The Relationship between Ecosystem Services, Human Health and Well-being and its Implication for Environmental Planning: An Agent-Based Model and Geosimulation

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ABSTRACT

A tremendous number of studies have examined the relationship between ecosystem health and human health and well-being, especially in urban settings. The project builds upon a nation-wide Canadian study by Crouse et al. (2017) which explored the correlations between urban greenness and cause-specific mortalities using Cox proportional hazard ratios. Crouse et al. (2017) concluded that increased urban greenness in proximity to participants’ residences is associated with decreases in the risks of cause-specific mortalities. The goal of this project is to develop an agent-based model using NetLogo to explore the relationship between ecosystem services, human health and well-being in the Credit River Watershed (CRW). The model utilizes a Normalized Difference Vegetation Index (NDVI) to establish values of urban greenness in the CRW. Then, hazard ratios are calculated from these NDVI values based on the association observed in the Crouse et al. (2017) study. The model uses a tree-planting, or greening, agent that changes the values of greenness in the study area, thus decreasing hazard ratios. The greening agent is counteracted by a developer agent which converts land adjacent to residential areas into new development. Consequently, this action decreases greenness and increases hazard ratios. This interaction occurs overtime and the results are shown through geosimulation. The model also provides a set of user-defined parameters that modify the nature of agent interactions and the underlying rules governing the model. Overall, the model serves as an educational and decision-support tool for stakeholders in the CRW, including residents, municipal planners, conservation authorities, and policy makers.

FOREWORD

My research interests lie with the observation of the empirical relationship between ecosystem services and public health and well-being outcomes. Surprisingly, there is little to no integration of ecosystem services in modern planning policies and practices, especially within an urban context. Moreover, I have grown to appreciate the usefulness of economic methods in measuring the value of and communicating the importance of ecosystem services to relevant stakeholders. As a planning student, my goal is primarily in the communication of this knowledge to municipal planners and policy-makers.

Dr. Bunch's research has studied the effects of ecosystem services on human health and well-being in the CRW. His current research project aims to develop a method of tracking ecosystem services in the watershed, measuring their benefits to residents and communities, and demonstrating their importance to stakeholders. Dr. Bunch's research goals align closely with mine and the development of an agent-based model provides a challenging and innovative method to achieving these goals.

The major research project contributed towards many of the learning objectives detailed in my Plan of Study. I developed an understanding of ecosystem services and their connection to human health and well-being through the literature review and from working on the model. Moreover, I used the model and data to perform calculations to measure and assess the impacts of tree planting on public health and economic outcomes. I read municipal and provincial policies and legislative documents, broadly concerning environmental planning in Ontario, but also about how tree planting budgets are planned and used, how urban forests are monitored, and how approaches to improving ecosystem health are developed. Finally, through my communication with planners and municipal officials, I gathered data on various parameters for the model including development charges, operating and capital funds for tree planting, the average cost of tree planting, commercial land use data, and population growth rates. I also learned how planners use data, policies and legislation to carry out their responsibilities. Finally, I reflected on how the model explores the connections between environmental policies, urban tree cover, and human health outcomes. In doing so, the geosimulation of these connections can produce greater understanding on how social and natural phenomena interact and improve life in urban watersheds.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Professor Bunch for his role as my research supervisor and allowing me to contribute to his research for my MES project. I appreciate his guidance and encouragement over the course of my research project. His feedback and constructive criticisms helped greatly in the completion of my research project. I would also like to thank Chaya Kapoor and Shuilin Zhao for their contributions to the model and for assisting me with any challenges I encountered. Finally, I would like to thank Professor Mark Winfield, my academic advisor, for his reliable guidance and insights throughout my MES program.

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CHAPTER ONE: PROJECT INTRODUCTION

The main goal of the project was to develop a model that explores and demonstrates the relationships between watershed ecosystem health and human health and well-being. The model employs agent-based interactions and geosimulation to quantitively represent and assess the impacts of environmental and social conditions on health and well-being outputs. The model is built upon the research of Crouse et al. (2017) which examined the association between residential greenness, measured using a normalized difference vegetation index (NDVI) derived from satellite data, and mortality hazard ratios. The model uses a residential tree-planting agent as the main driver of change in greenness in the Credit River Watershed (CRW). As trees are planted in the model environment, the mean greenness increases and the mean hazard ratios decrease. A developer agent, which is optional, converts land into additional residential neighbourhoods, thus decreasing the mean greenness and increasing hazard ratios. Development also generates development fees, which can contribute to planting budgets, building a feedback loop into the model. Another feedback loop is population growth, which increases the total tax contributions to tree planting budgets proportional to the population growth. Both agents' behaviours are constrained by environmental conditions and parameters built into the model. The model's parameters are calibrated with the most recent and available data in the CRW and Peel Region; however, users can modify the parameters to develop different scenarios and assess outputs under differing conditions. This allows for the model's use as a potential watershed management and decision-making tool for planners and municipal officials.

My contributions to the model for my MES final project are outlined below:

- I communicated with planners, foresters, and government officials across the Peel Region to learn more about the policies that guide municipal tree planting. I gathered data on the model's parameters from Mississauga, Brampton, and Caledon: municipal tree planting budgets, average cost per street tree, residential and commercial development charges, population growth projections, and value of statistical life (VSL).
- I parameterized the values for the model's inputs using best available and recent data. I calculated the values of some parameters (i.e., built ratio and commercial floor factor) using georectification rules and land use satellite imagery (see p. 50).
- I contributed to the design of the NetLogo interface to allow users to modify parameters and environmental conditions, and set up different modeling scenarios to analyze.
- I performed sensitivity analyses to examine different scenarios and compare model outputs, notably health and well-being metrics (i.e., mean greenness, mean hazard ratios, total economic values, and sum of deaths avoided).
- I helped add code that operationalizes the model, its parameters, and its outputs. I also tested the model to find any issues with the model's code and interface.
- I commented on how the model's methodology could be integrated into existing municipal planning practices, specifically concerning residential tree planting and its connections to human health and well-being.

