant species (Larsen-Gray & Loehle, 2022). Many small mammal species are edge tolerant, so any buffer area helps provide habitat and/or resources (Larsen-Gray & Loehle, 2022).

5.4 Cross Species Comparison

Shrew current maps showed less connectivity than the deer current maps and more barriers that had stronger effects. Greenspaces (including yards) had higher connectivity than the surrounding areas, with less connectivity overall and more barriers that were stronger than were present in deer maps. Increasing connectivity as urbanization decreased happened for both species, but shrews had less overall connectivity and more strong barriers. While large roads caused similar movement restrictions for shrews and deer, small roads impacted shrews much more heavily. Shrews were modeled to have the least habitat connectivity over waterways out of all the species modeled.

5.5 Summary

Shrews had low to moderate habitat connectivity over most of Kitchener; however, the areas that shrews would need to traverse are too hazardous or isolated for this to produce real world connectivity. The strongest barriers for shrews were roads and buildings. Shrews can survive in small patches of land, so yards and small parks may offer some refuge within the city. Despite the ability for shrews to survive in

the urban environment connectivity between habitats is minimal and concerted effort would be needed to improve it.

The methods for this study have one main shrew specific limitation. All connections are considered regardless of feasibility. Circuitscape models connectivity over any distance and any resistance as current is forced from one side to the other. Shrews have limited movement capability and tend not to cross large distances or go through high resistance areas but if there is no better route Circuitscape will use long or high resistance paths. This means that the results model connectivity in places where little connectivity potential exists.

To improve the landscape for shrews, quality and quantity of habitat is the biggest concern. Enhancing backyards and other small greenspaces could help to alleviate urban impacts but a focus needs to be placed on creating appropriate vegetative cover for small mammals (unmown ground cover provides shelter and resources for small mammals) (Baker et al., 2003; Gomes et al., 2011; Vergnes et al., 2013). Paved and built areas will remain barriers, and where possible, alternative movement routes should be provided (Galantinho et al., 2022; McGregor et al., 2008; Underhill, 2002).

Chapter 6 Snakes

6.1 Introduction

The previous three animals have all been mammals. Mammals tend to be well studied, making it easy to produce habitat suitability maps. Other animals remain important but are under-represented in connectivity literature. Other groupings to consider include invertebrates, birds and herpetofauna. Invertebrates are often tiny, so the scale used in this analysis is too large for most species. Species of butterflies and moths fly, so the scale may be more appropriate for them, but like bats the intermediate habitat is not as important due to their ability to fly. Birds on the other hand have too broad a scale, as many can move large distances, as a result birds were excluded from this analysis. Herpetofauna includes a wide range of animal sizes and movement abilities, so is the most promising for finding a species that fits well with this analysis.

Herpetofauna are not well studied in urban areas, but the effects from urbanization are largely negative and some do exist in remnant habitat in urban areas (Cassel et al., 2019; McGregor et al., 2015). Sensitivity to change and presence in urban areas makes them good bioindicators. Amphibians need water bodies, and urban landscapes often do not provide many of these or provide significant hazards when they are present, so focus was put on reptiles. Reptiles are generally more sensitive to habitat disturbance than mammals due in part to lower mobility and increased need for resources for things like thermoregulation, so they represent a more extreme use case for the urban environment (Gigeroff & Blouin-Demers, 2023). Snakes in general are thought to be good indicators, so they were selected (Kjoss & Litvaitis, 2001).

Snakes have been found in residual urban habitat and respond to restoration efforts in urban areas in Western France (Bonnet et al., 2016). Less research has been done on snakes than the mammals that are modeled. This meant that a species had to be chosen for available data rather than for best fit. Eastern garter snakes are one of the most researched species of snake (Placyk et al., 2007). They range across much of North America, so can be compared across cities (Blaesing, 1979; Dileo et al., 2010). They are found in residual habitat in urban areas and are well adapted to modified landscapes (Blaesing, 1979; Cassel et al., 2019; Gray, 2014; Ontario Nature, n.d.; Zappalorti & Mitchell, 2008). Other snakes are often found in similar areas (Dekays brownsnake), but other species tend to be more affected by habitat isolation (foxsnakes) (Dileo et al., 2010; Gray, 2014). Eastern garter snakes may be better adapted to urban areas than is ideal, as they tend to have similar numbers in semi-disturbed areas and undisturbed, and all of Southwestern Ontario has a similar genetic population suggesting that they can move between areas (Blaesing, 1979; Dileo et al., 2010). That being said, urban landscapes pose a challenge even for

eastern garter snakes, as they are in poorer condition in smaller habitat patches, like residual green space in urban areas (Kjoss & Litvaitis, 2001).

Eastern garter snakes probably entered Southern Ontario after the last glacial retreat (Dileo et al., 2010; Placyk et al., 2007). They are habitat and dietary generalists, helping them to adapt to modified landscapes (Dileo et al., 2010; McCoard, 2008; Placyk et al., 2007). They eat mainly amphibians and earthworms but will also eat fish and small mammals, taking larger and more endothermic prey as they grow (Carpenter, 1952; Hamilton, 1951; McCoard, 2008). They are ectothermic, so get their body heat by basking, and they also brumate, leading to additional habitat requirements for basking and brumating areas (McCoard, 2008; Ziv & Davidowitz, 2019).

6.2 Methods Applicability

The connectivity analysis used the same classification steps for all species, and these can be found in 2.3 Kitchener Landscape Data. Classification happened at a scale of 0.5m by 0.5m pixels. This scale fits the various species studied differently. Eastern garter snakes have home ranges that average from about 60m^2 to over 500m^2 and can travel about 500m for resource gathering (Gigeroff & Blouin-Demers, 2023; Most, 2013). Eastern garter snakes moved up to 17km between seasonal habitats (though this is on the high end of their movement) (Dileo et al., 2010; Most, 2013). These numbers are on the upper end of snake mobility, and most movements break down into a series of smaller movements, so though 0.5m cells may be on the small end for snakes, it should still be acceptable for snake movement. The broader scale of the city is also supported by these ranges, as more broad scale movement between residual habitat patches may be possible, but any barriers would pose a large problem. Movement over the entirety of the mapped area would be rare, but snakes might be able to move across a large amount of the area if it were connected.

Habitat suitability ranks were assigned based on how well suited each landscape classification category was for habitat. These values ranged from 0.1-1, with 0.1 representing the least suitable habitat for the species and 1 representing the best habitat for the species (Table 5), value meaning can be found in 2.4 Animal Habitat Preference Data and Transformation.

Table 5 - Eastern Garter Snake Habitat Values - Snakes were assigned habitat values from 0.1-1.0 based on desirability of the habitat for the species according to the rubric in 2.4 Animal Habitat Preference Data and Transformation.

Habitat	Suitability Value	Rationale

Roads - Category 4 Roads - Category 3 Roads - Category 2	0.1	• Roads are a threat to snakes in general (Cassel et al., 2019; Fahrig & Rytwinski, 2009; Matsoukas, 2021; Paterson et al., 2019) • Snakes have increased mortality due to the attractiveness of thermoregulation on the road itself (Fahrig & Rytwinski, 2009) • *Thamnophis sirtalis parietalis* were seen to avoid even gravel roads in Manitoba (Shine et al., 2004)
Buildings	0.1	• Buildings are solid objects that snakes cannot pass through • *Thamnophis sirtalis* have been known to hibernate in the foundations of buildings (Ontario Nature, n.d.) • Buildings may provide a resource, but they cannot be passed through
Roads - Category 1	0.2	• See Roads - Category 4, Roads - Category 3, Roads - Category 2 • Smaller roads with less traffic pose lower mortality risk than other roads (Shine et al., 2004)
Open Aquatic	0.2	• *Thamnophis sirtalis* can swim (Placyk et al., 2007) • Open aquatic is likely hard to cross as it includes larger waterbodies and waterbodies with current
Railways Sidewalks	0.4	• Railways and sidewalks are built areas that lack quality habitat • Garter snakes can be closer to pedestrians on paths before reacting than other snakes, but general guidance recommends paths be at least 400cm away from suitable snake habitat (Burger, 2001)
Shallow Aquatic Wetland	0.6	• *Thamnophis sirtalis* can swim (Placyk et al., 2007) • *Thamnophis sirtalis* like habitat with water edges or wetlands, but do not live in aquatic habitat (Carpenter, 1952; Cassel et al., 2019; McCoard, 2008; Most, 2013)
Golf Courses Parks	0.7	• In urban areas *Thamnophis sirtalis* can be found in the edges between forest and more open urban green spaces but prefer more natural habitat (Cassel et al., 2019; Dileo et al., 2010; Zappalorti & Mitchell, 2008) • *Thamnophis sirtalis* avoid things like walking paths, especially ones that have more people (Burger, 2001)
Forest	0.9	• *Thamnophis sirtalis* are habitat generalists but often prefer early successional habitat (Carpenter, 1952; Cassel et al., 2019; Gray, 2014; Kjoss & Litvaitis, 2001; McCoard, 2008; Most, 2013) • *Thamnophis sirtalis* prefers mesic habitats (McCoard, 2008) • *Thamnophis sirtalis* like to have basking areas with 50-75% cover (Burger et al., 2004) • *Thamnophis sirtalis* have been found in wooded areas even if it is not preferred habitat (McCoard, 2008; Most, 2013)
Meadow Savana	1.0	• *Thamnophis sirtalis* are habitat generalists but often prefer early successional habitat (Cassel et al., 2019; Gray, 2014; Kjoss & Litvaitis, 2001; McCoard, 2008; Most, 2013) • *Thamnophis sirtalis* often select areas between open area and forest, but edge habitats are not represented in the classification scheme chosen so more open areas like meadow and savana represent the best habitat (Zappalorti & Mitchell, 2008) • *Thamnophis sirtalis* like to have basking areas with 50-75% cover (Burger et al., 2004)

Buildings and all but the smallest roads were given a value of 0.1. Eastern garter snakes have been known to hibernate in the foundations of buildings, however for movement they do create a barrier that cannot be crossed, so were given the lowest value available (Ontario Nature, n.d.). Roads are a threat to snakes in general (Cassel et al., 2019; Fahrig & Rytwinski, 2009; Matsoukas, 2021; Paterson et al., 2019). Snakes are negatively affected by roads, not just from road avoidance, but also increased mortality due to the attractiveness of thermoregulation on the road itself (Fahrig & Rytwinski, 2009). Eastern garter snakes are often less susceptible to changes in landscape then other snakes, and though the effects of roads may be lower, they still pose a threat (Gigeroff & Blouin-Demers, 2023; Ontario Nature, n.d.).

Values of 0.2 were given to the smallest roads and open aquatic areas. Eastern garter snakes avoid even gravel roads, but they were crossed on occasion and represent a lower mortality risk than larger more heavily trafficked roads (Shine et al., 2004). Open aquatic areas were given a low suitability value despite eastern garter snakes swimming well (Placyk et al., 2007). This value was given because open aquatic represents many different types of aquatic ecosystems, some of which have strong currents or are large enough to make crossing difficult. As a result, open aquatic was given a lower value than other aquatic areas. Railways and sidewalks are less of a barrier or threat than buildings and roads but do not represent good quality habitat so were given a value of 0.4.

Shallow aquatic areas and wetlands received a value of 0.6. Eastern garter snakes are good swimmers (Placyk et al., 2007). They tend to like areas with water edges and wetlands, but water itself is not the preferred habitat, so though this may not provide a barrier, it might not be the chosen area for movement either, resulting in the moderate suitability value (Carpenter, 1952; Cassel et al., 2019; McCoard, 2008; Most, 2013).

Suitability values of 0.7 were assigned to golf courses and urban parks. Urban areas often exclude many snake species; however, Eastern garter snakes are known to persist and even thrive in urban environments. They will preferentially be found in the edges between forest and more open urban green spaces (Cassel et al., 2019; Dileo et al., 2010; Zappalorti & Mitchell, 2008). They avoid things like walking paths in these areas, especially ones that have more people (Burger, 2001). These urban green spaces provide some area for resource use and movement but are not ideal habitat.

Forests were given a value of 0.9, whereas meadow and savanna were given values of 1. Eastern garter snakes are habitat generalists but often prefer early successional habitat to more closed canopy areas even within cities (Cassel et al., 2019; Gray, 2014; Kjoss & Litvaitis, 2001; McCoard, 2008; Most, 2013). They

will often select areas between open area and forest, but edge habitats are not represented in the classification scheme chosen (Zappalorti & Mitchell, 2008).

The habitat ranks were then transformed to create resistance values for movement using the equation in 2.4 Animal Habitat Preference Data and Transformation. These resistances along with buffers along the edge of the map (to create to and from patches) were used in Circuitscape. Resistance maps were run twice, from top to bottom and from left to right and the resulting current maps were multiplied together and logged to create a single output raster per scenario.

6.3 Results and Discussion

Habitat connectivity for eastern garter snakes was low across Kitchener (Figure 5). There are several small areas showing higher relative connectivity (funneling), but these areas only exist due to the low connectivity across the map as low overall connectivity results in more of the current going through marginally better areas. Buildings and roadways provided hard barriers. Naturalized linear links and larger green spaces showed the highest connectivity but habitat connectivity was still low. Connectivity did increase with decreasing urban intensity (from downtown to the suburbs and into agricultural areas). This low connectivity was expected, as snakes tend to have limited mobility and high resources demands, making urban areas difficult to traverse. Overall, connectivity is lacking for snakes in Kitchener and improvement to urban habitat and connectivity is needed in Kitchener.

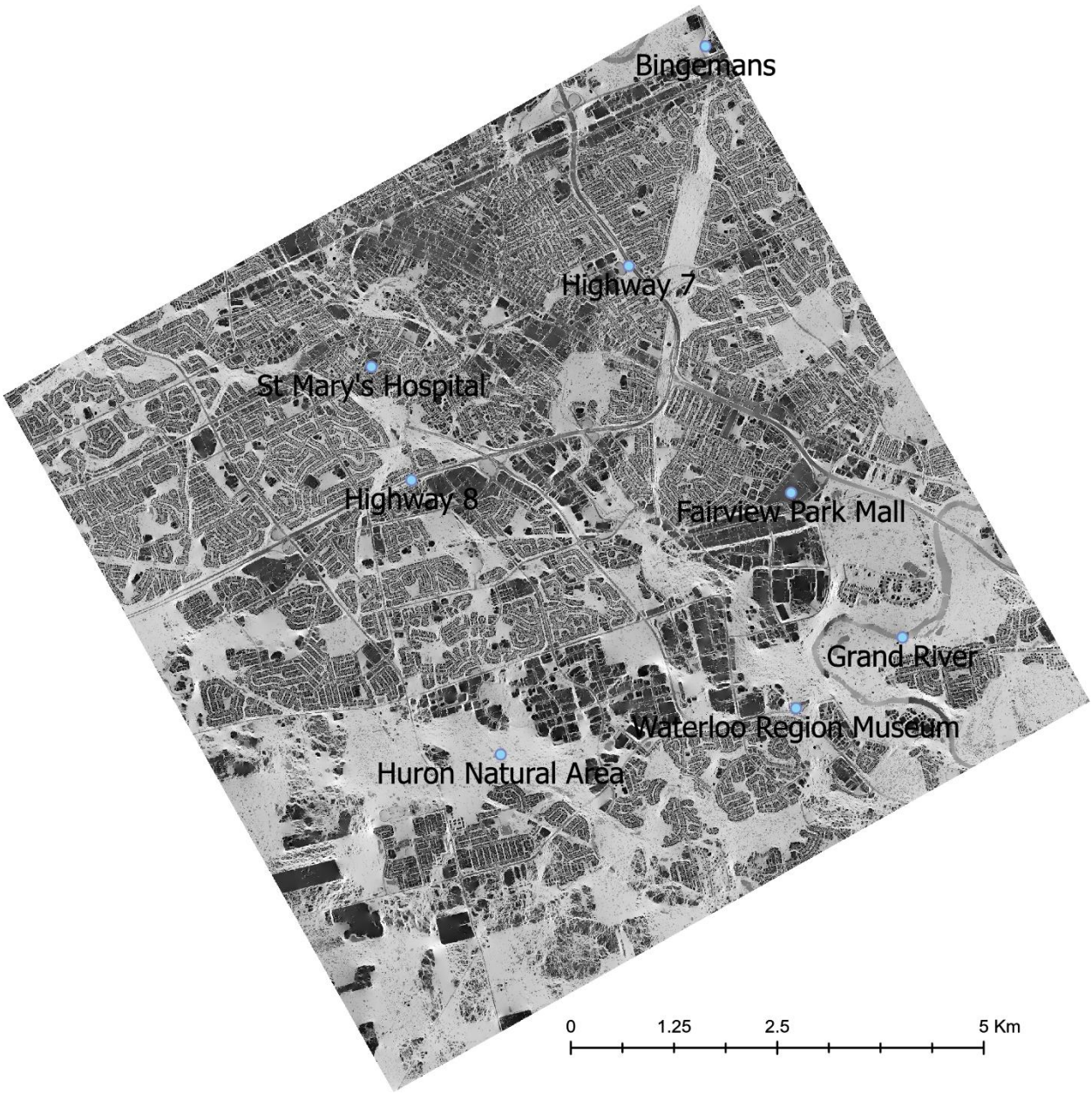


Figure 5 – Kitchener Eastern Garter Snake Current Map 2019 - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

6.3.1 Greenways and Green Spaces

The 2019 snake map showed moderate connectivity through linear links (greenways and walking paths). Narrower links and links that were closer to buildings tended to have lower connectivity. These areas included some barriers within them where connectivity was reduced but they were small, isolated patches. The hardest barrier was roads running through these areas. Roads tended to show less habitat connectivity

around linear links than elsewhere. One of the barriers was walking paths, but the degree to which they reduced habitat connectivity depended on the material of the path. In general, linear links had higher connectivity than the surrounding urban area. This was expected, as these areas include more herbaceous cover and wetland edge than forest, which was preferred by garter snakes in suburban habitat networks in Chicago (Cassel et al., 2019).

Linear links are long and narrow. Kitchener also features areas that are wider and have less edge, like golf courses, cemeteries and playing fields. These areas had moderate connectivity but higher than surrounding areas with some barriers such as manicured areas, sand traps, baseball infields and paths. Playing fields did vary in connectivity depending on the surrounding landscape, showing less relative connectivity when the areas around them had higher connectivity, suggesting that areas with better habitat contributed more to overall connectivity of the landscape. Similarly to linear links, these areas showed moderate connectivity but often contain less herbaceous cover and may need restoration to reach this connectivity potential.

Larger and more naturalized green spaces are found within Kitchener as well. These areas range from large urban parks to natural areas. Large urban parks tended to have less habitat connectivity than the smaller urban green spaces or linear links and had reduced connectivity near roads and built areas. Paths created different levels of barrier depending on the path material. These areas showed a small increase in connectivity relative to surrounding areas. Less connectivity in larger green spaces was unexpected, but this may have been because the smaller green spaces were in denser urban areas so had higher relative connectivity compared the areas around them. Large natural areas had slightly more connectivity than the smaller more urban green spaces but still feature a few potential barriers.