CHAPTER TWO: LITERATURE REVIEW

Introduction

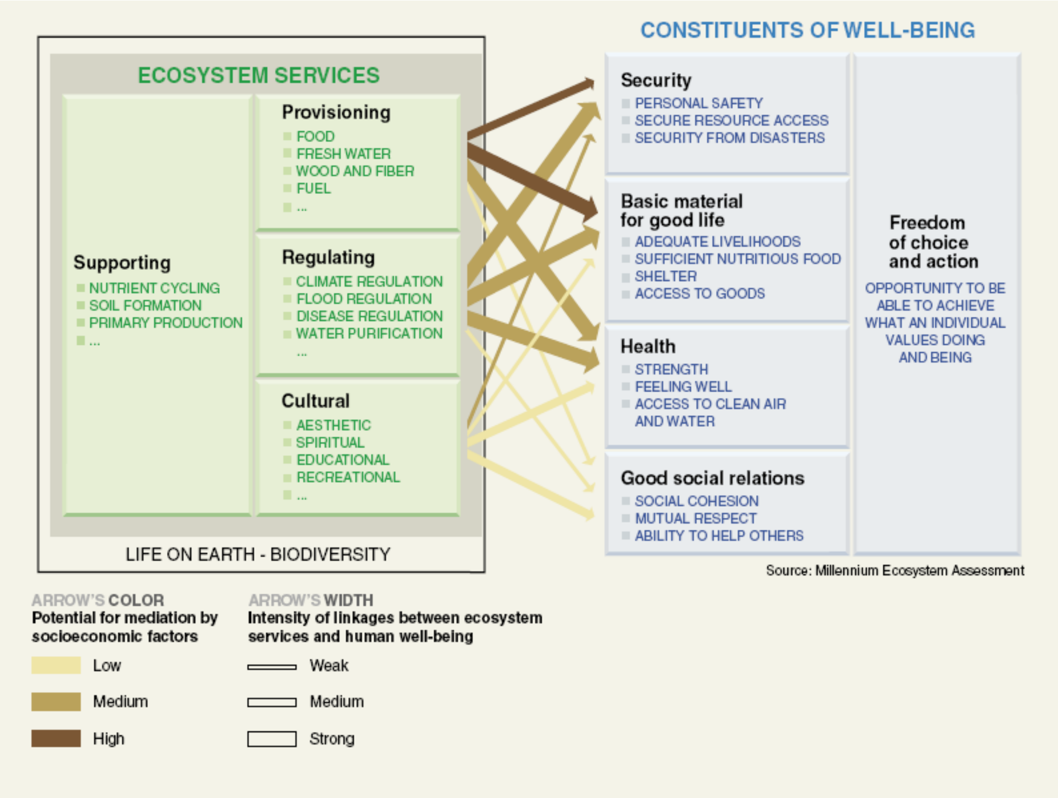
This chapter provides a summary of the key concepts behind the major project from the academic literature. Ecosystem services are defined and their relationship to human health and well-being is explored, chiefly through empirical evidence from studies conducted in urban areas. The benefits of economic valuation techniques are documented and examples of valuation studies are used to highlight their importance in the assessment of the impacts of ecosystem services on people and communities. This background knowledge is crucial in order to appreciate the utility of the NetLogo model in tracking and measuring relationships between ecosystem services and human health and well-being.

The literature review also provides a general overview of agent-based modeling (ABM) and how it differentiates itself from traditional modeling systems. The main advantages of ABM are summarized and examples of ABM applications are documented. Importantly, the idea of "emergence" is explored as the main appeal of ABM and why this property allows for a comprehensive analysis of the modeling system. This information provides an understanding of the logic behind ABM and why it was selected for the major project.

Ecosystem Services, Human Health, and Valuation

What are Ecosystem Services?

The Millennium Ecosystem Assessment (MEA) explains the environment as life's support system, in which humanity is not exempt (Millennium Ecosystem Assessment (MEA), 2005). The MEA defines ecosystem services as ecological processes of ecosystems that provide benefits to humans, either directly or indirectly (MEA, 2005). They are distinguished from ecological processes and functions, both of which contribute to ecosystem services, but are biophysical systems that are vital to ecosystem health regardless of their effect on human well-being. Braat (2013) further explains this distinction by highlighting the term ‘service’, as something from which humans derive benefits. In his view, ecosystem services do not exist unless their positive effect on humans is demonstrated (Braat 2013). Broadly, there are four main categories of ecosystem services: provisioning (e.g., food, water and fibre), regulating (e.g., carbon sequestration or water regulation), cultural (e.g., recreation, education or aesthetic), and supporting (e.g., primary production and soil formation) (MEA, 2005). Figure 1 (Haines-Young & Potschin, 2010, p. 25) illustrates the different types of ecosystem services and the intensity of their connections to different aspects of human health and well-being.



Source: Millennium Ecosystem Assessment

Figure 1. The Connections between Ecosystem Services and Human Health and Well-Being. *From 'The Links between Biodiversity, Ecosystem Services and Human Well-Being', by R. Haines-Young and M. Potschin, 2010, Ecosystem Ecology: A New Synthesis, p. 25.*

The ecosystem service paradigm can be conceptualized as a 'service cascade' model (Figure 2). The model provides a simplified and linear interpretation to illustrate a "production chain" between the environment and the social and economic systems (Haines-Young & Potschin, 2010). Any ecosystem service exists in a medium between the ecological structures and processes that generate it and the benefits and values derived by human populations. It is important to recognize that what constitutes a service depends on whether it is considered a benefit. Benefits are valued differently over time and in different places which can be identified using valuation techniques (see p. 10). Finally, the benefits acquired in the social and economic systems, and the values derived from these benefits, can put pressure on the ecological processes and functions. Possibly, if left unchecked, these pressures can undermine the supporting services of ecosystem services and risk the collapse of the entire system (Potschin-Young et al., 2018).

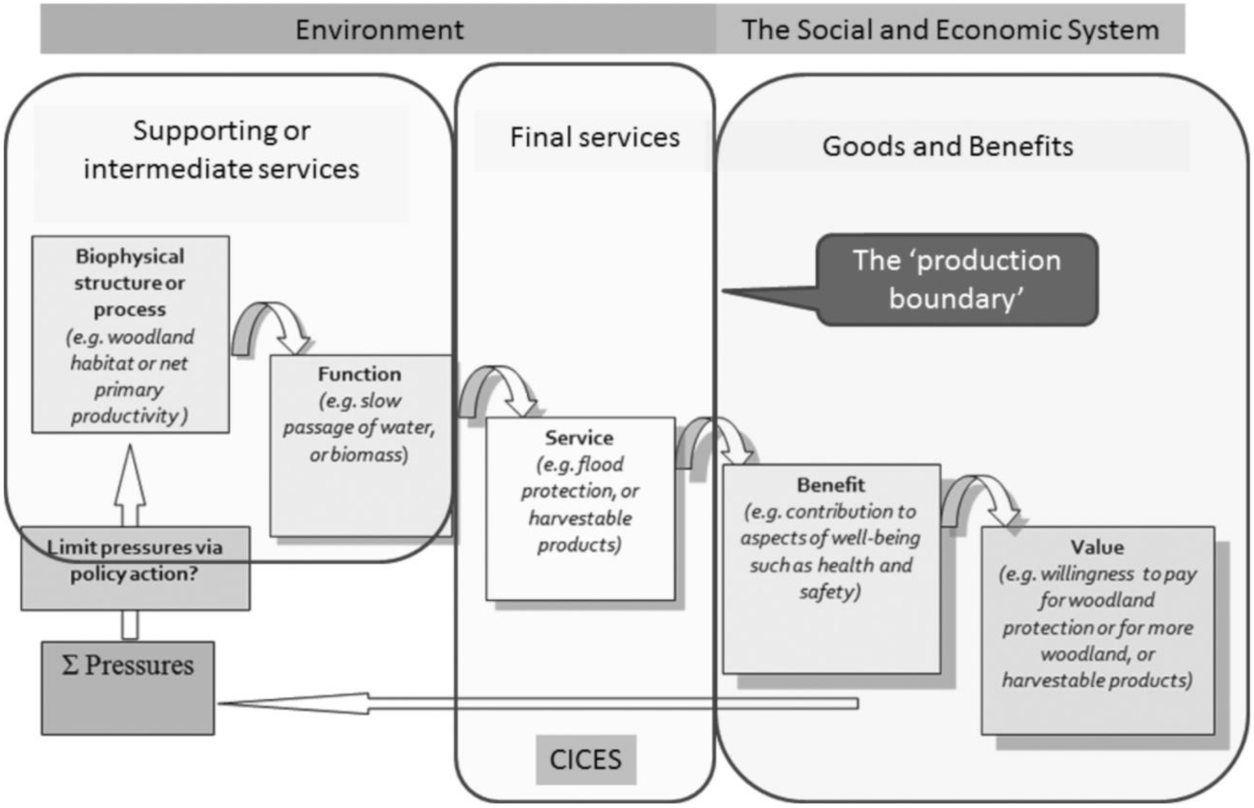


Figure 2. Ecosystem Service Cascade Model. *From 'Understanding the role of conceptual frameworks: Reading the ecosystem service cascade', by Potschin-Young, M. et al., 2018, Ecosystem Services 29, p. 431.*

Relationship between Ecosystem Services and Human Health

Although ecosystem services were studied in the late 20th century, they were not seriously considered until their decline became apparent, and in response, there has been a growing understanding in the ecology of ecosystem services and their benefits to human well-being. An ecosystem approach emerged in the 1980s to advocate for integrating human well-being into policy and projects at multiple geographic scales, from landscape management to global initiatives (Kay, J.J. et al., 1999). This approach recognized the importance of considering ecosystems beyond their market-based goods and incorporate the benefits they provide by existing (Haines-Young and Potschin, 2009). However, scholars acknowledged the importance of defining human well-being, and specifically how different ecosystem services affect it. Scholars referred to Maslow's hierarchy of human needs as a basis of well-being which is sub-divided into three categories: spiritual, psychological, and survival needs (Wu, 2013). The relationship between natural capital, ecosystem services and human well-being are interconnected; natural capital yield different ecosystem services that meet certain human needs on Maslow's hierarchy (Wu, 2013). For example, a regulation service of flood mitigation meets survival needs of individuals by ensuring the basic necessity of water (physiological) and by reducing the risk of flood damage (safety and security) (Wu, 2013).

Scholars have since expanded Maslow's hierarchy of needs, which originally considered the needs of the individual, to consider larger organisational structures of humans; in effect, to establish a universal framework of human well-being. However, well-being remains a broad term that can include both objective and subjective elements, the latter of which can prove difficult to measure. Early conceptions of human well-being have acknowledged its social, economic, and environmental factors, and in turn, promote a more holistic approach to policy-making (Summers et al., 2012). Some measures, such as reported life satisfaction or happiness, have been adopted by researchers to represent subjective well-being. Vemuri and Costanza (2006) demonstrate the importance of life satisfaction as a metric of human well-being using data from 171 countries. The results suggest that natural capital and ecosystem services are considered by people in self-assessments of life satisfaction. As a result, the authors advocate for natural capital, in addition to human, social and built capital, to be included in a National Well-Being Index (Vemuri and Costanza, 2006).

Human health, a central component of well-being, is also considered for its relationship to the environment. The MEA explains the environment as life's support system, in which humanity is not exempt, even if the health benefits of the environment are not always experienced directly in our modern world (MEA, 2005). On a global scale, the MEA explores the impacts to human health due to environmental changes and ecosystem impairment. Conceptually, climate change may increase the likelihood of floods of heatwaves (direct health impacts), while the depletion or contamination of freshwater sources may result in population displacement (indirect health impact). Mainly, the MEA documents the benefits of the environment through the diminishment or destruction of ecosystem services.

Ecosystem Services and Human Health in Urban Environments

The human health benefits are also observed at the local scale, especially in urban contexts, through proximity of green space to human populations. For example, Jennings and Gaither (2015) review scientific literature suggesting a correlation between engagement with green space and reductions in risk of cardiovascular health, heat-related illnesses and stress. Likewise, Salmond et al. (2016) note the importance of street tree planting programs, as trees provide several key ecosystem services, notably climate regulation, air quality regulation, and aesthetics, which contribute to improvement in human health and well-being in urban areas. However, the authors do suggest a more holistic approach focusing on different scales of analysis to fully understand range of impacts of these programs (Salmond et al., 2016). Douglas (2012) also highlights previous research where consistent access to local green spaces can help improve the psychological and community health of urban residents. Proximity to accessible and walkable green spaces was correlated with increased likelihood for exercise, lower risk to cardiovascular diseases, and generally improved health among the elderly (Douglas, 2012). A broader systematic review attempted to synthesize the findings of studies examining the relationship between greenness and mortality risk. Gascon et al. (2016a) examined twelve studies across the globe that vary in study population, study design, and green space assessment. The authors found that five studies discovered a statistically significant reduction in risk of mortality due to cardiovascular disease, ranging from 0 to 5%, in areas with access to residential green spaces (e.g., parks). All-cause mortality risks were less consistent in results; four studies found a decrease in risk to all-cause mortality, but two studies found an increase, in residential areas with higher greenness. One study highlighted concluded that residents in England with greater exposure to green space, namely public parks and agricultural land, were up to 28% less likely to die due to all-cause mortality risks than residents with the least access to green space (Mitchell & Popham, 2008). Moreover, the risks to most causes of mortality were higher for residents in lower income cohorts, independent of level of exposure to green space (Mitchell & Popham, 2008). Finally, Gascon et al. (2016a) conclude that more cohort studies are needed with better green space assessment and data on the socioeconomic status of study populations.