Urban green spaces provided higher connectivity areas compared to the surrounding landscape. These areas may be used by eastern garter snakes in reality, as they are habitat generalists, but overall connectivity levels were low and would be even lower for other snakes (Gray, 2014; McCoard, 2008). These areas tend to offer the highest levels of connectivity in the landscape but need to be improved. In general, snakes like early successional habitat which many of these areas could offer if planned accordingly (Kjoss & Litvaitis, 2001). These areas would also need to cover more of the areas between habitat sites, as snakes will not travel large distances and need habitat within the areas they are traversing.

6.3.2 Urban Gradient

Habitat connectivity increased from the urban core to the suburbs. Habitat connectivity increased with the decrease in barriers like buildings and roads. This was expected as buildings provide a complete physical barrier and road densities are known to impact garter snakes (Gigeroff & Blouin-Demers, 2023). The

downtown core did feature some areas of higher connectivity, in urban green spaces between the barriers of buildings and roads. Areas of high connectivity were generally misclassified cells that resulted in funneling through a lower connectivity area. The downtown core would have very low habitat connectivity in reality but connectivity may exist in more suburban areas. Eastern garter snakes have been recorded in suburban areas of New Jersey and Chicago so these areas may feature some real-world connectivity but are under increased pressure compared to surrounding habitat and other snake species would have less connectivity in these areas (Cassel et al., 2019; Zappalorti & Mitchell, 2008).

Habitat connectivity also increased from the suburbs into agricultural areas, but these levels of connectivity varied with farm colour from the aerial imagery. Lack of agriculture specific aerial data meant that these areas were mostly classified as various better habitats, so the habitat connectivity in these areas was overestimated. In reality, the habitat connectivity of agricultural land is highly dependent on crops and machinery used. Eastern garter snakes avoid agriculture areas but do like borders between open area and forest which are provided along the edges of some fields, so actual connectivity is hard to estimate (Maddalena, 2018).

6.3.3 Buildings and Yards

Buildings posed a strong barrier for eastern garter snakes. The yards around many buildings were showed more connectivity as they pulled current from the buildings. This makes sense, as eastern garter snakes have been known to use the foundations of buildings for shelter, so they would be found around buildings but not be able to go through them (Ontario Nature, n.d.). Yards had higher connectivity than buildings but connectivity in yards was still low to moderate. Yards tended to be small. The large distances between residual habitat means that yards will not provide habitat connectivity in reality.

6.3.4 Roads

Roads provided barriers for eastern garter snakes. The smallest roads when surrounded by habitat (often in small suburbs) did have moderate habitat connectivity but most were strong barriers. The strength of the barrier caused by roads did decrease with decrease building density and increasing agricultural and natural areas. Paved areas also posed a barrier to habitat connectivity. These results align well with other reports that have documented snakes avoiding even small, gravel roads (Cassel et al., 2019; Gigeroff & Blouin-Demers, 2023; Rytwinski & Fahrig, 2012; Shine et al., 2004). Potential threats from roads include avoidance (which fragments and decreases size of habitat) as well as road mortalities (increased by the good thermoregulation properties of road surfaces for snakes) (Fahrig & Rytwinski, 2009; Gigeroff & Blouin-Demers, 2023). Roads being a strong barrier means that they pose a serious risk to eastern garter

snakes. These impacts may be mitigated with increased habitat connectivity over the landscape or more locally by creating alternative crossing areas for herpetofauna in general (Balsas, 2019; McGregor et al., 2015). Roads can impact snake populations and need to be considered in urban development.

6.3.5 Waterways

Waterways in natural areas were the same low connectivity as the surrounding area. Waterways in built areas posed barriers with lower connectivity than the landscape around them. Built areas have low connectivity, so small increases in landscape resistance can change waterways that may be manageable in other circumstances into barriers. Waterways is a broad category with small ponds as well as larger "lakes" and rivers. Eastern garter snakes are good swimmers and known to be in areas like wetlands, but they may not move as well through larger or faster moving water bodies (Carpenter, 1952; Cassel et al., 2019; McCoard, 2008; Placyk et al., 2007). The focus on open aquatic areas meant that a decrease in connectivity for eastern garter snakes in waterways was expected, though some connectivity is feasible in reality. It was surprising that waterways near developed areas had lower connectivity than surrounding areas, but riparian zones which are the main areas of advantage near water were not modeled (Cassel et al., 2019; McCoard, 2008). Within waterways, the riparian zones are the areas most likely to aid habitat connectivity and as they were not modeled, suggestions for urban development are difficult to make.

6.4 Cross Species Comparisons

Snakes had the least habitat connectivity overall. Greenspaces (including yards) had slightly less habitat connectivity for snakes than shrews but also had fewer barriers. Snakes had the largest increase in connectivity with decreasing urbanization, with less connectivity in the urban core than shrews had but similar levels in agricultural areas. Barrier responses for buildings and roads were similar to shrews. Waterways provided the same connectivity as the surrounding area, resulting in slightly better connectivity for eastern garter snakes than for shrews.

6.5 Summary

Eastern garter snakes have low habitat connectivity throughout Kitchener, and barriers like buildings, roads, paved areas and large waterways reduce connectivity further. Urban areas are not prime habitat for eastern garter snakes, but they are still found in suburban areas so do move through the urban landscape and are affected by the connectivity of the landscape. Low connectivity paired with small habitat areas and large distances between them limits the use of the landscape by eastern garter snakes. It is also important to note that eastern garter snakes are one of the better adapted snake species to urban environments, so habitat connectivity is even worse for other snakes (Dileo et al., 2010; Gray, 2014).

Eastern garter snakes had some species-specific limitations based on these methods. The first is that landscape type is only part of what predicts potential use of an area by snakes and was used as the only factor for creating resistance rasters. Patch size also matters for snake presence, and many of the areas examined were under the minimum patch size of 1.5ha that is reportedly needed for snakes to be present in developed areas (Kjoss & Litvaitis, 2001). Another factor is whether snakes need to move. In general snakes are averse to moving, remaining in the spaces where they were initially found, meaning that it may take more than good quality habitat for snakes to move; garter snakes however have better mobility than most snakes (Carpenter, 1952; Fitch & Fleet, 1970). An additional limitation is that riparian zones were not modeled. These areas are good habitat for snakes and may help increase connectivity and leaving them out may have reduced the overall connectivity predicted (Cassel et al., 2019; McCoard, 2008). The effects of these limitations are small and do not limit the applicability of results.

Creating better connections for eastern garter snakes is crucial as urban density increases. In general, people are reducing the disturbances needed to create the early successional habitat that eastern garter snakes need and instead creating disturbances that create developed areas that are barriers for this species (Kjoss & Litvaitis, 2001). There is a need for less built area and more early successional habitat. Eastern garter snakes are habitat generalists, so the exact nature of this habitat is flexible and may include somewhat open urban greenspaces, though these benefit other snake species less (Gray, 2014; McCoard, 2008). The larger these patches are the better, but small patches should not be removed as they may offer refuge to specific species (Delaney et al., 2021). Creation of habitat should be the priority, but for movement between habitats to happen, ensuring high quality open areas with limited pavement and buildings is important.

Chapter 7 Scenarios

7.1 Introduction

Kitchener's population is growing faster than average for Ontario cities with a projected population of over 3000,000 by 2031 (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014; Statistics Canada, n.d.). Densification plans focus on increasing density in already built areas to protect natural and rural landscapes (City of Kitchener Official Plan A Complete and Healthy Kitchener, 2014). At least 50% of growth is required to be densification of built landscapes (A Place to Grow: Growth Plan for the Greater Golden Horseshoe, 2020). This growth will impact the amount and connectivity or urban habitat. Intensifying land use around fragments of urban habitat could further isolate them. While preserving natural and rural spaces helps to minimize impacts of densification there is also opportunity to plan to protect or enhance urban habitat as the landscape is already changing (Bailey, 2007).

One tool for looking at the impacts of habitat change on the urban landscape is examining how habitat connectivity may respond to changes to the landscape. Predicting how future development will occur is difficult, as though city plans exist, they are often nonspecific and open to interpretation or even ignored. Based on how the city might change in the future, three scenarios were developed. The first two scenarios model what could happen if the amount or quality of habitat was increased, while maintaining the current building footprints (intensification would be solely vertical). Green space development is required for large developments, but given that cash in lieu of this can be granted, it is anticipated that increases in greenspace will be minimal if at all. This led to the third scenario where the number of buildings and their footprints was increased to meet the projected density for 2031. These three scenarios reflect the extreme ends of how the city could develop. It is expected that the densification process will leave the city somewhere in between these outcomes, however, knowing the potential benefits and drawbacks that come with how the city is planned are important for decision making. The scenarios were created using steps laid out in 2.5 Creating Scenarios.

7.2 Results

7.2.1 Habitat 5% and 10%

The first scenario created increased the amount of habitat (meadow) by five percent (Figure 6, Figure 7, Figure 8 and Figure 9). All four species showed minimal change to habitat connectivity with a five percent habitat increase from the 2019 baseline. Shrew and snake maps did show some increased

connectivity isolated to a couple of cells around the habitat change. These tended to be easiest to see in large greenspaces. The second scenario increased habitat (meadow) by ten percent (Figure 10, Figure 11, Figure 12 and Figure 13). Changes in connectivity from the 2019 baseline remained difficult to see. Zoomed in to individual cells, there were more changes than were present in the five percent increase. The number of small, isolated changes for shrew and snake connectivity increased and became noticeable in bat and deer maps.

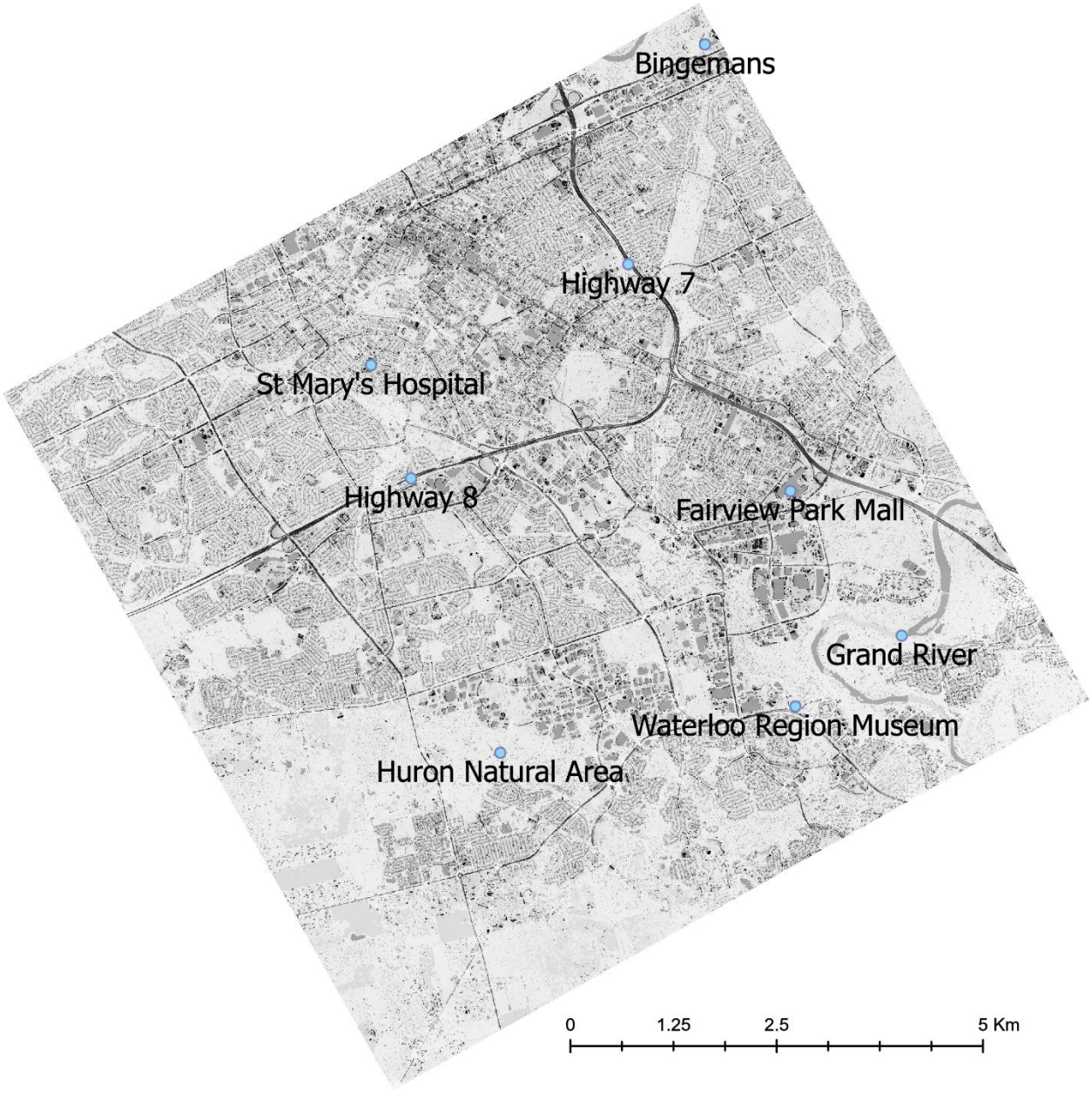


Figure 6 – Kitchener Bat Current Map with a 5% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

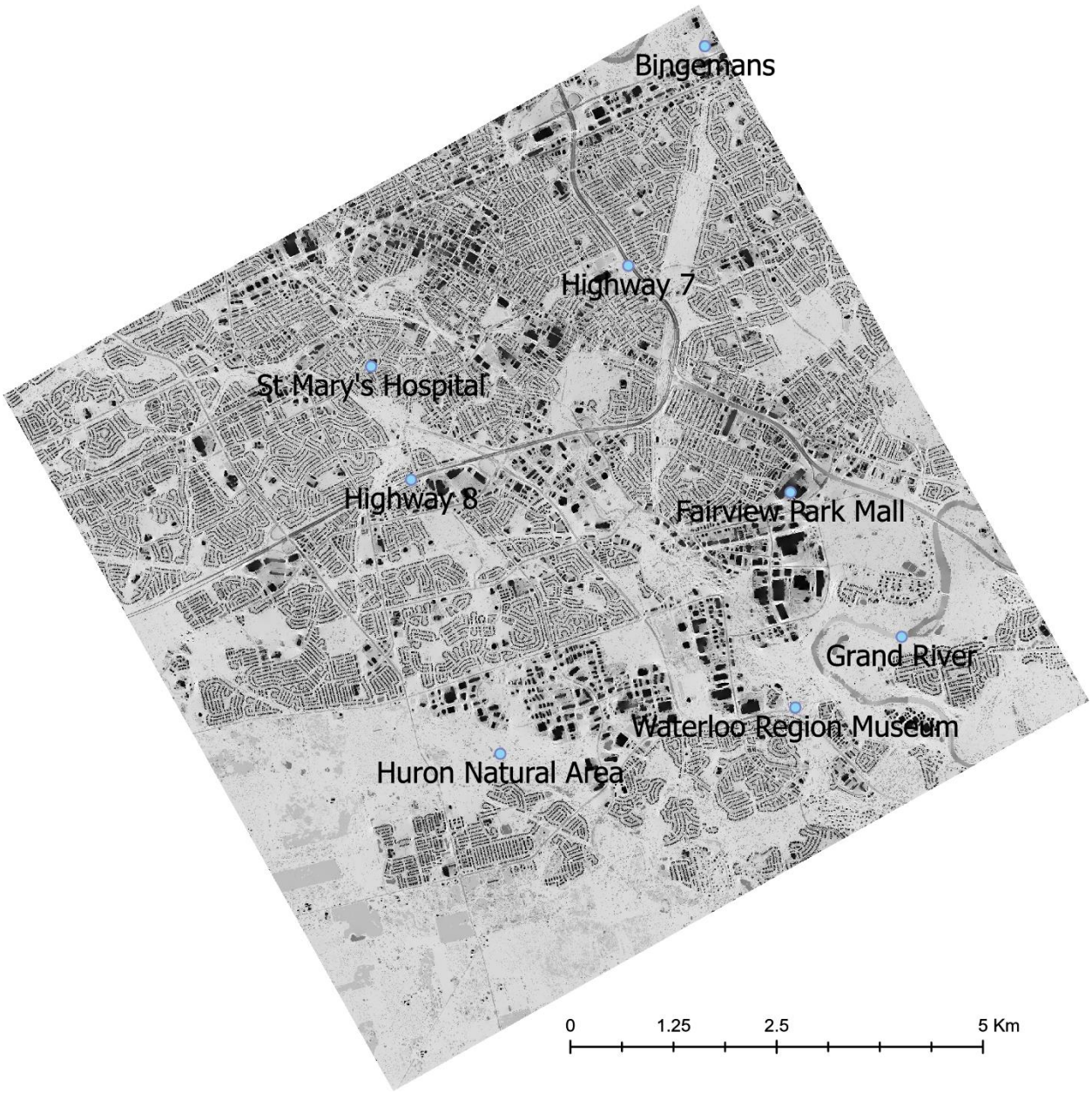


Figure 7 – Kitchener Deer Current Map with a 5% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