A recent study of Canadian data by Crouse et al. (2017) examined the association between urban greenness and cause-specific risks of mortality. It incorporated personal covariate data on age, household income, level of education, and marital status. Crouse et al. (2017) used satellite-derived Normalized Difference Vegetation Index (NDVI) to estimate participants' exposure to greenness within 250 m and 500 m of their residences. The authors calculated Cox hazard ratios to estimate the relationship of residential greenness and mortality. Overall, the researchers found an 8 – 12% decreased risk from all-cause mortality with increased exposure to greenness near participants' residences (Crouse et al., 2017). The use of NDVI has been documented previously as an important tool in epidemiological studies that examine the association between public health measures and greenness, especially in urban contexts. Gascon et al. (2016b) primarily attribute NDVI's usefulness to its ease of detecting green spaces and of obtaining vegetation indices. Due to NDVI's ability to generate quantitative values of greenness using spectral reflective measurements, researchers can use this data to estimate public exposure to green spaces by proximity to residences.

Importance of Valuation of Ecosystem Services

In their seminal article, Costanza et al. (1997) made a case for the valuation of ecosystem services, which was influential in the proliferation of valuation methods and case studies today. Historically, only market-priced ecosystem goods (e.g., timber or fuel) were priced, but to accurately assess natural capital and ecosystem services, non-market valuation ought to be involved (Adamowicz & Olewiler, 2016). Valuation has chiefly been conducted within an economic framework because ecosystem services are integral to the concept of natural capital. Using this framework, ecosystems are seen as systems that produce a flow of services over time (Costanza et al., 2017). One of the most famous examples of this valuation is the Catskills watershed in New York. In 1996, in response to poor water quality, officials from New York City discovered they could invest between $1 billion and $1.5 billion in the ecological restoration of the Catskills watershed and its water purification capacity (Sagoff, 2002). Despite the environmental benefit of restoring the Catskills, there was also a clear economic benefit; the alternative solution of building a filtration plant was estimated to cost anywhere from $6 billion to $8 billion with $300 million in annual operational costs (Sagoff, 2002). The example of the Catskills spurred other ecologists, economists, and governments to investigate other cases where valuation could reveal the economic benefit to preserving ecosystem services (McCauley, 2006).

This example falls within the young interdisciplinary field of environmental economics, which incorporates research from the natural sciences, traditional economics, political science, and human psychology. The main goal of environmental economics is to provide non-market valuation to ecosystem services (Costanza et al., 2017). This field made the case for the economic valuation of natural capital by incorporating externalities in economic decisions. Costanza and Daly (1992) described these externalities by explaining how even though individuals may benefit from economic decisions, the costs are often social, and therefore, they expressed the importance of valuation as a social decision versus an individual one. Adamowicz & Olewiler (2016) expand on this phenomenon when examining how market failures can arise from negative externalities (e.g., air pollution) from private-sector decisions and must be addressed, both economically and socially, by the public.

Valuation methods of ecosystem services are distinguished between revealed and stated preferences. Revealed preference methods involve the inference of value from the choices that consumers make (Costanza et al., 2017). A common approach among ecosystem services is to infer their value from market data. For example, Phaneuf et al. (2008) demonstrated that urban forest and wetland ecosystems provide water purification and filtration services which may contribute to nearby real-estate values. Conversely, stated preference methods are hypothetical and rely on individuals' responses to different scenarios. These methods often comprise of choice experiments and contingent valuation from which ecosystem service values can be inferred (Costanza et al., 2017). Boxall et al. (2012) utilized these methods to infer the value of conserving threatened marine mammal species in the St. Lawrence Estuary among Canadians' marginal willingness to pay (WTP) for several proposed recovery programs. The authors explain that stated preferences are required because species conservation is a non-market value as there is no market analog from which revealed preferences can be drawn (Boxall et al., 2012).

Non-market valuation techniques can be used to present the benefits of ecosystem services to human well-being in economic terms. For example, Kardan et al. (2015) studied the potential health benefits to the urban tree canopy in Toronto. The authors found that an additional 10 trees, on average, on a city block improves perception of health comparable to an increase of $10,000 CAD in median income or being 7 years younger. Moreover, 11 trees decrease cardiovascular and metabolic conditions comparable to an increase of $20,000 CAD in median income or being 1.4 years younger in cardiovascular health (Kardan et al., 2015). This research indicates the highly localized nature of health and well-being benefits from ecosystem services in urban centers. Additional research has expanded valuation studies to include a spatial analysis to study how ecological conditions differ due to landscape heterogeneity. Kennedy and Wilson (2009) performed a spatial valuation analysis in the Credit River Watershed to provide a baseline estimate of the flow of ecosystem services benefits provided to residents. The spatial analysis reveals that flow of benefits are important as ecological services are not constrained to watershed boundaries and are often dependent on the surrounding land use types. Kennedy and Wilson (2009) estimated the flow of $490 CAD per capita per year to the residents' well-being from a variety of ecosystem services including climate regulation, water supply, and recreation.

Despite the prevalence and utility of economic valuation of ecosystem services, its efficacy is debated within the academic literature. Chee (2004) criticizes the approach using an ecological perspective and supposes that a top-down economic valuation is unsuitable given the stochastic nature of ecosystems. Chee argues that uncertainty within the valuation process will result in difficulties to assess ecosystem services individually given the complex interconnectedness of natural systems (Chee, 2004). Similarly, McCauley (2006) argues that top-down, economic valuation methods are not universally effective for ecosystem conservation programs. Instead, he asserts that there should be a shift from a market-based conservation approach to a moral one; that nature be conserved based on its intrinsic value derived from aesthetic, cultural, and scientific significances (McCauley 2006).

Ecosystem Service Policy and Planning

Research demonstrating the benefits of ecosystem services to human health and well-being, using non-market valuation and spatial analysis, is well-established. However, how this research can be used in the development of environmental policies and planning is less certain. Recently, an ecosystem approach emerged in the 1980s to integrate human well-being into policy and management at a landscape-scale. This approach recognized the importance of considering ecosystems beyond their market-based goods and of incorporating the benefits they provide to individuals and communities (Haines-Young and Potschin, 2009). Slocombe (1993) expanded on the ecosystem approach to notably include the following elements: different scales of land use, the well-being of people, and sustainability. Selman (1999) describes this change in environmental planning to acknowledge environmental capital and take more holistic approaches to its decisions. Similarly, the International Development Research Centre (IDRC) sponsored ecosystem approaches in interventions to improve human health in communities in economically-deprived countries, specifically in the Global South (Charron, 2012). Importantly, the IDRC notes that, in combination with multistakeholder participation, transdisciplinarity, and evidence-based interventions, ecosystem approaches are holistic and more impactful in tackling ecohealth challenges (Charron, 2012).