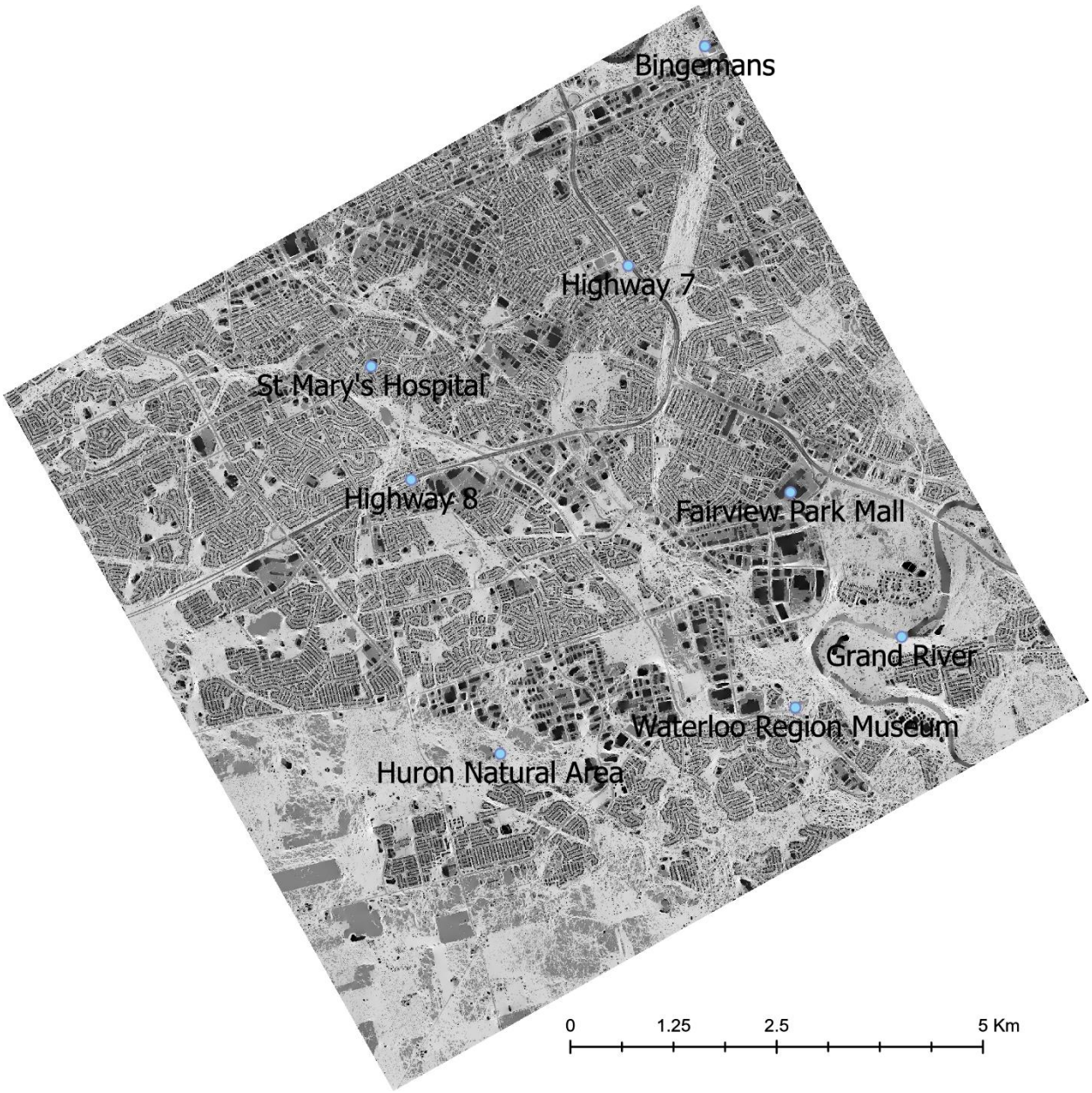


Figure 8 – Kitchener Shrew Current Map with a 5% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

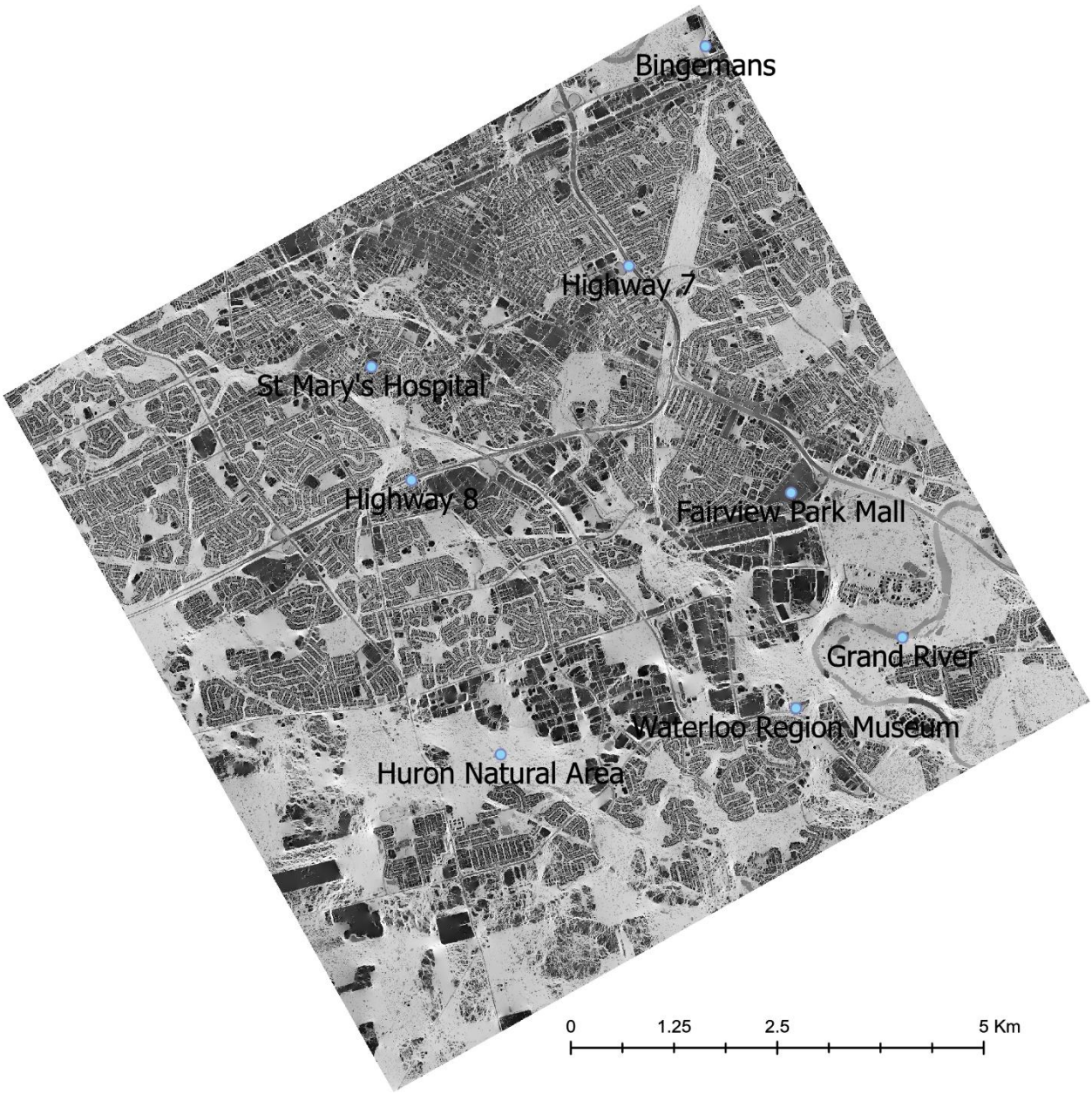


Figure 9 – Kitchener Eastern Garter Snake Current Map with a 5% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

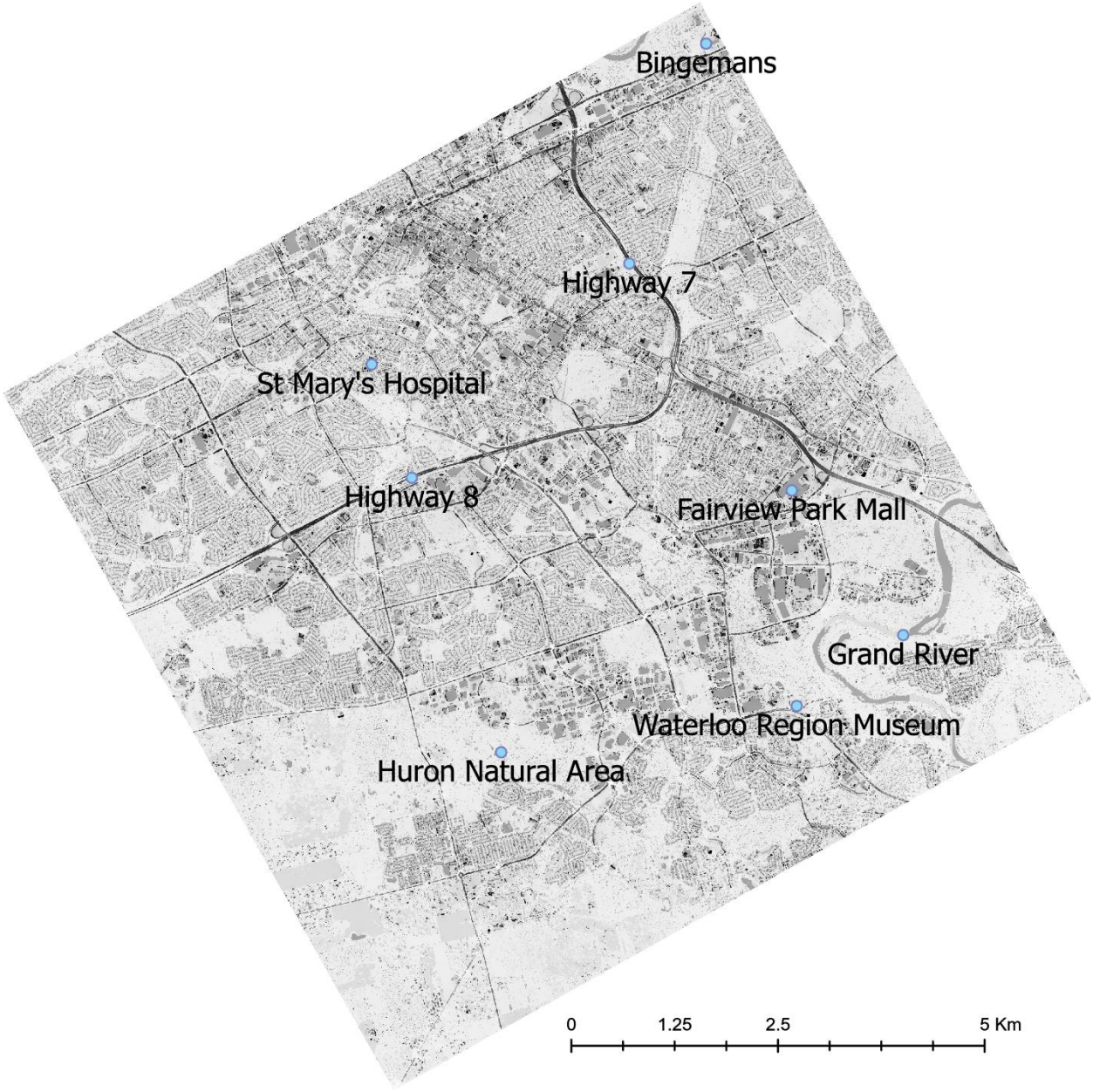


Figure 10 – Kitchener Bat Current Map with a 10% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

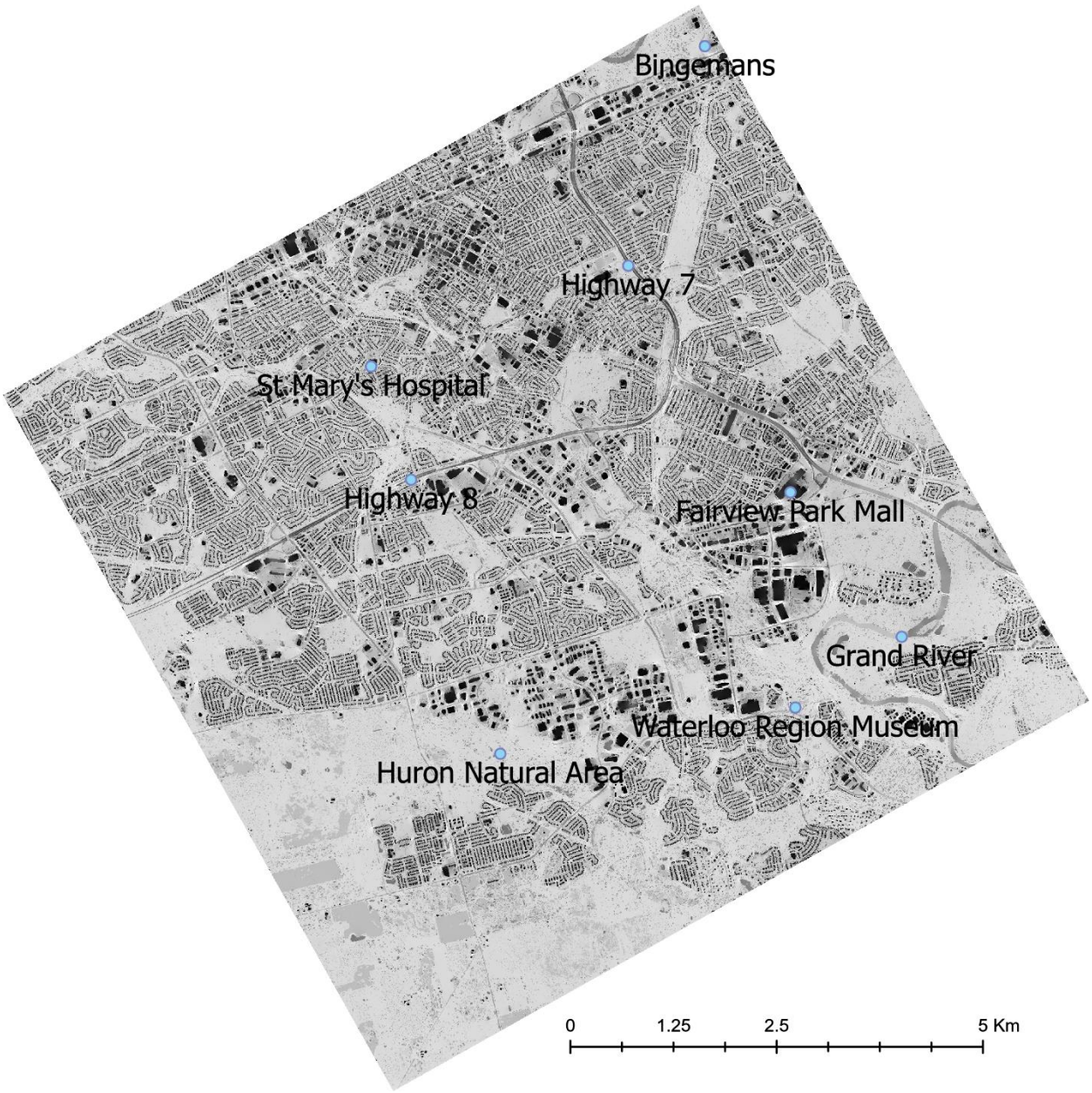


Figure 11 – Kitchener Deer Current Map with a 10% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

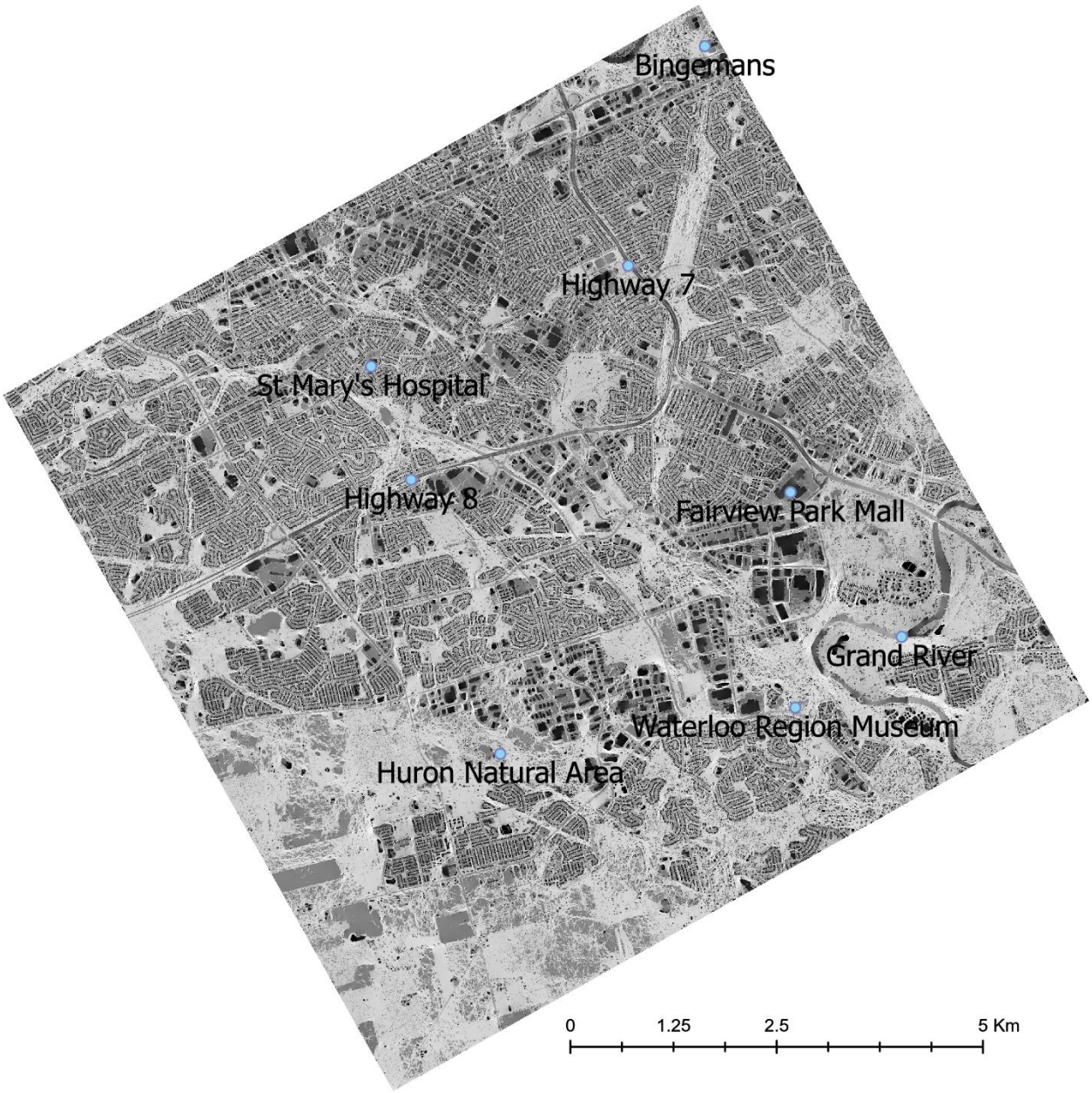


Figure 12 – Kitchener Shrew Current Map with a 10% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

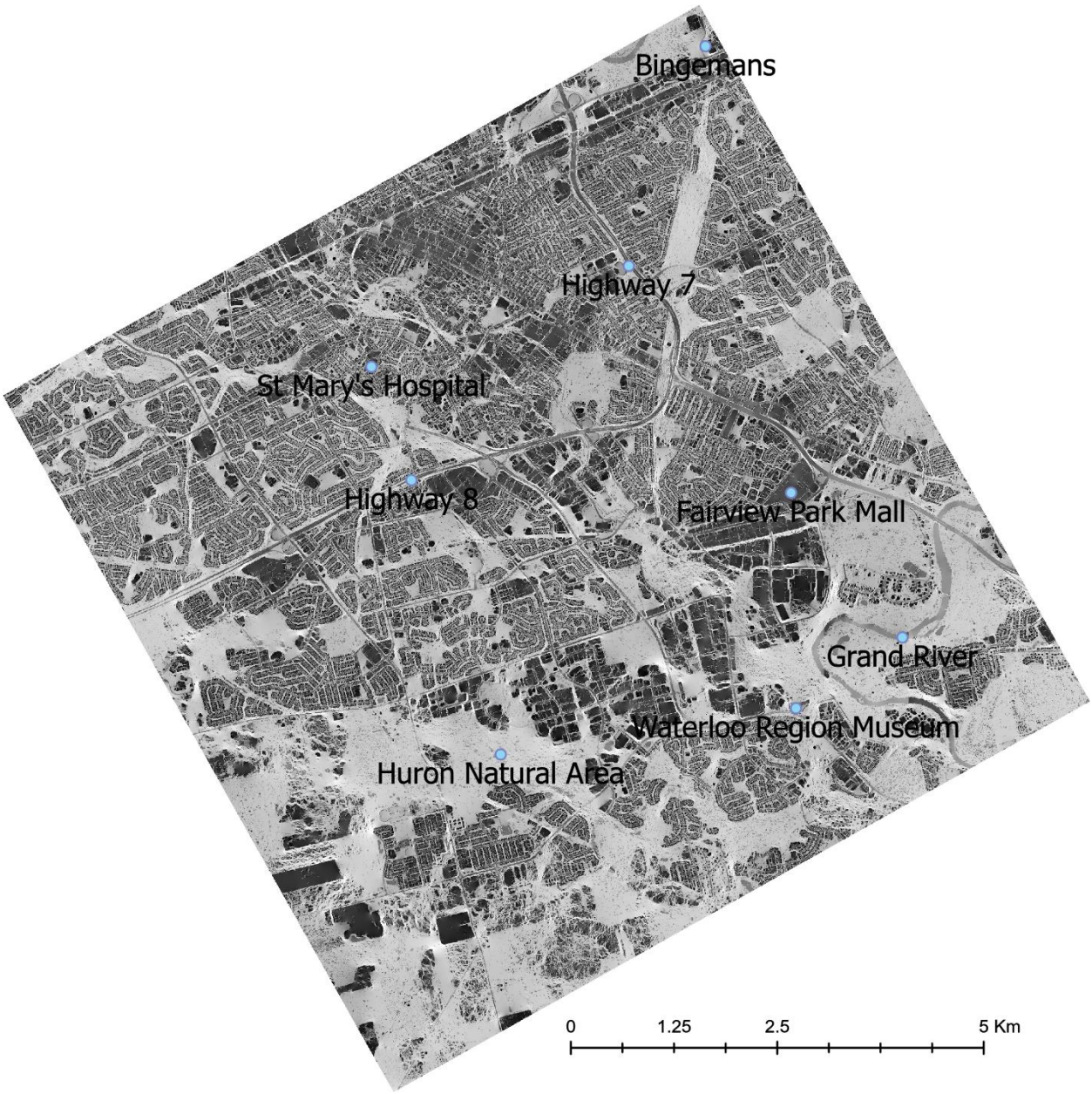


Figure 13 – Kitchener Eastern Garter Snake Current Map with a 10% Increase in Habitat - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

The visual differences between these two scenarios and the 2019 baseline were difficult to see, so difference maps were created between each scenario and the 2019 habitat connectivity map for each species. The bat connectivity difference maps for a five percent increase in habitat (Figure 14), showed small increases in habitat connectivity that were isolated around changed cells. Little change was present over the broader map. Deer difference maps showed more change (Figure 15), but it was still minor

increases that were isolated to areas of change. Shrews and snakes showed the strongest changes (Figure 16 and Figure 17). These effects were still mostly isolated to the areas immediately surrounding the change for shrews, but there was some habitat connectivity increase across the maps (especially in linear links) for snakes. In the urban to agricultural gradient, the effects were less isolated further from the downtown core. The increases were largely in urban green spaces while sometimes marginally decreasing the need for habitat connectivity in industrial areas by creating better habitat nearby. These areas are the best place to focus efforts in urban areas when resources exist to perform restorations. Built areas like roads, buildings and to a lesser extent the Grand River and other waterways showed extremely little change. Hard barriers tended to remain unchanged with habitat increases, though some minor barriers (like small roads) did show some change with increased connectivity near them, but not many. Hard barriers existing in areas where overall connectivity is increased may pose a threat if animals start to interact with them (e.g. cross roads). The difference maps for the ten percent scenarios (Figure 18, Figure 19, Figure 20 and Figure 21) were similar to the five percent but with more locations of change, changes a few cells further from the changed cell and a stronger increase in habitat connectivity across the map, but changes remained small.

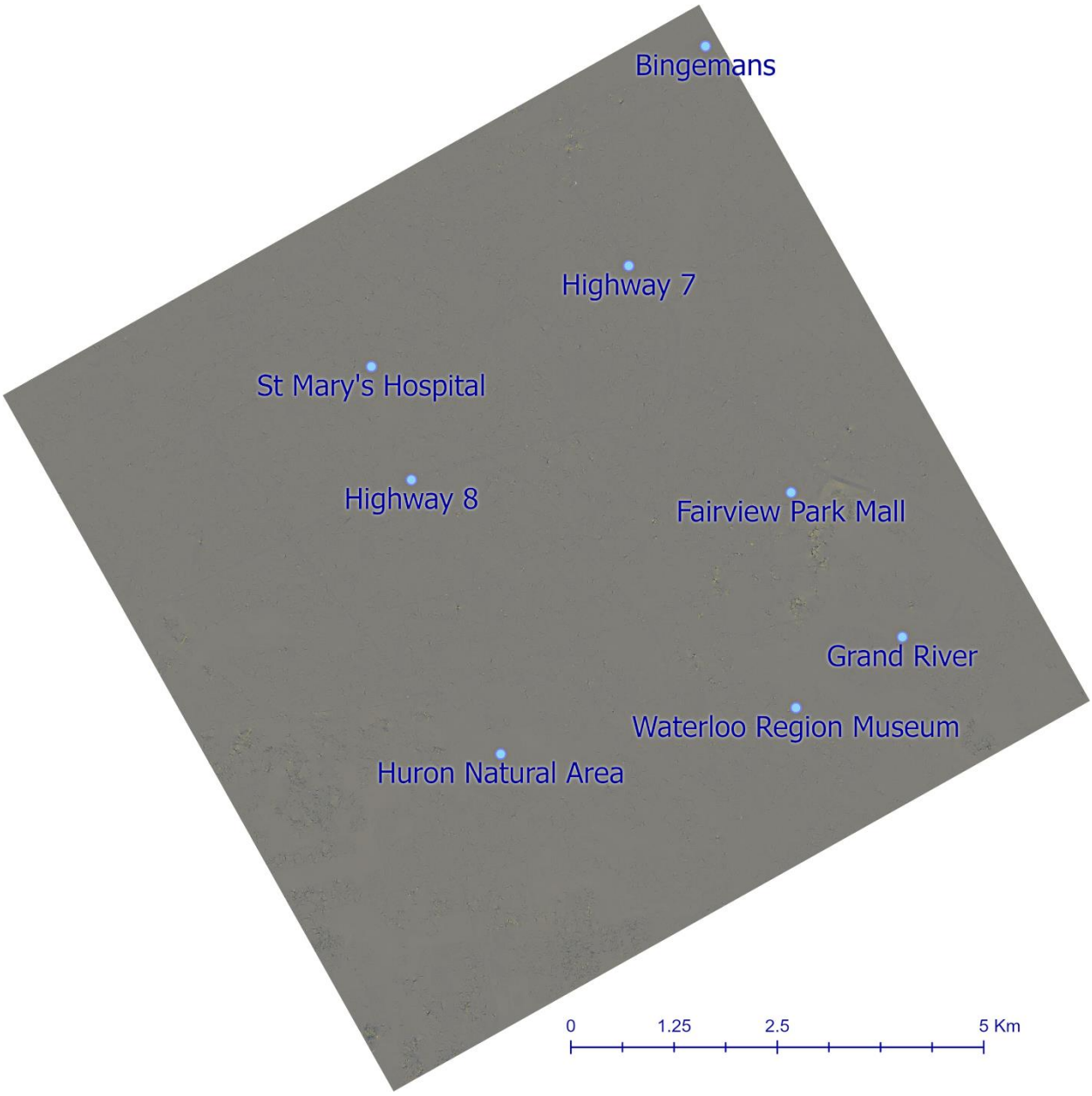


Figure 14 – Kitchener Bat Current Map 2019 Minus the Kitchener Bat Current Map with a 5% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

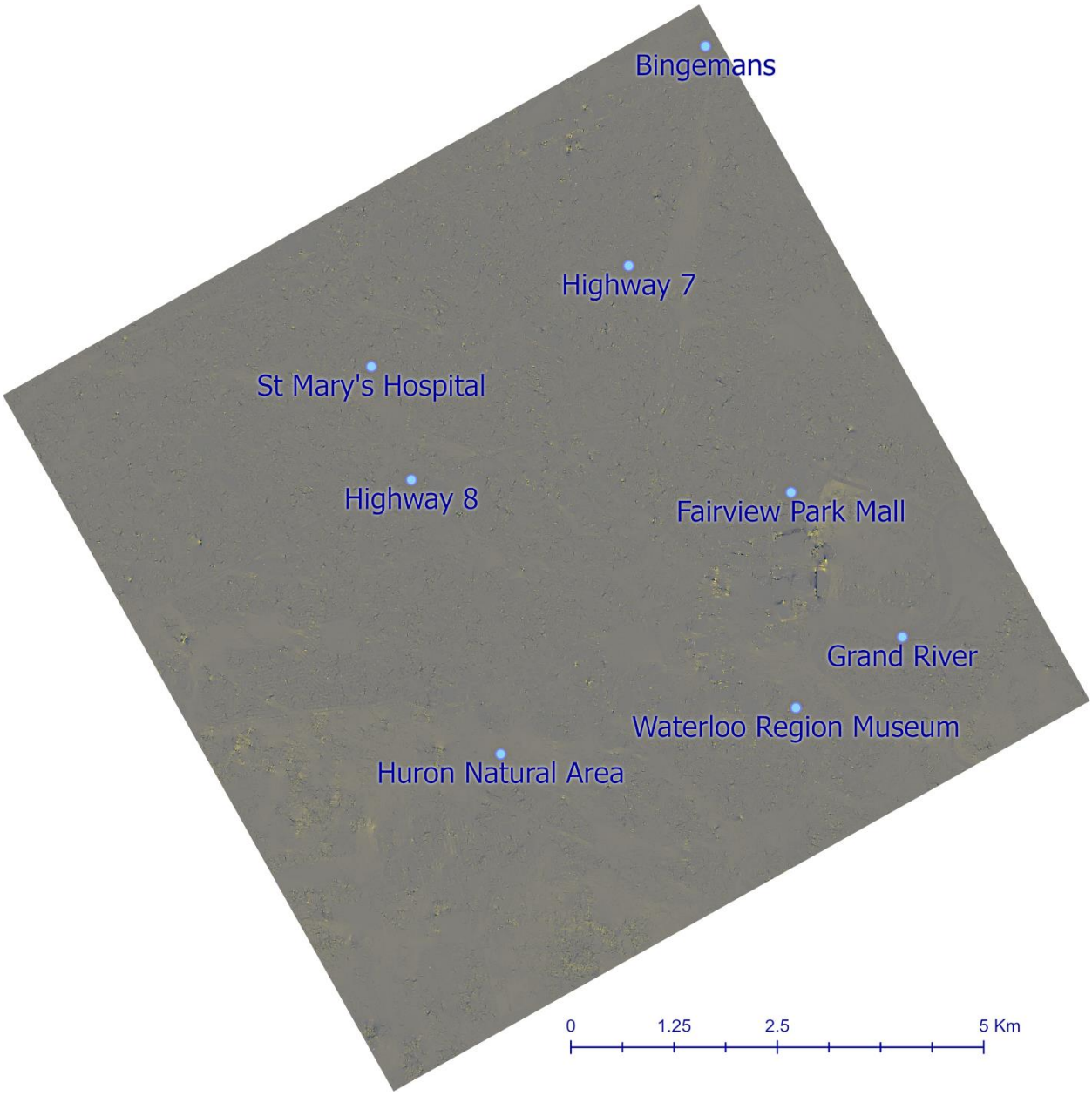


Figure 15 – Kitchener Deer Current Map 2019 Minus the Kitchener Deer Current Map with a 5% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

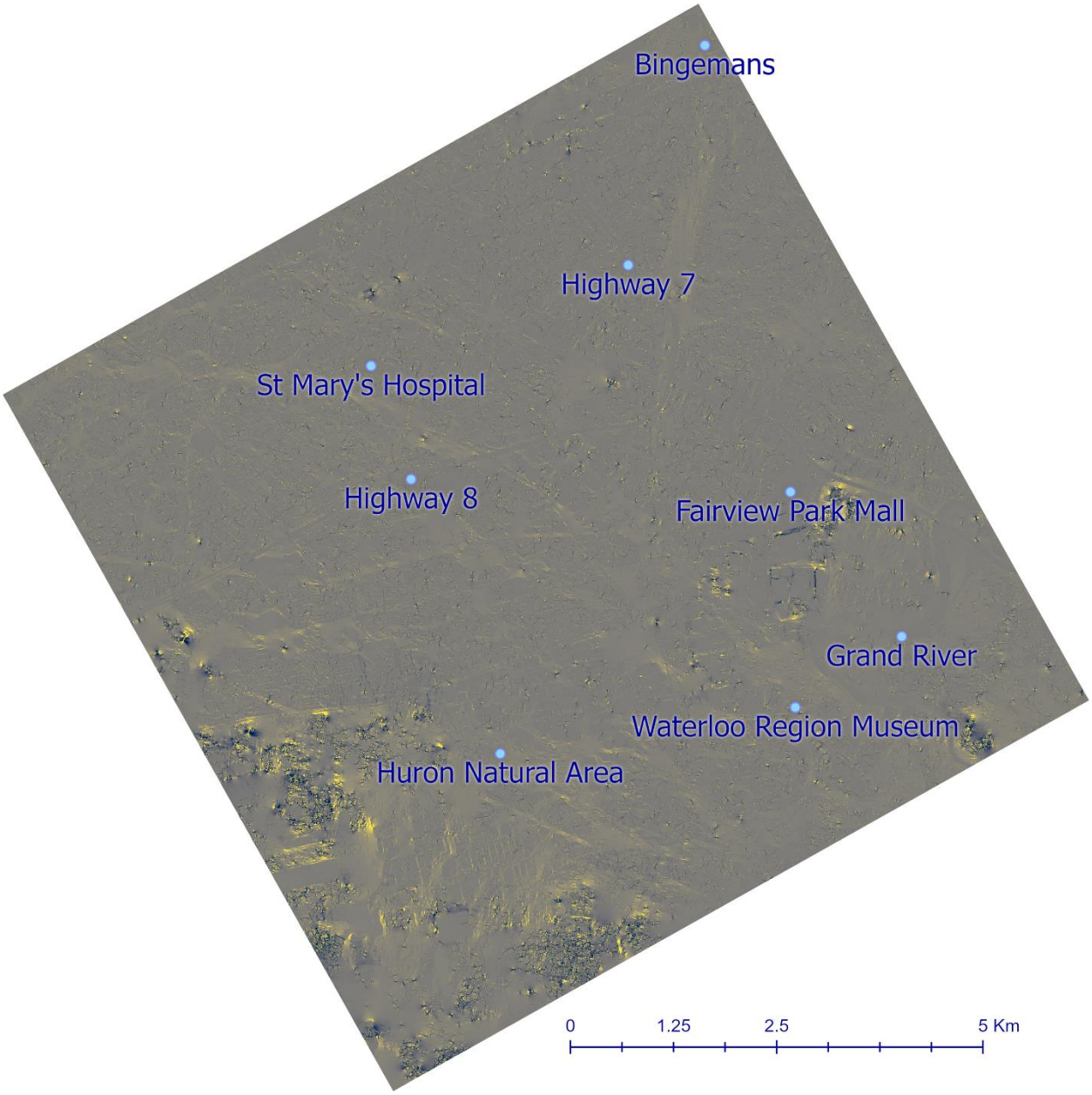


Figure 16 – Kitchener Shrew Current Map 2019 Minus the Kitchener Shrew Current Map with a 5% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

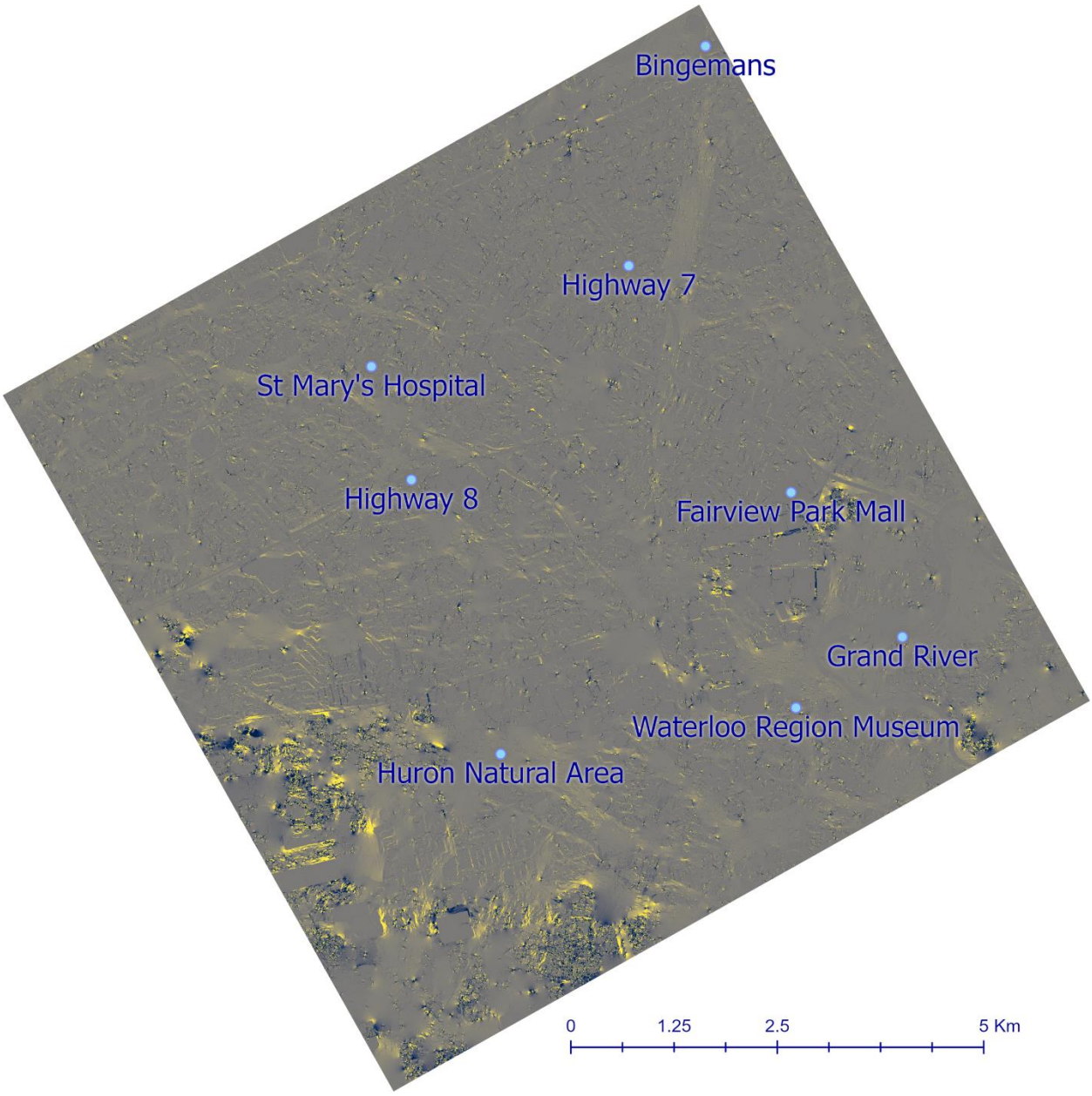


Figure 17 – Kitchener Eastern Garter Snake Current Map 2019 Minus the Kitchener Eastern Garter Snake Current Map with a 5% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