Tammi et al. (2017) show how spatial valuation analysis can integrate with regional planning and development decisions. The authors show hot-spots of human-nature interaction for recreation in the Tampere region of Finland. The results demonstrate the importance of urban nature and the need to include discourse on natural capital and ecosystem services in planning (Tammi et al., 2017). Tammi et al. (2017) conclude that their spatial analysis and valuation framework of the

Tampere region expanded pre-existing planning practices and reformulated land-use regulations, in addition to generating interest among stakeholders and promoting participatory landscape planning. Similarly, Spatial Informatics Group et al. (2009) promote the use of a spatial ecosystem service valuation framework to design better environmental policies. This framework would serve a tool for planners and decision-makers to compare differences in welfare outcomes for beneficiaries under different policy configurations.

Agent-Based Modeling (ABM)

What is ABM?

Agent-based modeling and simulation (ABM) provides a new approach towards computational analysis in a variety of disciplines. Its use is becoming widespread because of its ability to model the complexity and interdependency of systems where traditional modeling tools prove inadequate (Macal & North, 2005). The foundation of ABM is the agent: an identifiable, autonomous unit with a set of characteristics and rules that govern its behaviour. An agent is populated in the model environment where it interacts with other agents and has the ability to recognize the characteristics of other agents. However, an agent is goal-directed and follows the rules which dictate its behaviour within the ABM software (Macal & North, 2005). Importantly, an agent has the capacity to adapt its behaviour over time in the face of the new information. This requires an agent to have memory in the form of a dynamic agent attribute which indicates a current stock of one or more resources (Macal & North, 2009).

The characteristics of an agent may vary depending on how the modeling and simulation systems are defined. Heckbert et al. (2010) elaborate on how the definition of ABM systems can alter depending on the research context, but summarize the methodology into two defining attributes: (1) interactions between agents that produce measurable outcomes and (2) dynamic behaviour of heterogeneous agents. The authors argue that these two attributes are essential to explore how microlevel behavioural interactions among agents can produce macrolevel understanding of complex systems. Berry et al. (2002) expand on the underlying principle of ABM systems; in contrast to how traditional social sciences examine how social structures and characteristics affect behaviour, ABM focuses on how agent interactions create larger patterns of behaviours. These patterns of behaviour and social structure create "emergent" properties, and thus, ABM can be used as a "generative" application in social science (Berry et al., 2002). This strength of ABM is possible through its ability to create controlled environments and modify parameters when required. In addition to the agent, another strength of an ABM system is in its simulations. Agent-based simulations refers to the model's dynamic process of agent interactions which can be repeated over time, whether in a time-stepped process or in discrete events (Macal & North, 2009).

ABM's Advantages over Older Simulation Methodologies

Davidsson (2000) explains how ABM simulation differ from older methodologies of computer simulation, referring to it as a *micro* simulation technique that models specific behaviours of individuals (or agents). In contrast, other systems focus on *macro* simulation wherein population averages are derived from mathematical models and computation. An example of *macro* simulation, Discrete Event Simulation (DES) bases simulations on events that occur within the model and how these events affect the system overall. The state changes in DES occur at points in time dictated by a time-stamped *event list*; once an event occurs, and the effects of the event on the system are simulated, the state change occurs, and the model continues until the value of the time stamp of the next event is met (Davidsson, 2000). Davidsson (2000) then compares ABM with DES and identifies the following advantages of using the former over the latter. ABM:

- implements pro-active behaviour which is useful for simulating agents (e.g., humans) that can act independently without external stimuli.
- supports distributed computation as each agent can be implemented in separate software, and improve performance and stability.
- allows for agents to be enabled or disabled during simulations without interruption to the model. This allows for dynamic simulation scenarios with different properties.
- enables non-programmers to assist in model and simulation process due to approachable and realistic methodology.

Others have expanded on the importance of ABM to the social sciences. Bankes (2002) states the unsuitability of other modeling and simulation methodologies to address questions in the social sciences. Other methodologies are seen as either too restrictive or are founded on unrealistic assumptions that oversimplify or misrepresent natural or social systems. However, as Bankes (2002) explains, despite the weaknesses of older methodologies, ABM has yet to proliferate in use to explore research questions in natural or social systems. He explains this is primarily due to the lack of confidence in computer modeling and simulation overall in addressing social science questions. However, Bankes (2002) argues that a change in perspective is needed to view ABM as an example of experimental science that uses computational experiments to lead to credible research questions. With ABM's focus on agent-based interactions and emergent properties derived from those interactions, he argues the methodology can more accurately represent how individual behaviours create social dynamics. Consequently, outcomes from ABM could prove more useful in informing public policy and programs than traditional modeling methodologies (Bankes, 2002). Essentially, ABM reveals emergent patterns and behaviours of systems to researchers rather than relying on broad predictions.

ABM and "Emergence"

While one of ABM's advantages is in exploring the *emergence* of behaviour and social systems, the definition of what constitutes *emergence* is contested. Originating in philosophy, emergence was seen as a distinguishing property of a system, even as complexity in the system's components and the interactions between them grew (Teo et al., 2013). Conventionally, it was believed that the emergent properties of a system are identified only when the system is studied as a whole because predicting or verifying emergence is difficult. The conventional approach was, once the system produces a representative result, to predict emergent phenomena by observing the outcome (Teo et al., 2013).

A foundational example of discovering emergent behaviour in computational science is the Boids Model. Reynolds (1987) developed a model that simulates the flocking behaviour in birds that was emergent from the interactions of self-determined agents. Each bird agent followed the following three rules: (1) avoid crowding with other birds, (2) move toward average heading of birds, and (3) move toward the average positions of birds. The result demonstrated that flocking behaviour emerges when all three rules governing bird agents are implemented; this does not occur if any one of the rules is removed (Reynolds, 1987).

Applications of ABM

ABM is applicable to modeling the complexity and interdependency of social and ecological systems (SES) which is instrumental to the fields of ecological economics, natural resource management, land-use change and urban planning (Heckbert et al., 2010). As Heckbert et al. (2010) explain, ABM has many applications that explore economic choice in urban environments such as how decisions can impact human activity and well-being. ABM can model SES across different temporal and spatial scales due to the highly dynamic nature of the environment, but the complexity of SES makes it difficult to parameterize the model and subsequently analyze scenarios (Schulze et al., 2017). The authors note the opportunity for future ABM to continue to explore the interplay between social and ecological agents and address the challenges of previous modeling (Schulze et al., 2017).

In terms of public health, ABM was chiefly used to model transmission pathways for infectious diseases. By examining how infectious diseases transfer between individuals, and between individuals and their environment, patterns can emerge that inform researchers about population-level transmission and persistence (Tracy et al., 2018). More recently, ABM use has expanded beyond traditional infectious disease research to include broader public health behaviours and patterns. For example, Tracy et al. (2018) explores the application of ABM in exploring the relationships between environmental characteristics and physical activity. Studies using ABM have demonstrated how unequal distributions in land use, among other environmental resources, affect different socioeconomic populations.