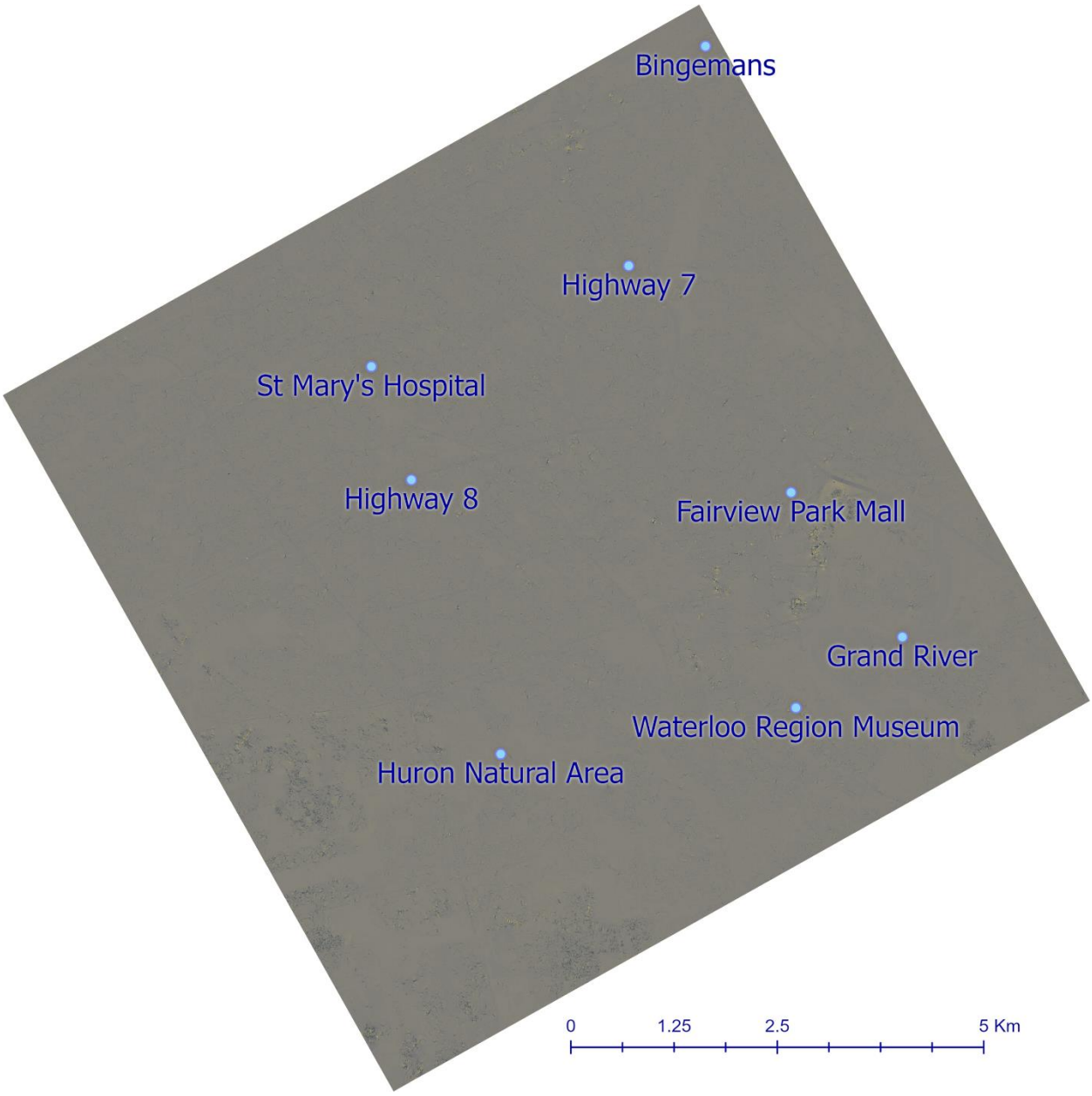


Figure 18 – Kitchener Bat Current Map 2019 Minus the Kitchener Bat Current Map with a 10% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

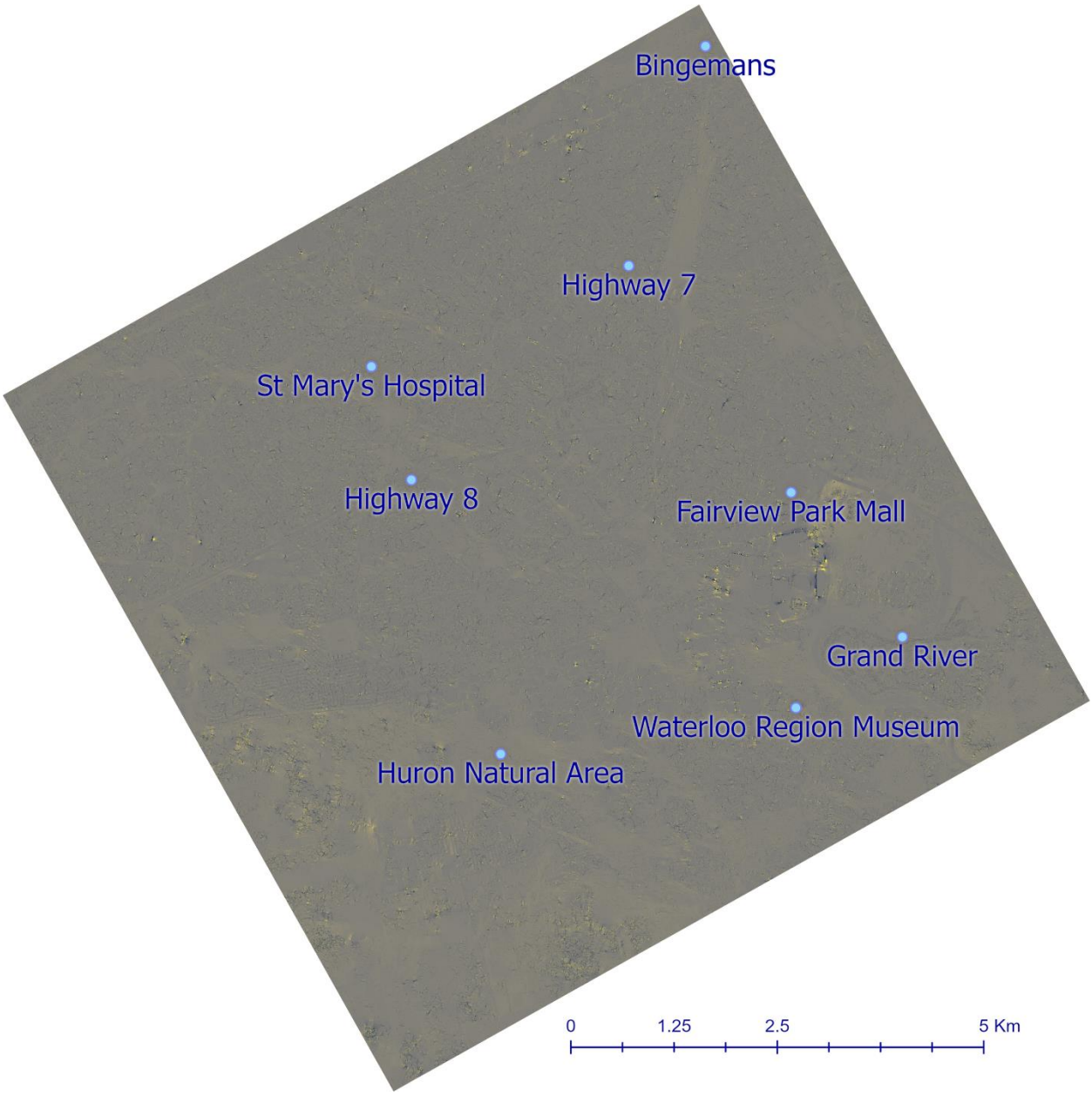


Figure 19 – Kitchener Deer Current Map 2019 Minus the Kitchener Deer Current Map with a 10% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

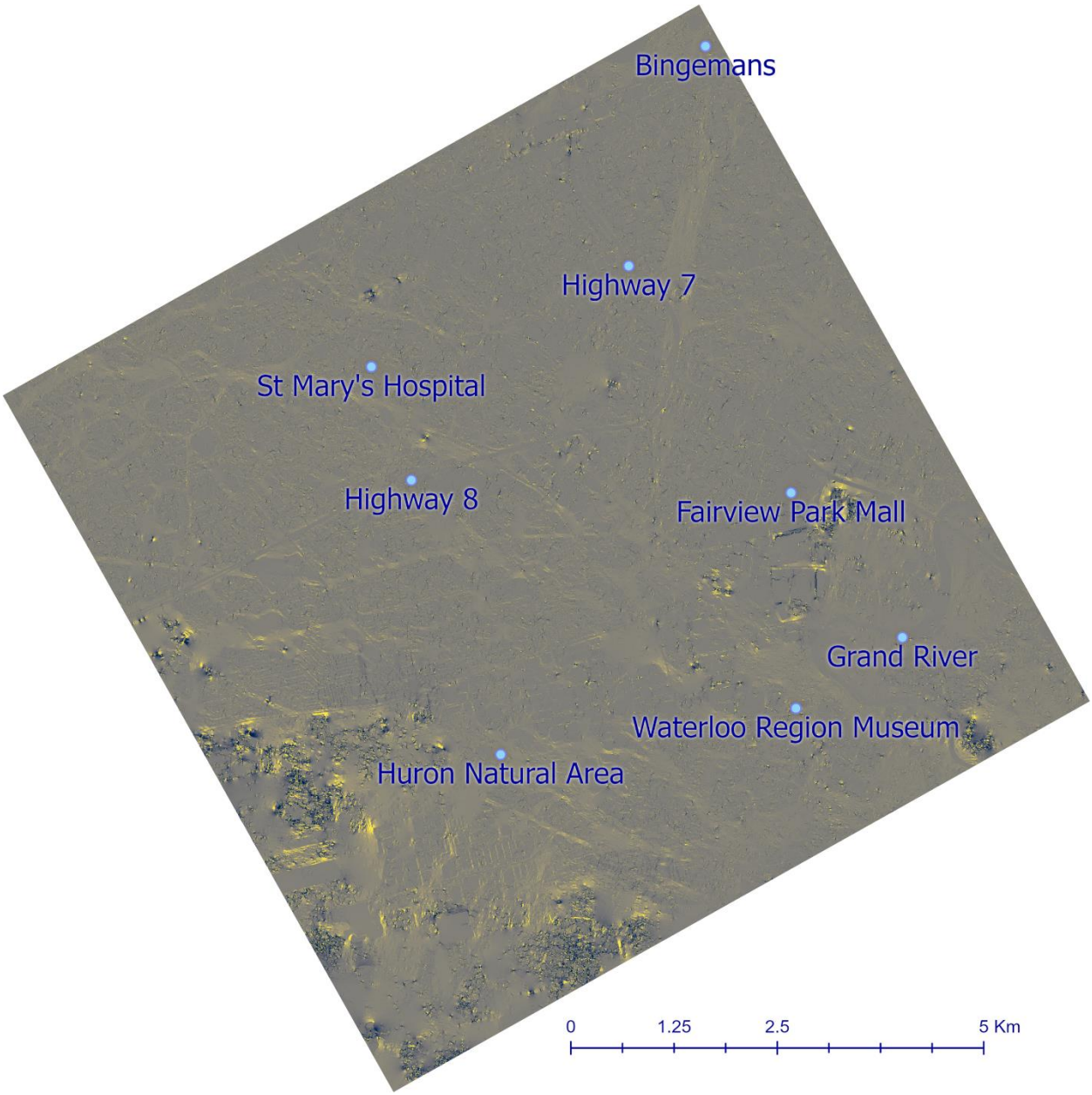


Figure 20 – Kitchener Shrew Current Map 2019 Minus the Kitchener Shrew Current Map with a 10% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

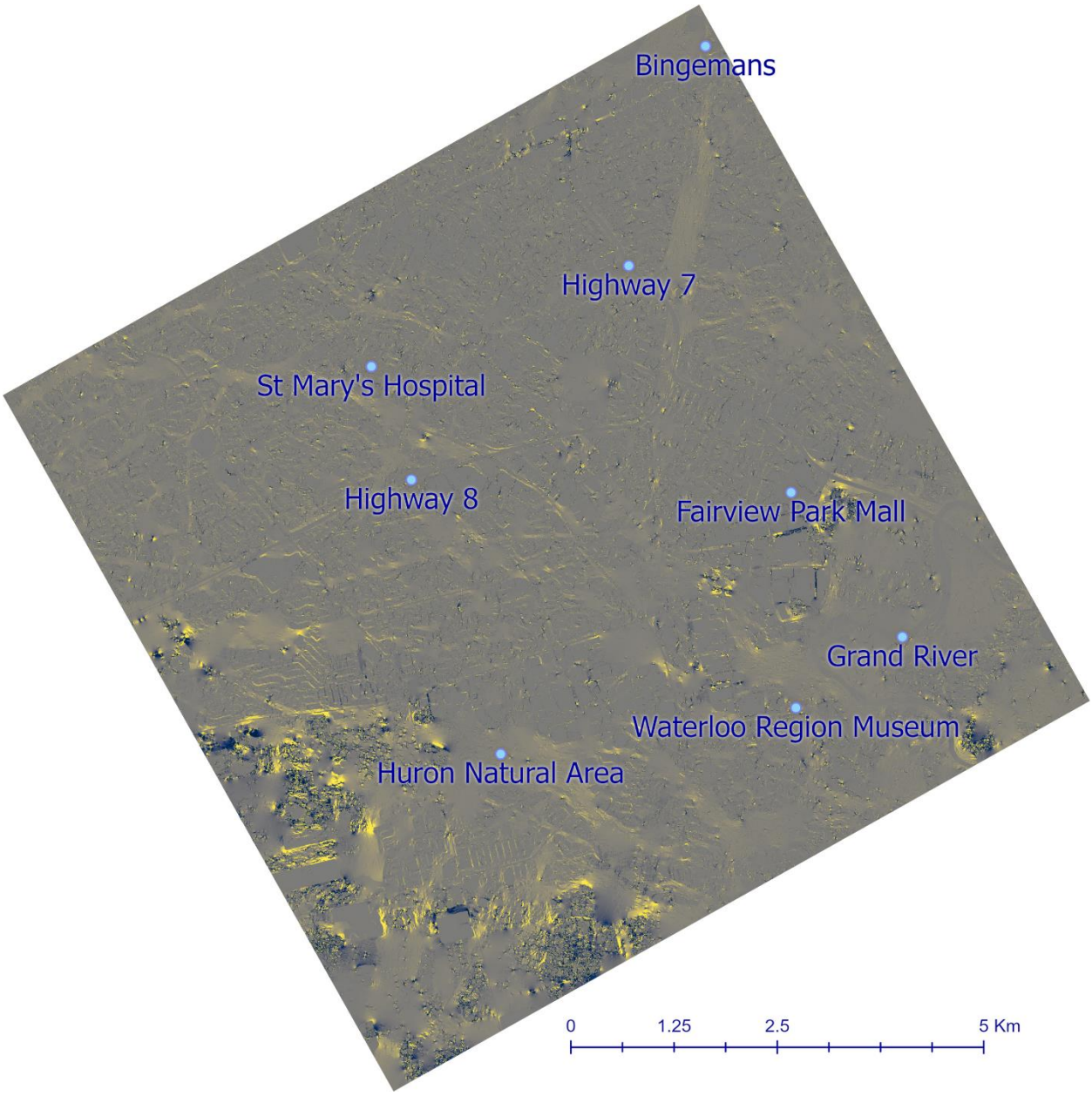


Figure 21 – Kitchener Eastern Garter Snake Current Map 2019 Minus the Kitchener Eastern Garter Snake Current Map with a 10% Increase in Habitat - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

Resistance values represent overall connectivity across the maps and were computed for the east-west and north-south run for each scenario and species (Table 6, Table 7, Table 8 and Table 9). Changes in resistance values between the habitat increase scenarios and the 2019 connectivity map for all species were small and likely within the error bounds of the methodology. The small differences between

resistance values between the habitat increase scenarios and the 2019 connectivity map reiterate how small the connectivity changes are a five to ten percent increase in habitat. Changes noted from the difference maps are scaled up to show what the differences were but the actual change from these was very small.