Summary

The literature review detailed the well-studied relationship between ecosystem services and human health and well-being. Empirical studies and meta-analyses summarize the evidence of associations between exposure to greenness on a variety of health outcomes. The advantages of economic valuation in assessing ecosystem services are explored, including examples on different valuation techniques and their utility in studying human health and well-being. Moreover, the role of ecosystem services in public planning and policies is explored.

The theory and logic behind ABM are detailed to distinguish it from traditional modeling approaches. The advantages of ABM over traditional modeling are stated, specifically its main appeal in revealing emergent properties of natural and social systems. Finally, some applications of ABM across disciplines are discussed to illustrate its utility and broad appeal.

Chapter 3 details the methodology of the ABM model used in the major project. A general overview of NetLogo is provided to explain the basic functions of the software and why it was selected for the model. The next chapter also explores the interface of the model with which users will interact with the model’s parameters and outputs. Moreover, the parameters and data sources of the model are detailed. Finally, an overview of the model is provided, including a description of its agents and their interactions.

CHAPTER THREE: NETLOGO MODEL

Introduction

This chapter provides an overview of NetLogo, a programmable agent-based modeling software for simulating natural and social systems and phenomena, to illustrate why it was chosen for the major project. A technical description of the model describes its logic and basic functions, the data and its sources, and a summary of the parameters. Finally, the chapter explores the model's interface, the user-defined parameters, and examples of outputs.

NetLogo

NetLogo is a programmable, modeling environment used to simulate complex natural and social systems over time. Authored in 1999 by Uri Wilensky, NetLogo runs on the Java programming language and is designed to support research across a wide range of disciplines. Users can create their own models or open simulations and interact with them. NetLogo is an agent-based software that allows its modelers to explore the relationships between the micro-level interactions of individuals and the macro-level patterns that emerge in the system (Wilensky, 2021). NetLogo is made up of several components that all contribute to its overall function. These components are summarized in the following sections.

Agents

NetLogo is comprised of agents which are programmable beings that carry out instructions set by the user. NetLogo has four types of agents:

- *Turtles:* Agents that move through the environment.

- *Patches:* Agents that compose a square piece of the two-dimensional modeling environment. *Turtles* move over the *patches.*
- *Links:* Agents that connect two or more *turtles.*
- *Observer:* Agent that views the modeling environment and interactions between the other agents; also known as the *user* (Wilensky, 2021).

Instructions

Agent behaviours are determined by instructions in the NetLogo code. Instructions are defined by three main characteristics:

- Instructions are either implemented by the user (*procedures*) or are built into NetLogo (*primitives*).
- Instructions can produce an output (*reporters*) or not (*commands*). A *reporter* provides instruction to product a result and reports it. The instruction is preceded by *to-report* and concluded by the *end* keywords. Alternatively, a *command* describes an action for agents to carry out. It is preceded by *to + a verb* (e.g., create) and concluded by *end.*
- Instructions can have a single, multiple, or no inputs. Inputs are values that modify the instructions for the agents to carry out (e.g., number). (Wilensky, 2021).

The user can use the *ask* command to specify commands to be taken by certain agents. The *ask* command can target all of a particular type of agent, (e.g., *ask turtles*), or a particular agent, (e.g., *ask turtle 2*).

Variables

Variables are defined to store values using the *set* command. Global variables have one value and can be accessed by every agent. Users define global variables in the Interface tab by adding a switch, a slider, an input box, or a chooser. Alternatively, global variables can be defined using the *globals* keyword in the Code tab. Local variables are used only in a particular context (i.e., part of a procedure). Users define local variables using the *let* command.

Ticks

In NetLogo, time occurs in discrete steps called *ticks*. A tick counter above the view records how many *ticks* have passed. Usually, the tick counter starts at 0 and increases by 1 each time, but can be advanced in fractional amounts as well.

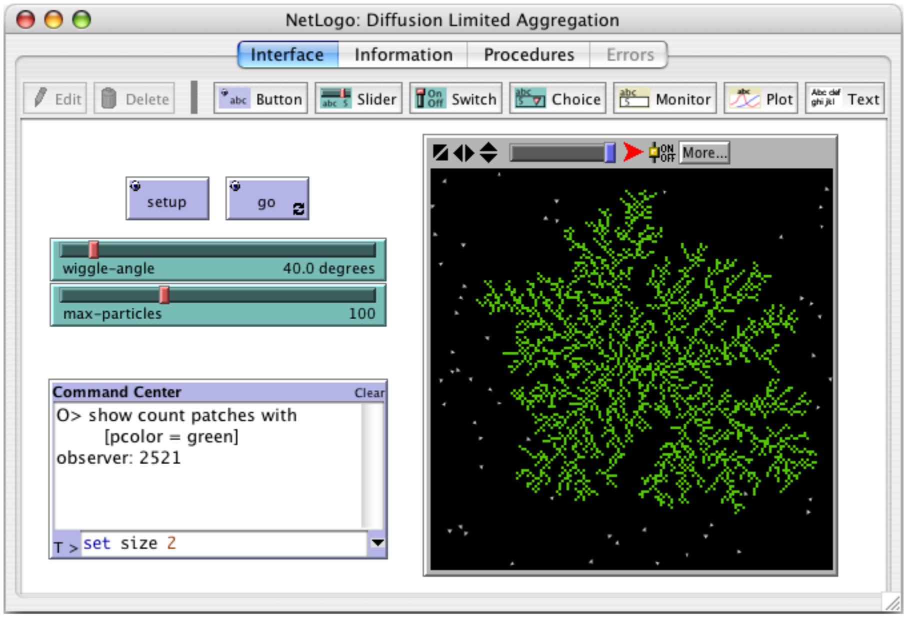
Interface Tab

The Interface tab is where the user can setup the model, alter parameters, and view outputs of the model as it runs. The Command Center allows the user to issues commands without adding new model procedures. The Interface tab allows the user to create items to interact with the model. These elements are summarized below (Table 1):

Item	Description
Button	Executes instructions once or forever (until the user stops the action)
Slider	Global variable that allows the user to change the value of the variable
Switch	Global variable that can be turned on (true) or off (false)
Chooser	Global variable that has a list of values in a drop-down menu
Input	Global variable that allows the user to input a value

Table 1. Summary of Interface Elements. *The descriptions of common interface elements that can be added by the user in the Interface tab.*

An example of a NetLogo Interface tab is shown below:



wiggle-angle 40.0 degrees

max-particles 100

```
O> show count patches with
        [pcolor = green]
observer: 2521
```

```
T > set size 2
```

Figure 3. Example of NetLogo Interface. *From 'NetLogo: A Simple Environment for Modeling Complexity', by Tisue, S. & Wilensky, U., 2004, Center for Connected Learning and Computer – Based Modeling Northwestern University, p. 3.*

Info Tab

The Info tab allows the author to explain the model, including how the model was created and how to use it. The author can also highlight specific features of the model for users to explore.