Table 6 - Resistance Value for Bats for all Scenarios

Scenario	East West Total Resistance	North South Total Resistance	East West Resistance % Difference	North South Resistance % Difference
2019	0.52401	0.52553	0.00%	0.00%
Habitat 5%	0.52396	0.52548	-0.01%	-0.01%
Habitat 10%	0.52391	0.52544	-0.02%	-0.02%
Building	0.55343	0.55411	5.62%	5.44%

Table 7 - Resistance Value for Deer for all Scenarios

Scenario	East West Total Resistance	North South Total Resistance	East West Resistance % Difference	North South Resistance % Difference
2019	0.74322	0.75828	0.00%	0.00%
Habitat 5%	0.74314	0.75819	-0.01%	-0.01%
Habitat 10%	0.74305	0.75811	-0.02%	-0.02%
Building	0.97209	0.96231	30.79%	26.91%

Table 8 - Resistance Value for Shrews for all Scenarios

Scenario	East West Total Resistance	North South Total Resistance	East West Resistance % Difference	North South Resistance % Difference
2019	1.04123	1.07357	0.00%	0.00%
Habitat 5%	1.04023	1.07264	-0.10%	-0.09%
Habitat 10%	1.03923	1.07171	-0.19%	-0.17%
Building	1.37560	1.38185	32.11%	28.72%

Table 9 - Resistance Value for Snakes for all Scenarios

Scenario	East West Total Resistance	North South Total Resistance	East West Resistance % Difference	North South Resistance % Difference
2019	1.24894	1.32718	0.00%	0.00%
Habitat 5%	1.24775	1.32607	-0.10%	-0.08%
Habitat 10%	1.24654	1.32496	-0.19%	-0.17%
Building	1.61689	1.66678	29.46%	25.59%

7.2.2 Buildings

The third scenario increased building coverage by 83% to account for the projected population levels but maintain population density (Figure 22, Figure 23, Figure 24 and Figure 25). This represents a worst-case scenario, as though the population is set to increase, plans to accommodate it focus on increasing population density to minimize the impact. For all four species this scenario showed more change in habitat connectivity than either of the habitat increases. The building scenarios changed the total resistance values from 2019 by 5-33% whereas the habitat increases changed the resistance values by less than 0.2% (Table 6, Table 7, Table 8 and Table 9). This was expected as more cells were changed. The change involved an increased number of barriers, with each new building being added being a new barrier (especially in the urban and suburban areas). New buildings that were placed in areas like green spaces and agricultural areas are unlikely to occur as intensification is mainly planned in already built areas. This decreased habitat connectivity across the map for deer, shrews and snakes but only marginally for bats. These differences were mainly in the suburban areas as urban areas were already too dense to have much infill. This created barriers between suburban houses that had previously been areas of comparatively high habitat connectivity.

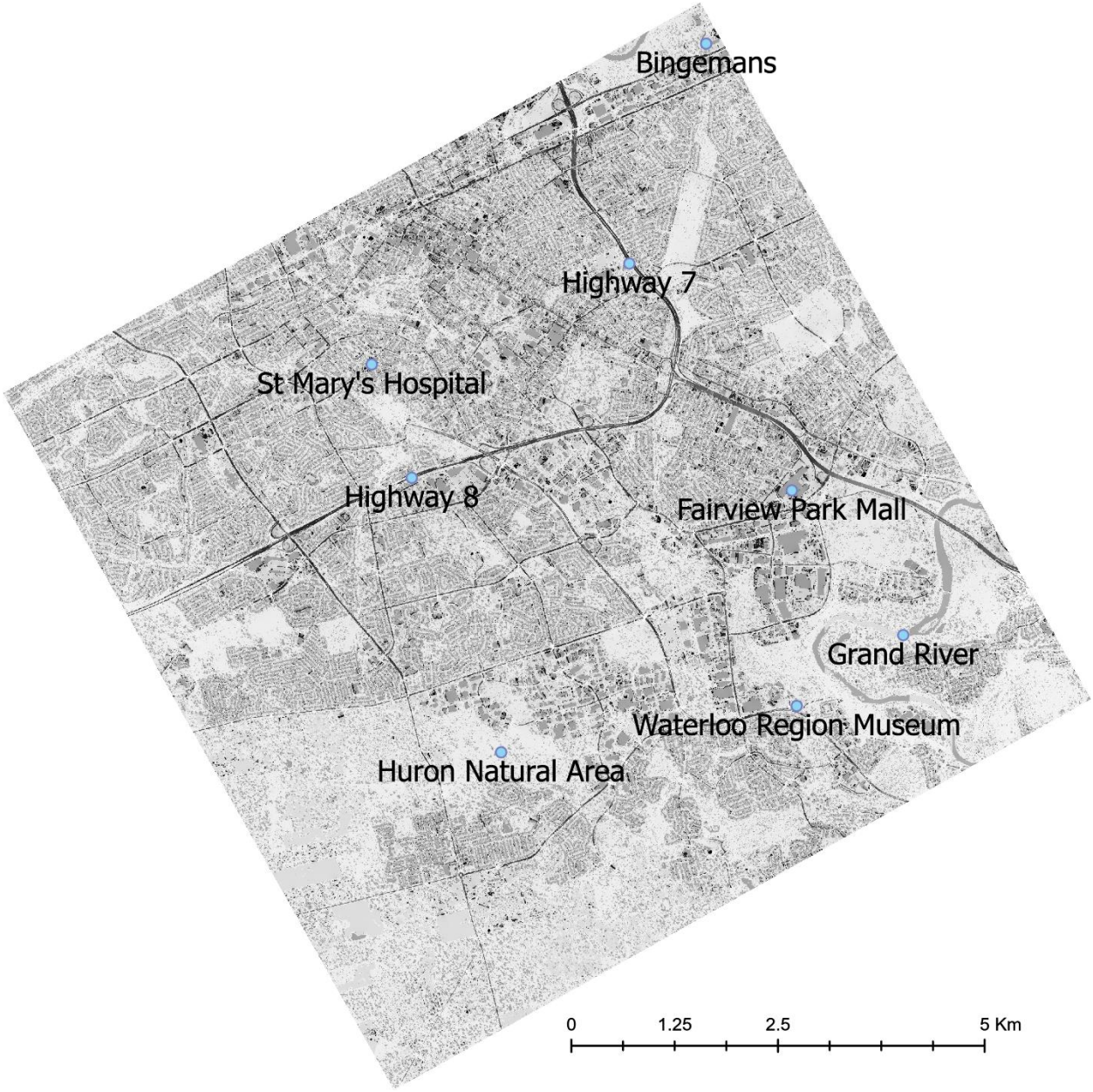


Figure 22 – Kitchener Bat Current Map with an 83% Increase in Building Coverage - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

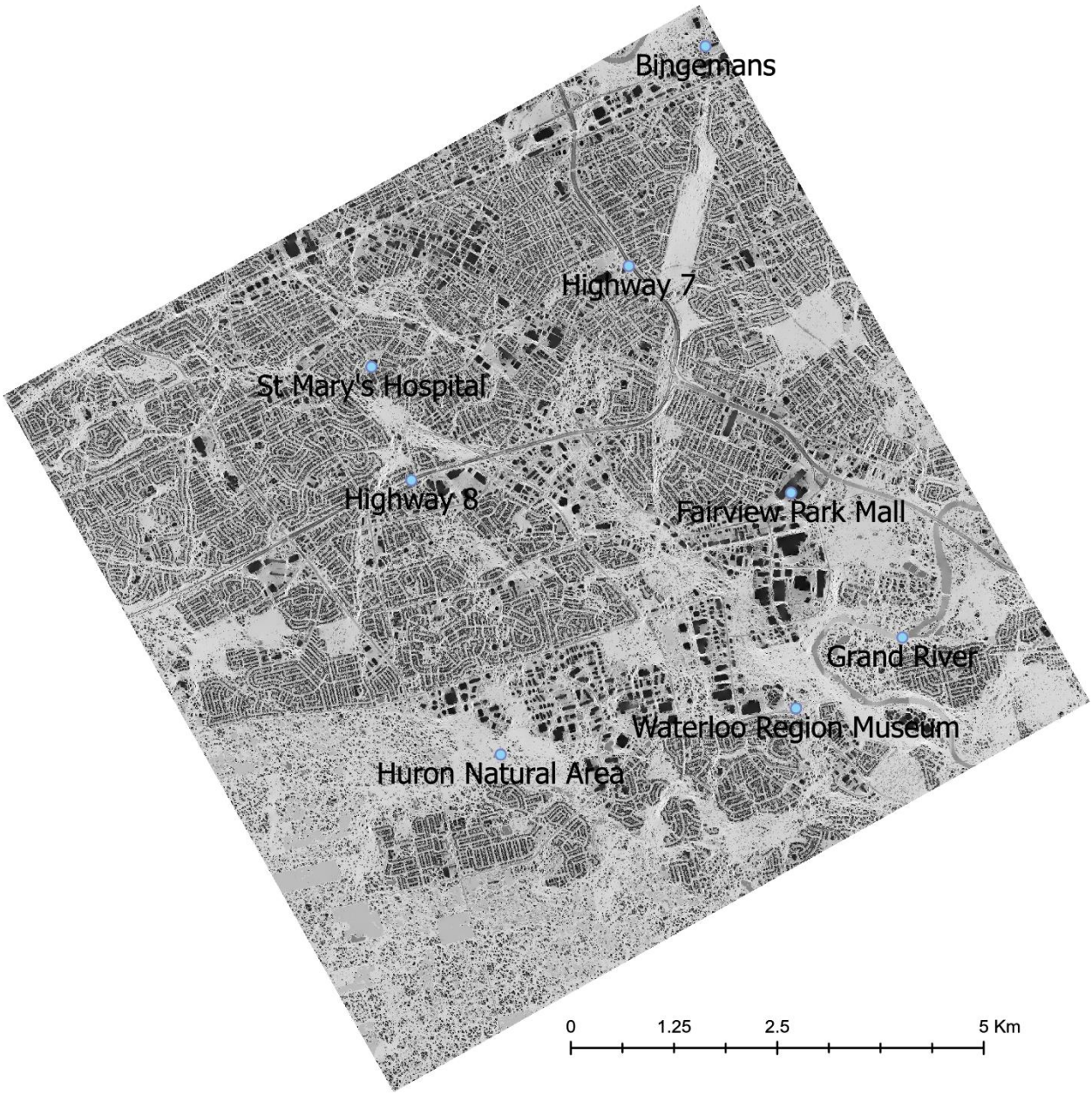


Figure 23 – Kitchener Deer Current Map with an 83% Increase in Building Coverage - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

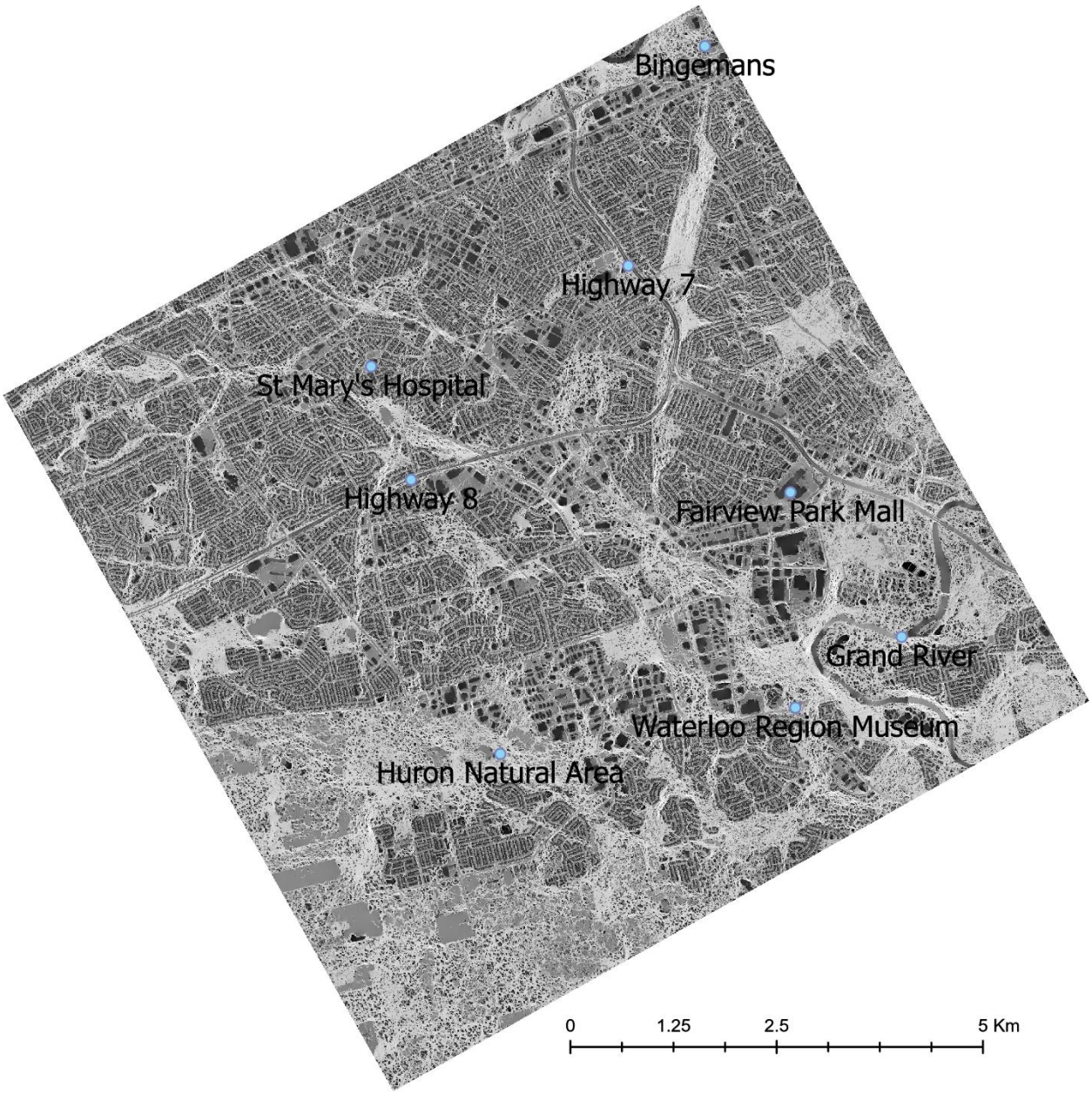


Figure 24 – Kitchener Shrew Current Map with an 83% Increase in Building Coverage - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

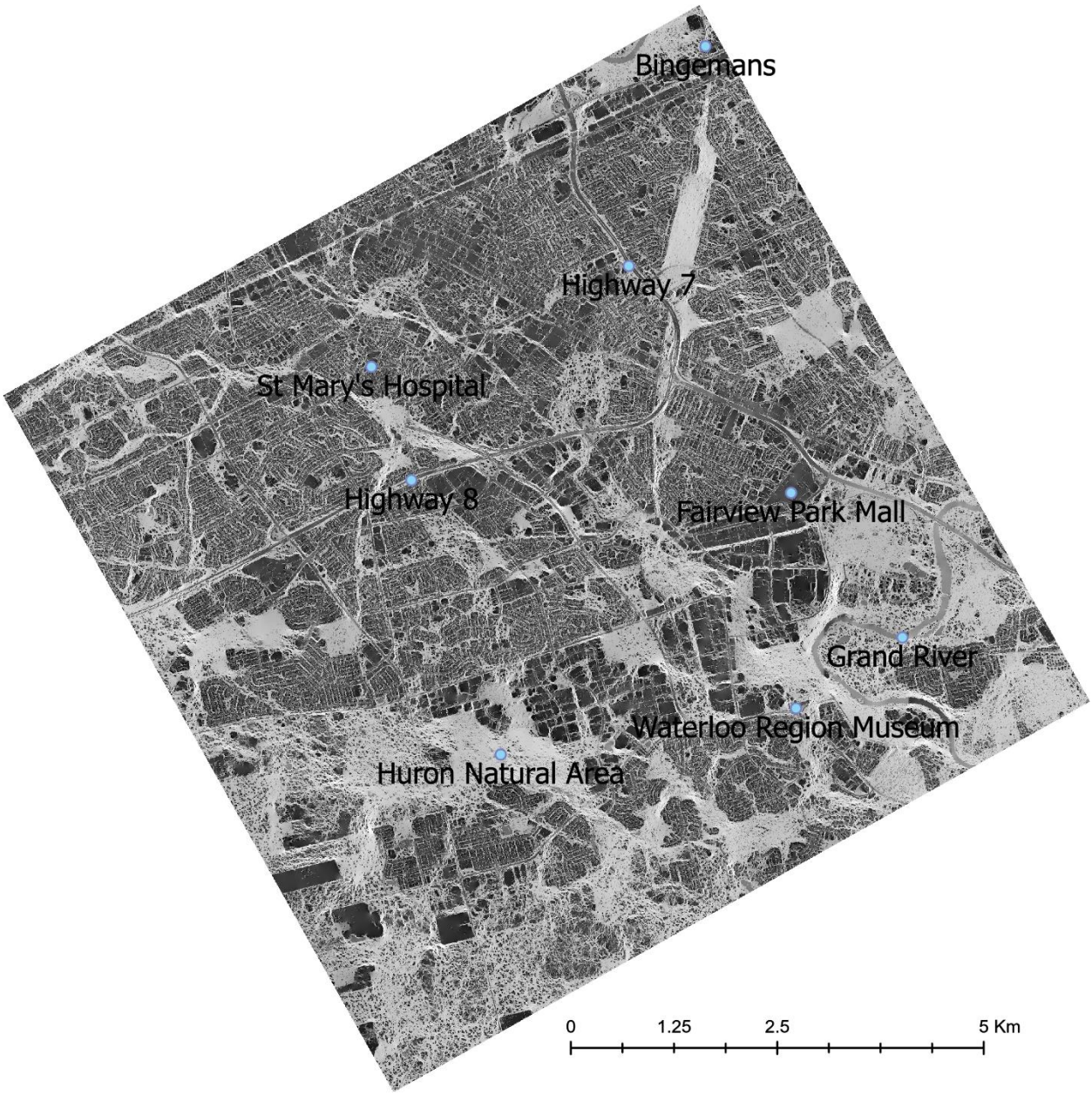


Figure 25 – Kitchener Eastern Garter Snake Current Map with an 83% Increase in Building Coverage - This map shows a stretched gradient of logged current value with black being the lowest current and white being the highest.

Difference maps were created between each species building scenario and the 2019 connectivity map (Figure 26, Figure 27, Figure 28 and Figure 29). In addition to the increase in barriers from buildings, habitat connectivity decreased around pre-existing buildings and major roads, increased in green spaces and had little change for other road types, buildings and waterways. The increased relative habitat

connectivity in large open spaces shows a growing need for these species to help maintain urban animals with densification.