Code Tab

The Code tab stores all the code necessary for the model to function. Unlike the Command Center in the Interface tab, the procedures in the Code tab are used repeatedly and can be saved. The Code tab contains an error-checking function that searches the code for any syntax errors. If an error is found, a highlighted message will appear notifying the author.

Model Description

The model is based on the negative correlation between greenness and hazard ratio observed in Crouse et al. (2017). The model simulates tree planting in residential neighbourhoods across the Fletcher’s Creek subwatershed of the CRW in the Peel Region. While the model operates within one subwatershed, the methodology is applicable to the CRW broadly with the appropriate changes to parameter values (see p. 31). As trees are planted in patches, the mean residential greenness increases and the mean residential hazard ratio decreases. The model tracks the change in hazard ratio over the 50-year run and, in turn, estimates the number of deaths avoided. The model also calculates the economic value of the change in hazard ratio is estimated using the value of a statistical life (VSL). The model may include development of residential areas which lowers greenness and increases the hazard ratio. The model includes additional environmental conditions and parameters that affect the outputs, detailed further in Chapter 4.

Model Resolution

The model uses a resolution of 50 metres for the NetLogo patches and the raster data layers (e.g., the NDVI layer). A 50-metre resolution provides a reasonable size of land use for tree planting and conservation actions that affect greenness in urban areas. Also, the resolution is divisible into the 250-metre and 500-metre distances used in Crouse et al. (2017) to calculate mortality risk with respect to proximity to greenness in Canadian cities.

Agents

The model uses two agents that act autonomously and move within the CRW to perform separate, yet connected, goals.

1. A greening agent
2. A developer agent

Greening Agent

The greening agent moves within the watershed to plant trees. The agent's behaviour is dictated by a set of if-then rules and environmental conditions that are described below.

The agent is limited to a user-defined tree planting budget. The agent will continue to plant trees until it has exhausted the tree planting budget (see p. 43) or the simulation has run for 50 years, whichever occurs first. The environmental conditions that influence agent behaviour and/or model outcomes include population growth (which changes the planting budget proportionally), yearly carry forward budget balance (yes or no), development charge contributions to the tree planting budget (which is influenced by a number of other parameters), the natural tree growth rate, the number of trees planted on patches, and the average cost per street tree.

The agent plants trees on plots with suitable conditions, prioritizing areas with low greenness values as calculated using a Normalized Difference Vegetation Index (NDVI) calculated from remote sensing imagery (see p. 56). By default, the agent is coded to plant a predetermined number of trees per patch in each year (or one "tick" which equals one year). This is represented by the p*lant_tree_number_per_time* parameter (see p. 30). The agent is only able to plant trees in an eligible patch once per tick, at which point, it will move to the next eligible patch, and so on, until the next tick. The greening agent can re-visit patches to plant additional trees during the model's runtime, but each patch cannot exceed the value of the *max_trees_planted_number_per_patch* parameter. By default, a patch can have a maximum of 75 new trees planted through the model's runtime. The *max_trees_planted_number_per_patch* value can be altered in the user interface (see p. 30). Besides the planting of new trees, the average natural growth rate of trees increases the greenness values over the model's run. In addition, any remainder in the tree planting budget is not carried over to the next tick. This reflects the reality of operating tree planting budgets which are set each year by the municipality and do not consider any leftover funds from the previous budget year. In the model, this is parameterized as the Carry Forward Balance and is turned off by default. These default values of the parameters can be changed by the user in the NetLogo interface.