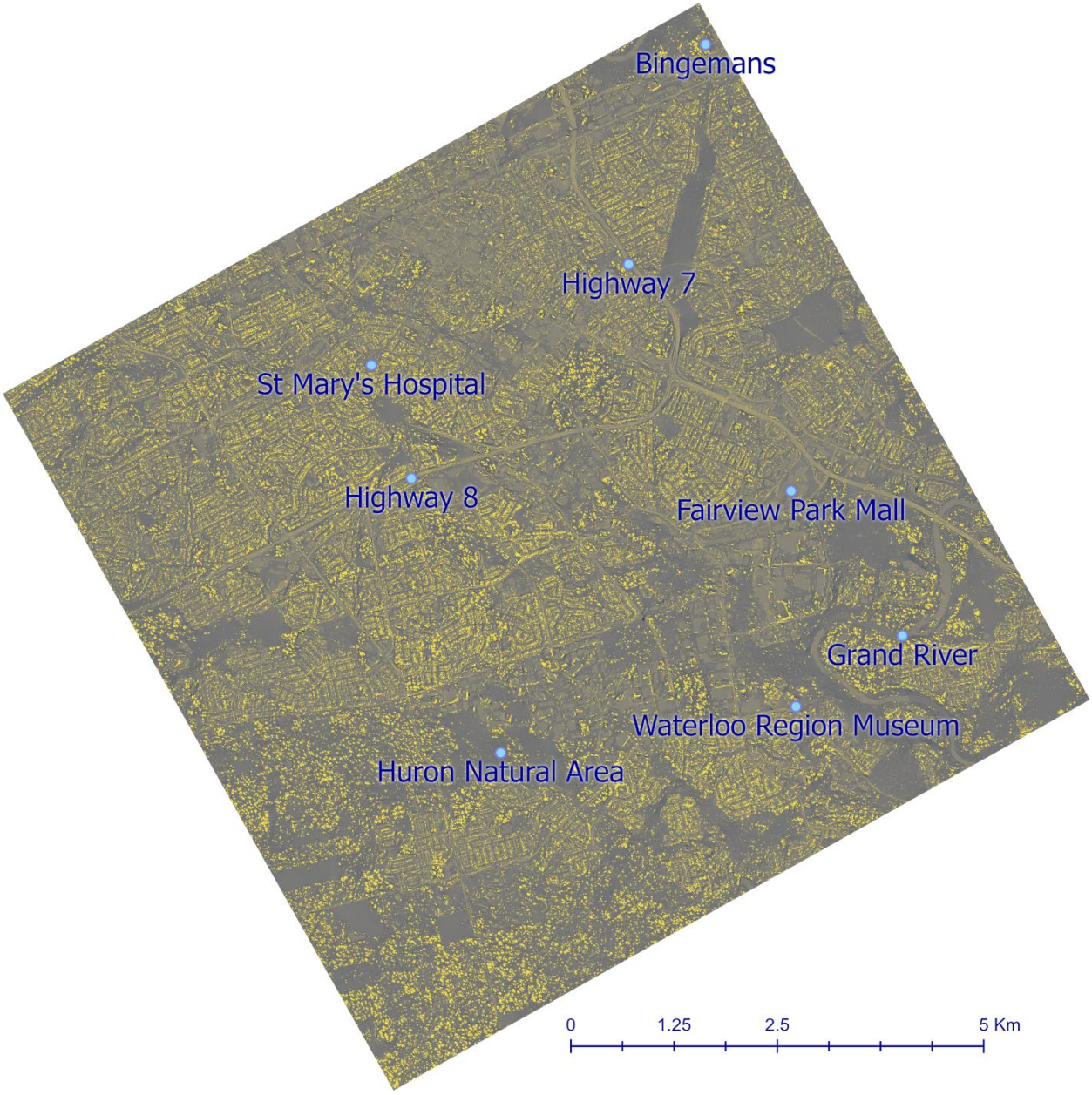


Figure 26 – Kitchener Bat Current Map 2019 Minus the Kitchener Bat Current Map with an 83% Increase in Building Coverage - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

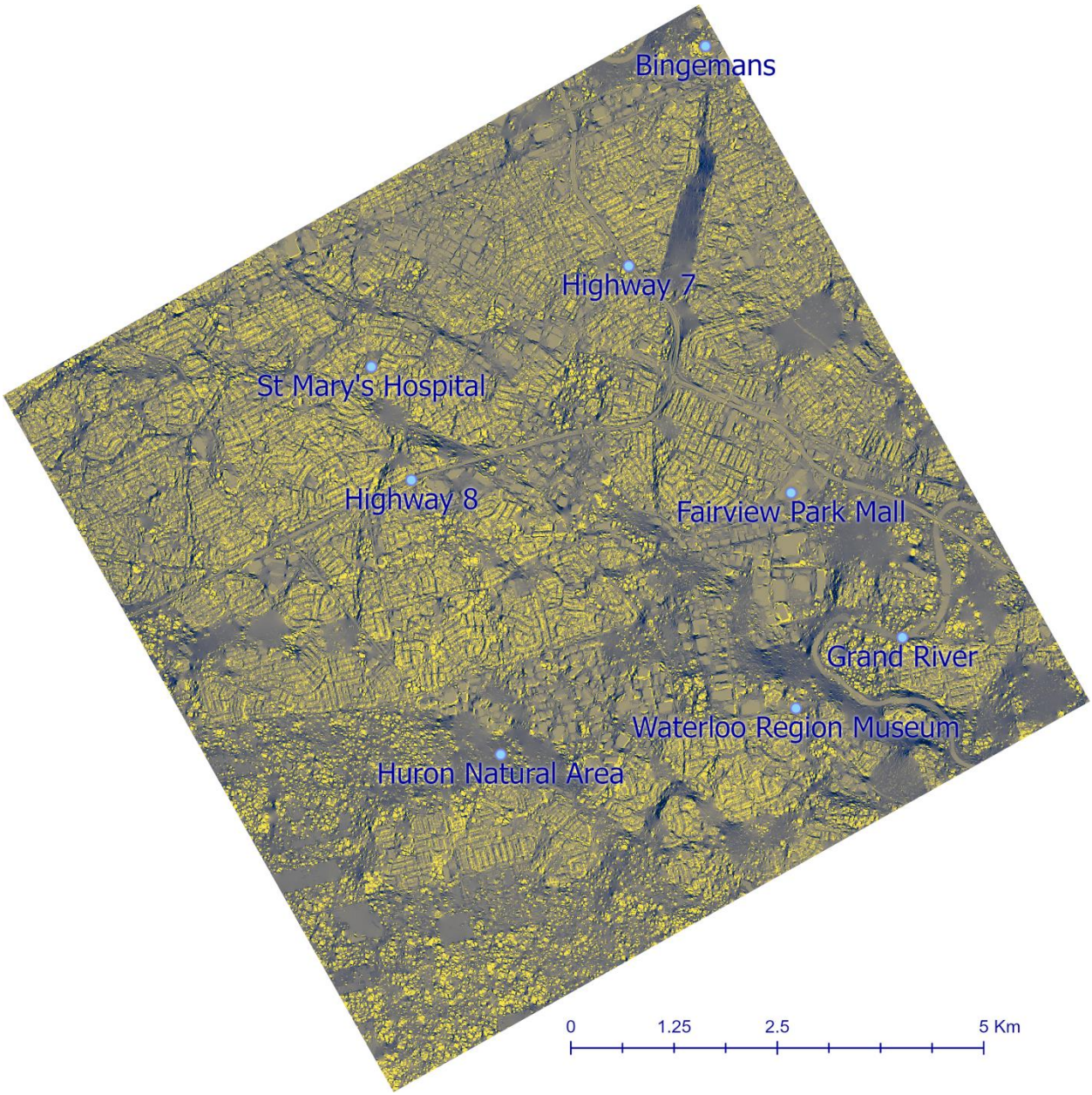


Figure 27 – Kitchener Deer Current Map 2019 Minus the Kitchener Deer Current Map with an 83% Increase in Building Coverage - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

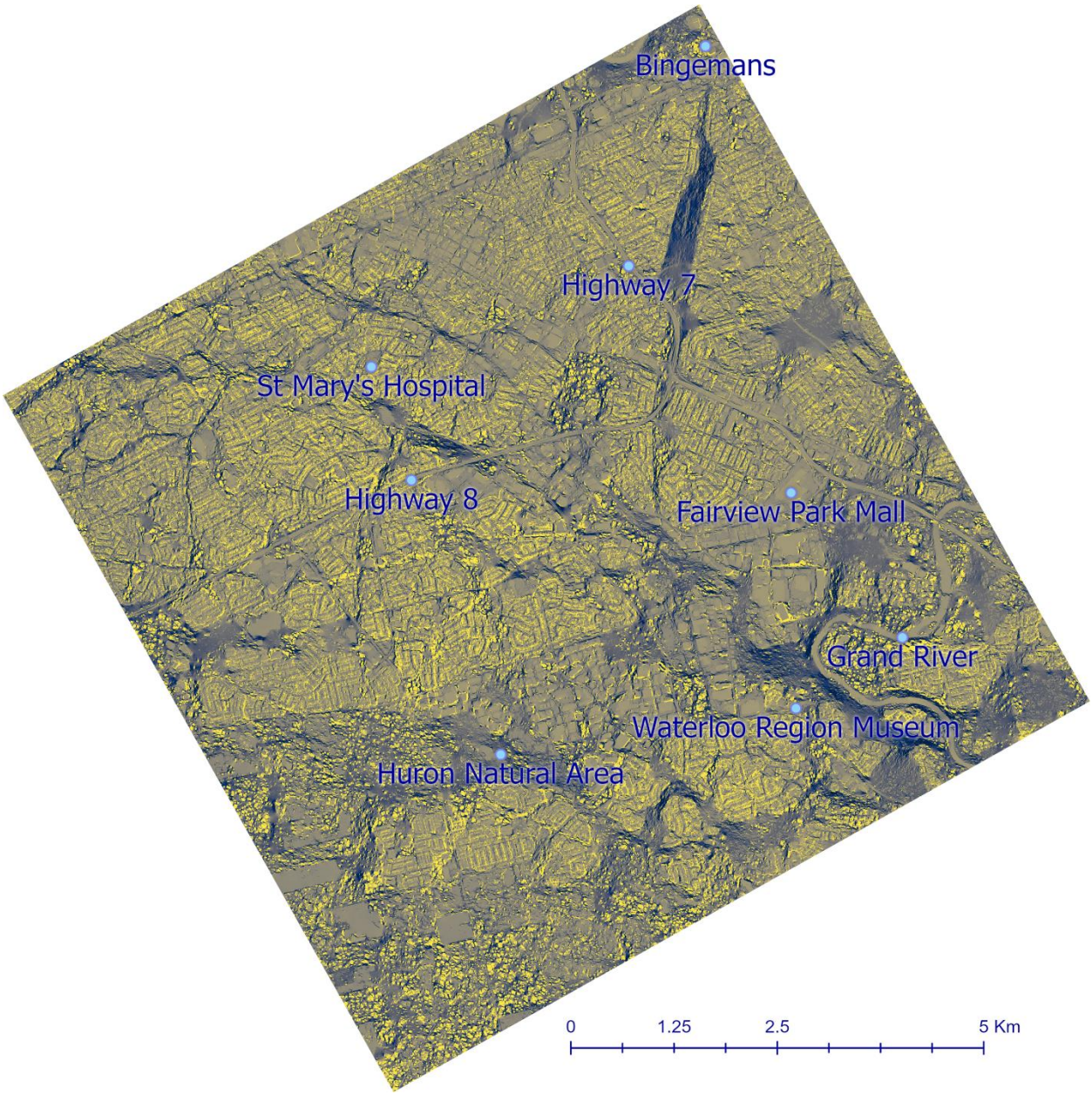


Figure 28 – Kitchener Shrew Current Map 2019 Minus the Kitchener Shrew Current Map with an 83% Increase in Building Coverage - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

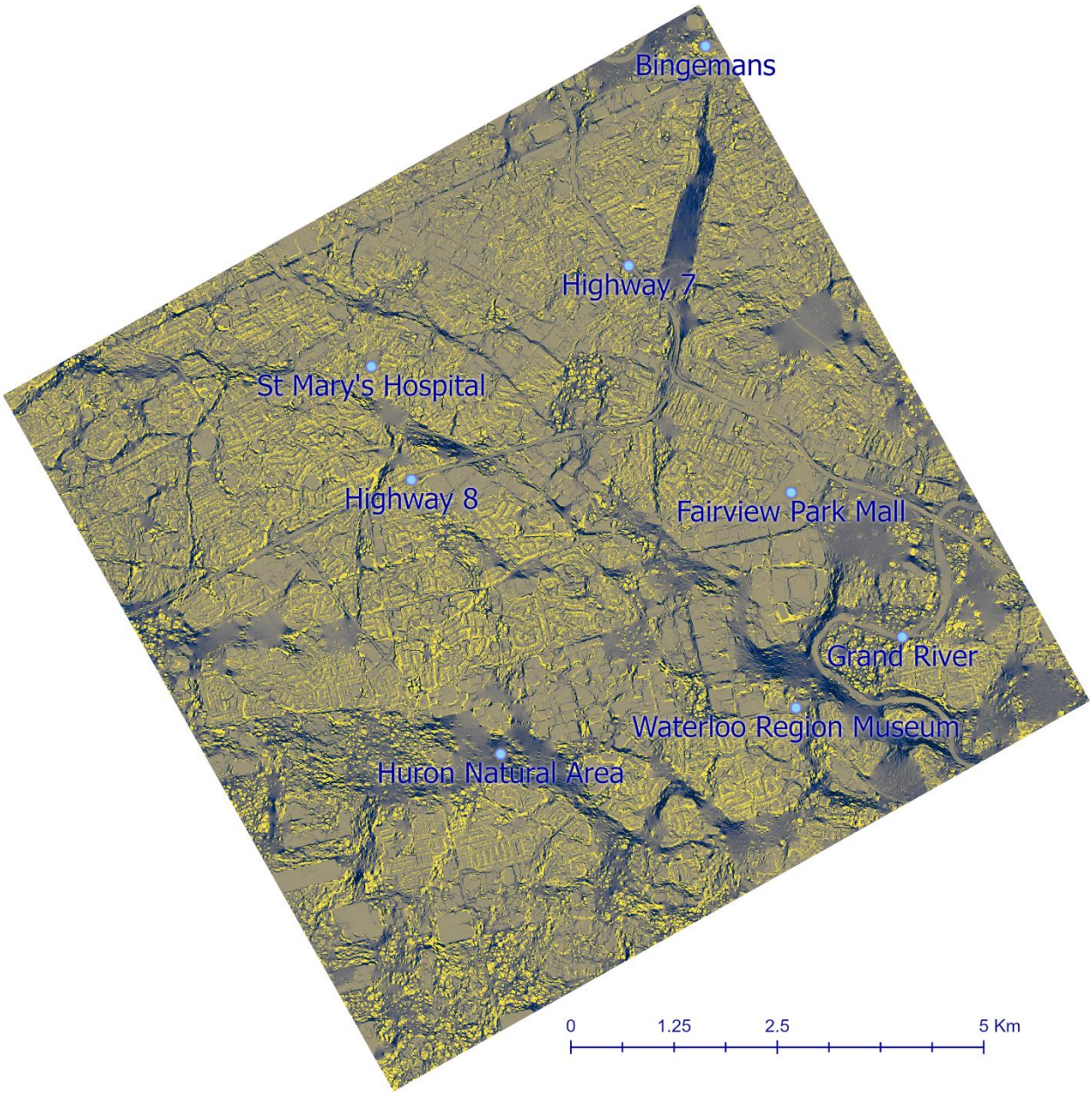


Figure 29 – Kitchener Eastern Garter Snake Current Map 2019 Minus the Kitchener Eastern Garter Snake Current Map with an 83% Increase in Building Coverage - This map shows a gradient of change where blue is an increase in current from the 2019 case, yellow is a decrease and grey is neutral. These values have been stretched to better identify areas of change.

Changes in resistance values (Table 6, Table 7, Table 8 and Table 9) were greater with the increased building scenarios than either of the increased habitat scenarios with all differences being greater than 0.2. The change in resistance values for deer, shrew and snakes was all within a 25-33% change from the 2019 resistance values. These numbers represent a sizeable change if the number of buildings increases by this

much as the population increases. Bats had smaller changes only featuring a 5% increase over 2019 values. This was expected as bats can fly giving them the ability to move over buildings and reducing the effects of these barriers. This change does still meaningfully reduce the amount of habitat connectivity for the species.

7.3 Discussion

The isolated effects of changes from increasing the habitat amount by five to ten percent showed that feasible habitat increases did not have meaningful impacts on overall connectivity. Effects on connectivity were strongest for small animals with limited movement, so they should be the focus for urban restoration. Lack of change in connectivity should not be taken to mean that additional habitat is not beneficial. There was so little habitat that these animals are unlikely to be able to move long distances through this matrix, and any additional increase in quantity or quality of habitat will provide more area for them to live even if it would not increase habitat connectivity.

The scenarios developed showed little improvement to connectivity with small habitat increases, but a larger effect from uncontrolled densification. Densification is likely to exacerbate urban problems for species both by decreasing available habitat and by decreasing connectivity between habitats. It is important moving forward to minimize the impact of this development by densifying existing areas first and maintaining habitat areas that still exist. Planning should focus on mitigating impacts of densification rather than on creating new green areas. The addition of new green areas could cause positive local changes, which add some value beyond what was shown using this methodology. This scenario should model the worst case, as city plans include population density increases to help decrease the effects of increased building density, but effects of densification on habitat connectivity of local fauna should still be considered in city plans as they have the potential to affect fauna.

These models provided valuable information for planning for Kitchener Ontario. Scenarios based on projected densification or restoration within other cities in Southern Ontario may provide benefit for urban planners.

Chapter 8 Conclusions

8.1 Overview

The urban environment affected all four species differently. Habitat connectivity for each species was negatively impacted by high densities of urbanization; however, urban greenspaces provided opportunity to connect residual habitat. Greenspaces in the urban core tend to be small, far apart and highly maintained, but the suburban area has lower building density and more greenspaces allowing for more habitat connectivity. Greenspaces in both locations are important for habitat connectivity so should be maintained, enhanced and protected where possible to support urban wildlife, especially as the city densifies. Most areas contain some hard barriers, like buildings, roads and to a lesser degree large open waterways. These barriers tend to affect snakes and shrews more than deer and bats, as it is easier for them to avoid these areas. Care must be taken to minimize the impacts of built areas as densification occurs, to promote the utility of urban space for habitat connectivity.

Current maps showed that habitat connectivity was generally best for bats, with deer having less connectivity but still having good connectivity in some spaces. Shrews and snakes had low habitat connectivity. This matches the habitat suitability values (Table 10), with snakes and shrews having more low scoring landscape types than deer and bats. Habitat connectivity increased with increasing mobility of the species. Resistance values suggested a similar ranking, with bats and deer having more habitat connectivity than shrews and snakes (Table 11).

Table 10 - Habitat Suitability Values - Species were assigned habitat values from 0.1-1.0 based on desirability of the habitat for the species according to the rubric in 2.4 Animal Habitat Preference Data and Transformation

		Species			
		Snake	Shrew	Deer	Bat
Habitat	Roads - Category 4	0.1	0.1	0.1	0.2
	Roads - Category 3	0.1	0.2	0.2	0.2
	Roads - Category 2	0.1	0.2	0.3	0.4
	Buildings	0.1	0.1	0.1	0.3

Roads - Category 1	0.2	0.2	0.4	0.4
Open Aquatic	0.2	0.1	0.2	0.3
Railways	0.4	0.3	0.5	0.6
Sidewalks	0.4	0.4	0.5	0.6
Shallow Aquatic	0.6	0.2	0.6	0.9
Wetland	0.6	1.0	0.6	0.9
Golf Courses	0.7	0.7	0.6	0.7
Parks	0.7	0.7	0.7	0.7
Forest	0.9	1.0	1.0	1.0
Meadow	1.0	1.0	1.0	0.9
Savana	1.0	1.0	1.0	1.0

Table 11 - Species 2019 Resistance Values - Resistance values for each run of Circuitscape

	East West Total Resistance	North South Total Resistance
Snake	1.248941571	1.327178279
Shrew	1.04122764	1.073567263
Deer	0.7432245592	0.7582761598
Bat	0.5240057387	0.5255279074

Habitat connectivity is important, but in the urban landscape it is worth noting that it only matters if there is enough high-quality habitat to support populations of species and if it is close enough together for species to move between them. This means that preservation and creation of naturalized areas within cities is crucial and should be a higher priority than creating connections between them. If urban animal

populations are to be stable moving forward, more habitat areas are needed and the connections between them need to be improved.

8.1.1 Greenways and Green Spaces

Linear links in cities are often designed for active travel or as additional recreational space, but they may also provide habitat and connectivity for local flora and fauna. In Kitchener, they range from naturalized space to open greenspace. Linear links provided better connectivity than the surrounding built environments for all species. Deer, shrews and snakes had moderate connectivity in linear links and bats had comparatively high connectivity. These areas had barriers, but they were few so had little impact on connectivity. Roads that passed through linear links showed higher relative connectivity than roads that were surrounded by built area. Creating and improving linear links should be a priority for urban conservation. As the areas around these greenspaces densify, urban planning should account for the increased potential human animal interaction in these areas (like animals on streets or in yards).

Golf courses, cemeteries and playing fields are large urban greenspaces but offer mostly manicured areas. Habitat connectivity of these areas varied with species. Shrews and snakes saw low connectivity that was interrupted by barriers like paths, waterways and buildings. Snakes occasionally had lower overall connectivity than shrews in these areas. Deer had similar barriers but moderate to high habitat connectivity. Bats had high habitat connectivity in these areas with few barriers. Golf courses and cemeteries have been reported as places that allow for urban species movement and provide resources, so the increased connectivity in these areas relative to the built landscape was expected (Andrews, 2022; Craig, 2022; Drake et al., 2023). Golf courses can enhance urban connectivity and support some urban adapters, but this is compared to the surrounding urban areas and not natural spaces, as negative impacts on water and soil quality from areas like golf courses are a problem (Andrews, 2022; Drake et al., 2023). These open urban areas may add to connectivity, but natural areas are the better option. The potential for urban connectivity in these areas means that designing and enhancing these areas for urban species is important. Human use also limits use of urban green spaces and needs to be managed to promote areas that species can use without contact. These spaces may look different for different species. Large open areas are difficult for shrews and snakes to cross, so a connected habitat through the course would be ideal. Deer can be helped by ensuring enough forage and cover (Gallo et al., 2017). Bats are generally roost limited, so providing roosting sites is more helpful for them (e.g. leave standing dead trees) as well as closed canopy areas and water features (Drake et al., 2023).

Larger urban green spaces also exist within Kitchener, some of which are manicured but many are naturalized areas. These larger areas provide habitat in addition to connectivity within the city. Snakes and shrews had moderate connectivity in these areas, deer had moderate to high connectivity and bats had high connectivity. Barriers like waterways, paths and buildings remained even in naturalized areas. These large areas offer increased connectivity within the urban landscape, but they do not provide connectivity across the entire landscape as they are isolated by the surrounding urban landscape, so smaller patches remain important as well.

Large habitat patches are often held up as the ideal habitat, but high-quality small habitat patches can have similar diversity and may harbor more habitat sensitive species (Delaney et al., 2021). Small patches have been used as steppingstones for animals to travel between large patches (Ossola et al., 2019). Many connected small patches also allow for a diversity of habitats to be created. This is important, as even within this set of urban animals there are different habitat needs. Despite an emphasis on large habitat patches for conservation, small habitats may be the only way to create connections between residual urban areas without dedicating vastly more area to conservation. It is imperative that these areas be maintained and added to as density increases, as it becomes harder to restore built areas than to keep up and upgrade existing green space (Gallo et al., 2017). In general, development of urban green spaces should take a larger role in city planning (Park, 2017).

8.1.2 Urban Gradient

Density of cities often decreases from the downtown core out through the suburbs and to the rural areas. The densest areas contain many barriers like buildings and pavement, and as a result snakes and shrews had very low connectivity downtown, with shrews having marginally more connectivity as paved areas posed less of a barrier. Deer had low connectivity here with more connectivity in paved areas than shrews and better connectivity in urban green spaces. Bats had opposite barriers, where connectivity over buildings was low to moderate, but paved areas were barriers creating an area with more connectivity overall. Urban density decreased with distance from the urban core. In suburban areas, snake maps continued to have very low connectivity, but shrew maps showed some increased connectivity and deer and bat maps showed moderate to good connectivity in suburban areas. Densification decreased from suburban to agricultural areas. These agricultural areas showed a little increase in connectivity from suburban areas. This is exaggerated by the lack of an agricultural landscape type, as many of these areas were classified as better land use types than are present. An increase in connectivity with decreased density was expected, as animal diversity and abundance are lower in more developed areas with impact decreasing with decreasing density (Coleman & Barclay, 2011; Łopucki et al., 2013; Müller et al., 2018;

Thaweepworadej & Evans, 2022). Many species had a large increase in connectivity from urban to suburban areas. This may be due to moderate disturbances supporting some species and suburban areas providing resources like new food sources or in the case of bats roosts within buildings (Dietz et al., 2020; Gomes et al., 2011). Connectivity in both urban and suburban areas can be improved. Green space within these areas is limited but necessary for animal movement. It is important to ensure an adequate amount and quality of green space, so plans for city greenspace should be created as part of densification plans. Snakes and shrews avoid the downtown core, as the suburban areas already impeded movement to a large degree, so efforts would be more beneficial in the suburban than urban areas.

8.1.3 Buildings and Yards

Buildings were hard barriers for snakes, shrews and deer. They were barriers for bats, but some connectivity remained over them. Buildings are actual physical barriers that prevent most animals from passing through them, but bats can fly over many of them, so this ordering makes sense (Russo & Ancillotto, 2015).

Yards provide some open space around buildings that can allow for some connectivity. Shrews and snakes had low to moderate connectivity for yards. Small animals may use suitable garden space as habitat, but if it does not represent good habitat, yards may be large enough to be hard to cross (Baker et al., 2003; Gomes et al., 2011; Vergnes et al., 2013). Deer maps were similar but tended more toward moderate connectivity. Suburban yards offered similar habitat connectivity to the surrounding natural areas for deer. Deer were limited more by size and surrounding habitat access for yards than by the habitat itself. Deer may use yards for supplemental resources, but they are small and represent an area that is quickly moved through if suitable resources are not present (Blanchong et al., 2013; Kilpatrick & Spohr, 2000b, 2000a; Potratz et al., 2019). Yards had high connectivity for bats and were similar to natural areas. Yards had some of the stronger connectivity on these maps, but fences were not included in this analysis, and they provide barriers that limit real world movements (Jakes et al., 2018). Yards in general represent a meaningful fraction of the total green space (often being over 20% of total land cover) and tree canopy within cities, and they are often overlooked despite representing urban space that could be used to connect larger urban green spaces (Daniel et al., 2016; Loram et al., 2007; Ossola et al., 2019). Yards tend to be small, so it is important to view yards as a collective rather than individually, making it important for city planners to advise and incentivise various ecological yard improvements in different areas, or for people in an area to collectively restore portions of their yards (Daniel et al., 2016; Goddard et al., 2010; Loram et al., 2007).

8.1.4 Roads

Roads are one of the largest causes of fragmentation in urban areas and are considered one of the major threats of biodiversity in the world today (Baker et al., 2003; Galantinho et al., 2022; Meunier et al., 1999). Roads can divide up land areas, destroy or degrade habitat, introduce run off and pollutants and for some species serve as a source of mortality from car strikes (Ascensão et al., 2015; Holderegger & Di Giulio, 2010; Ryckman, 2020; Underhill, 2002). Roads posed a barrier for all species. The barrier effect was strongest for bats. Roads were an exception to the pattern of increased connectivity for more mobile species. Snake and shrew maps showed roads as moderate barriers. Shrews and snakes are capable of crossing roads depending on the size of the road and traffic. Major roads were moderate barriers for deer, but smaller roads in less dense areas showed some connectivity. All species had areas of high relative connectivity where animals were modeled through areas they would not travel through. Roads were an expected barrier, as many studies have found various animals to be harmed by roads, though to differing extents (Fahrig & Rytwinski, 2009; Holderegger & Di Giulio, 2010; Oxley et al., 1974; Paterson et al., 2019; Ryckman, 2020; Underhill, 2002). They represent one of the largest human caused habitat changes, pose risk to wildlife through mortality and can limit habitat by causing animals to avoid areas or destroy and degrade habitat altogether (Fahrig & Rytwinski, 2009; Holderegger & Di Giulio, 2010; Paterson et al., 2019).

Despite roads posing a barrier to many species there is still some habitat connectivity through these areas, so it is important to mitigate risks from roads (McLaren et al., 2011). Ideally the number of roads would be as small as possible. The best way to avoid roads and traffic is to promote public transit and other modes of transit (cycling and walking). Roads will remain necessary, so measures should still be taken to minimize their impact. Road placement and size are important things to consider. Care should be taken to avoid known movement routes of animals and to facilitate movement across roads when plausible (e.g., animal crossing structures) (McGregor et al., 2015). Some species would also benefit from reduced lighting where it is safe to do so, or even buffers between lighting and habitat (Azam et al., 2018). Road verges, though separate from the road itself, also impact potential animal movement. They represent edge-habitat that is extremely long and narrow (Underhill, 2002). These areas can offer resources to certain animals, though there is some risk to drawing them closer to roads through increasing road mortality both for them and their predators (Adams & Geis, 1983; Ascensão et al., 2015; Galantinho et al., 2022; Holderegger & Di Giulio, 2010; Oxley et al., 1974; Underhill, 2002). To get these benefits, it is important to maintain vegetation in these areas and avoid mowing it (Galantinho et al., 2022; Oxley et al., 1974).

8.1.5 Waterways

Waterways are larger open water areas and exist as ponds, small lakes and rivers within Kitchener. Shrew and snake maps showed waterways as barriers. Deer maps showed some habitat connectivity limitations for waterways but often they were hard to distinguish from the surrounding areas. Waterways posed no additional barrier to bats from the surrounding landscape. Regardless of traversability, waterways are an important resource to animals as a source of water, as potential movement areas, for food resources and even potential habitat, so urban greenspaces should incorporate these features where possible (Mahan & O'Connel, 2005). Water quality needs to be protected as well, as increased urbanization generally reduces water quality (Lintott et al., 2015).

Riparian buffers were not classified due to a lack of available data. They help to support various species, depending on the width and type of flora they have, so varying sizes and types of riparian system should be considered for urban waterways, both for connectivity as well as habitat (Larsen-Gray & Loehle, 2022; Millward et al., 2022). Riparian zones sometimes get left in place during development to help prevent flooding, so can represent areas that are already being maintained and provide an opportunity to improve on existing urban ecosystems as the quality at which they are maintained is often lacking (Aronson et al., 2017).

8.2 Summary

Each studied species has options for improving connectivity with differing levels of potential effect for effort required. Bats had the most overall connectivity. Bats can fly over sub-par areas, so with a small urban core, bat populations could be connected, so increasing connectivity would take more effort. The potential for increasing urban connectivity for flying species has been reported to be lower than for terrestrial species, so they should not be the focus of connectivity planning (though some attention should still be given to them) (Bourgeois et al., 2024). Deer were found to have lower levels of urban connectivity than bats, but they still have fairly high levels everywhere except the downtown core. Large mammals are often thought to avoid urban areas, but they are found in suburbs, so planning for them is important but will not protect animals with less maneuverability and should not be the focus of connectivity planning (Magle et al., 2014). Shrew and snake maps showed a lack of urban connectivity. Fragmented landscapes are known to be more challenging when animals have lower mobility, so this was expected (Gigeroff & Blouin-Demers, 2023). The small size of these animals allows them to exist in

small urban patches, even yards, so the potential to improve connectivity for these animals is higher and they should be the focus on connectivity planning.

Connectivity for all four species could be improved by creating more habitat and improving existing habitat between what residual natural habitat remains. For example, naturalizing areas in parks, golf courses, cemeteries and back yards could improve the amount of habitat available for smaller animals and potentially connect habitats. This would take a concerted effort to prioritize restoration of municipal areas and to incentivize restoration of privately owned areas. Ideally, these efforts would have city oversight and funding to facilitate individual projects working together and matching the urban animals that could most benefit from them. This oversight needs to account for many urban species by favoring a diversity of landscapes with edge and early successional habitat being impactful for shrews and snakes but bats and deer requiring more forested areas (Bourgeois et al., 2024). These improvements can even be planned into the lifecycle of urban infrastructure to decrease total cost, as cities tend to invest more in infrastructure upkeep than urban ecology (Neeson et al., 2018).

It is also important to mitigate the impacts of barriers. The four modeled species had similar barriers, with differing intensities. Major barriers included the urban core, buildings, roads/paved areas and to a lesser degree waterways. City centres often lack green space, but this is unlikely to change, so focus should be on planning growth to minimize impacts on species. This can be done by minimizing urban sprawl by increasing population density in areas that are already inaccessible to animals while maintaining existing green spaces, in suburban areas. Buildings will remain hard barriers to non-flying species. It is important to reduce building footprints and increase the quality and amount of greenspace around them, so animals have ways around buildings. In the suburbs, this could include use of yards. These yard areas need to be planned in groups and should reflect nearby naturalized areas to extend/connect habitats. This would need support from the municipality and local community groups to recommend and incentivize different types of restorations in certain areas. Paved areas should be avoided where possible, especially in areas of high animal presence. Roads should also have minimized traffic and speed or, as a last resort, crossing structures for local fauna. One of the best ways to do this is to increase the use of public and active transportation. Water was a barrier but also represented a key resource for animals in the area. Instead of avoiding water features, they should be included but properly maintained, as water quality and the overall quality of water bodies in urban areas is often lacking.

A strong need for increased habitat quantity and quality to create connectivity has been demonstrated across the species. These conclusions were the easiest to draw, but the overall isolation of residual urban habitats makes it difficult to draw conclusions beyond this about how feasible urban changes could

positively impact urban connectivity. Despite lack of clarity on the overall effects of connectivity both theoretically and in this model, it can be assumed that improvements in habitat quantity and quality are beneficial, and these should be the focus for urban planning. If habitat quantity and quality are limited, connectivity theory could help to understand potential areas of interest for habitat connectivity in Kitchener, Ontario and may be useful for other cities in Southern Ontario.

The applicability of this research was constrained by a few factors. One of these was the availability of data. Connectivity is species and landscape specific, so ideally local data would be available for species and landscape (Adriaensen et al., 2003; C. D. Anderson et al., 2010; Bourgeois et al., 2024; Fahrig, 2003; Fleishman & Mac Nally, 2007; Keinath et al., 2017; Tischendorf & Fahrig, 2000a). Multiple species were chosen to extend the applicability of the research to a range of urban species. Urban data on the movement of species was sparse, so habitat preferences were used as a proxy for movement preferences, but available data was limited to urban adapted and generalist species. This narrowed the scope of this research to species that have increased movement in the area. In the future, research into the movement of a broad array of urban species would help increase the accuracy of these models and increase the applicability of them beyond urban adapters and generalist species.

Data for landscape classification is a key input for the model. Landscape types like roads and buildings were well mapped for urban areas but little data was available to classify natural or agricultural areas, and no data was available for things like noise and light pollution, fences, riparian zones and more. Data was gathered from many sources to combat this (city databases, natural area managers, etc.). To help with this in the future, urban databases need to include high quality mapping for recreational and natural areas as well as for the built environment. Quality of the landscape classification was also impacted by discretization (Cushman et al., 2006; Ziolkowska et al., 2016). This reduces accuracy by simplifying the landscape, but this simplification helps in data processing. The effects of discretization were mitigated in part by trying to align the cell size with the perceptive range of the species, estimated with home range sizes. To further reduce the effects of discretization, future work should have species specific cell sizes. Ideally these would represent the perception of a given species, but more research is needed to understand perceptive ranges as these are species and landscape specific. In addition to data availability constraints, there were data processing constraints. The amount of processing power constrained the number of species and scenarios, cell size and the size of landscape. Cloud computing allowed for larger data sets to be processed than were attainable with a personal computer. In the future, fine tuning the software and increasing processing power available to researchers would be beneficial and both are already underway.

This analysis was intended to comment on the potential of connectivity theory to apply to urban planning in Southern Ontario. It is hard to draw conclusions about the applicability of connectivity specific metrics, as the results showed a lack of habitat quantity and quality for Kitchener that was more important than the lack of connectivity. Connectivity was lacking in Kitchener, which suggests that it is also lacking in other major cities in Southern Ontario. The low levels of connectivity suggest that targeting areas that would connect isolated habitats with restoration efforts may be beneficial and did help to identify what barriers were the strongest for each species (though all results here were expected). It is much easier to assess habitat quantity and quality than connectivity, and these two metrics will have a large impact on the utility of urban green spaces for use for urban animals. Pending more research on urban connectivity, habitat quantity and quality metrics should be the priority. If habitat amount and quality are not decreased when enhancing potential connectivity, these metrics may offer a way of prioritizing potential habitat improvements. If connectivity metrics are used, care should be taken to address the potential hazards of connectivity as well, like the spread of invasive species or disease, drawing plants and animals closer to potentially hazardous areas (roads, harmful interactions with humans), linking habitat sources to sinks and more.

Future research should be focused on clarifying the role of connectivity as a tool for ecological management. Further research is needed to draw connections between connectivity and impacts on urban flora and fauna, in the form of long-term studies with a before/after and an impact/control design at different scales and for various potential urban species (Rytwinski & Fahrig, 2015; Soanes et al., 2024). Long-term studies are needed on the effects on species diversity and species movement once changes are made based on connectivity models. These long-term studies should be published periodically so that long term trends are made known as they appear, because ecological action needs to happen before all the results are finalized to improve cities. In the meantime, studies can be done that test the short-term impacts of connectivity, by comparing connectivity levels and species movement and diversity between cities with varying levels of remaining connectivity between habitats. Testing of the various modeling software available is also imperative before use of connectivity theory should be a priority for urban areas. Until more studies like that exist, urban connectivity metrics should not be a high priority, but rather metrics about total amount and quality of habitat within an urban area should be used. Even if these lines of research suggest that connectivity analysis is important for urban areas, there is still a lack of data on species movement and landscape classifications. Movement is species and landscape specific, so more research needs to be done on the movement of a test set of species within urban areas. Urban landscapes also need more ground truthed landscape data about green spaces and residual habitat (built areas like buildings and roads tend to be well mapped whereas more natural areas often lack data).

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