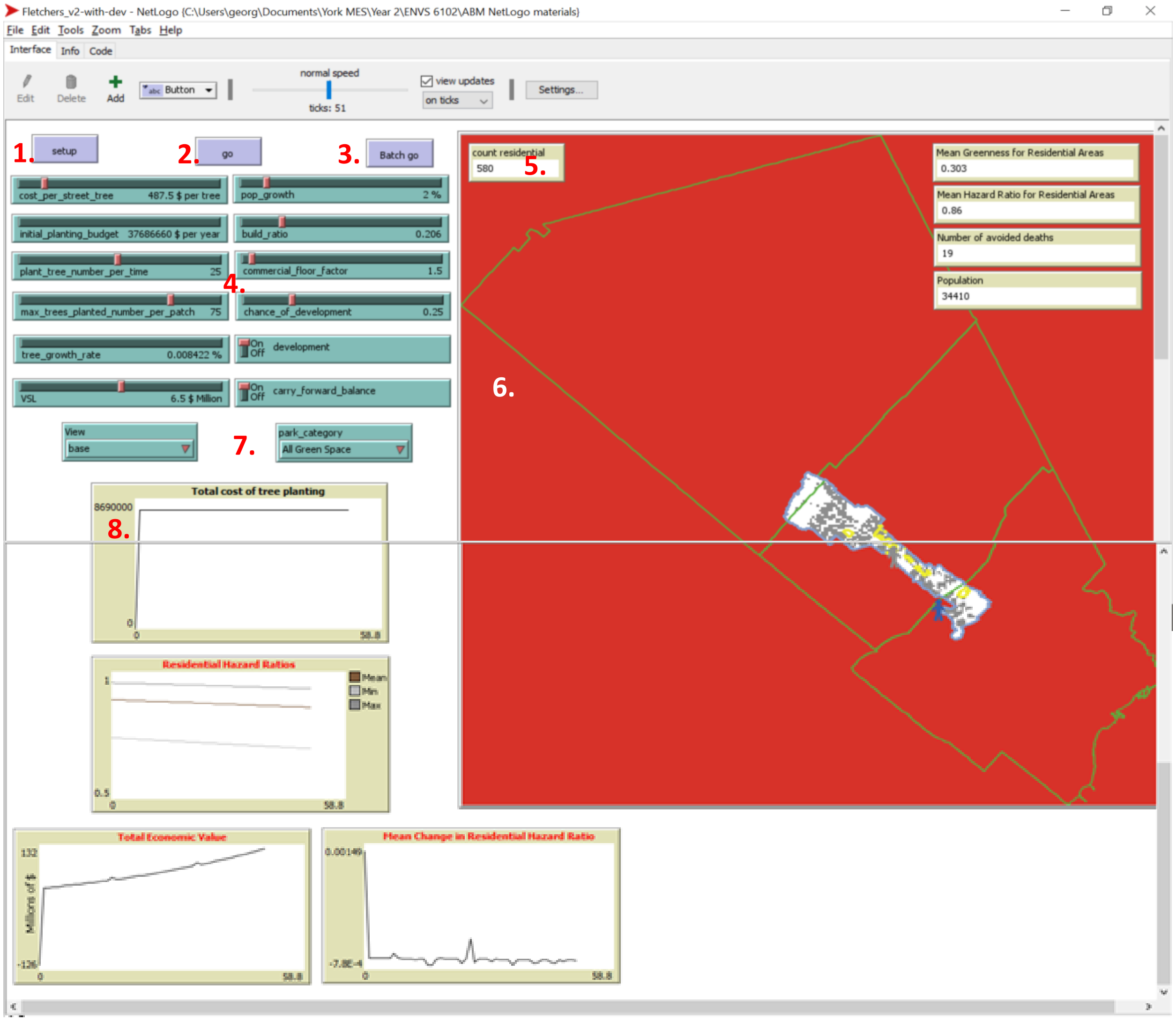
Developer Agent

The developer agent moves within the watershed and converts plots adjacent to residential land use into new residential area. The developer is bound by a chance of development each time it moves to a developable plot; if development occurs, the plot is converted to residential, and if development does not occur, the plot does not change. The developer can identify residential area using land use classification data built into the model. The developer's activity in the watershed lowers the greenness value and therefore increases the hazard ratio. Effectively, the developer agent creates new suitable plots for the greenness agent to plant new trees.

By default, the developer agent is turned off in the model. The user can switch the developer on and off using the *development* switch (see p. 33). In addition, the chance of development is set to 0.25 and can be altered using the slider on the user interface. The environmental conditions and parameters that affect the agent's behaviour and/or the model's outputs include the development charges (which are generated from new developments), and the built ratio and commercial floor factor (which affect the calculation of commercial development charges).

User Interface

The user interface (Figure 2) was designed to allow users to interact with the model, modify its parameters, and view its outputs. The numbered components of the interface are explained below:



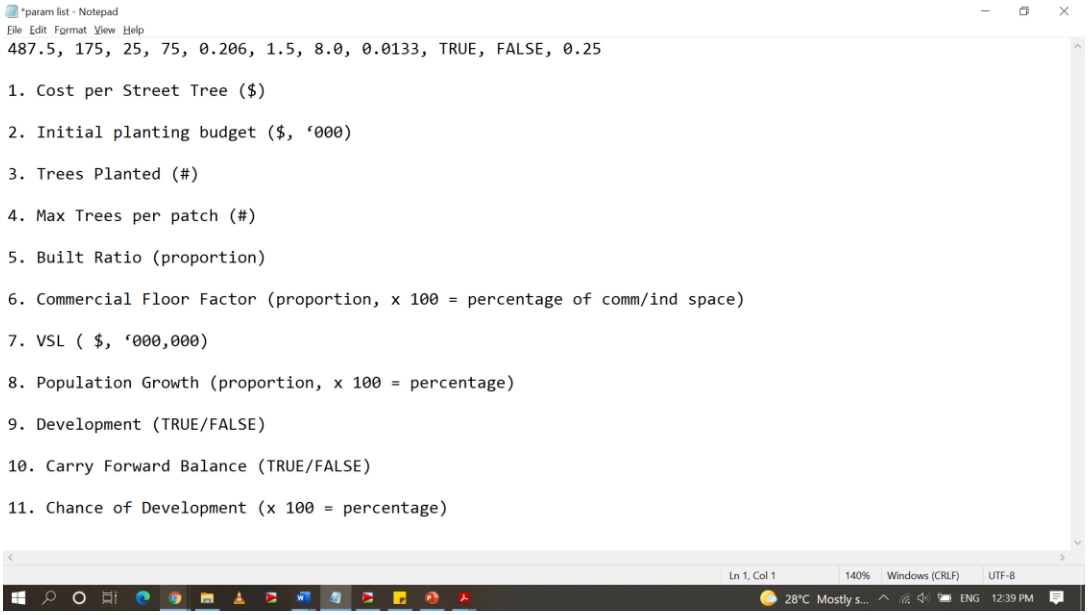
cost_per_street_tree 487.5 $ per tree
pop_growth 2 %
initial_planting_budget 37686660 $ per year
build_ratio 0.206
plant_tree_number_per_time 25
commercial_floor_factor 1.5
max_trees_planted_number_per_patch 75
chance_of_development 0.25
tree_growth_rate 0.008422 %
On Off development
VSL 6.5 $ Million
On Off carry_forward_balance
View base
park_category All Green Space

count residential 580
Mean Greenness for Residential Areas 0.303
Mean Hazard Ratio for Residential Areas 0.86
Number of avoided deaths 19
Population 34410

Figure 4. Model Interface. *The user interface of the NetLogo model. The main components are numbered and described in further detail below.*

1. The *setup* button contains the procedure required to initialize the model environment. Upon pressing the *setup* button, the model reconfigures itself following the code in the Code tab. It loads the GIS data to view, the greening and developer agents, and calculates initial parameter values for greenness and hazard ratios. The user needs to press the *setup* button to reconfigure the model to its initial state before every new run.

2. The *go* button executes the code with the parameter values selected in the interface (see #4). The model runs until the *go* button is pressed again, or when 51 ticks have passed, whichever comes first.
3. The *batch go* button functions as the *go* button, but reads the parameter file for the initial parameter values. Each additional line in the parameter file is another scenario for the model to run (Figure 3). The user can modify the parameter values and the number of scenarios to run. The user needs to change the following code within quotations under the *batch go* procedure with the name of the desired parameter file: file-open "inputs/parameters.txt".



```
487.5, 175, 25, 75, 0.206, 1.5, 8.0, 0.0133, TRUE, FALSE, 0.25

1. Cost per Street Tree ($)

2. Initial planting budget ($, ‘000)

3. Trees Planted (#)

4. Max Trees per patch (#)

5. Built Ratio (proportion)

6. Commercial Floor Factor (proportion, x 100 = percentage of comm/ind space)

7. VSL ( $, ‘000,000)

8. Population Growth (proportion, x 100 = percentage)

9. Development (TRUE/FALSE)

10. Carry Forward Balance (TRUE/FALSE)

11. Chance of Development (x 100 = percentage)
```

Figure 5. Parameter File for Batch Go Procedure*. The 11 parameters that can be modified by the user in the parameter file. Each parameter and its default value are identified. The order of the parameters must be kept consistent for the code to be executed properly.*

4. The twelve parameters that modify how the model runs and how the agents behave. Each parameter can be altered by the user using its corresponding interface elements. The

default value of each parameter, and the range of values possible, are summarized (Table 2). Each parameter is explained briefly below:

- *Cost_per_street_tree*: A slider that sets the average cost per street tree planted by the greening agent.
- *Initial_planting_budget*: A slider that sets the initial tree planting budget available to the greening agent. The tree planting budget increases with residential population growth and a proportion of development charges if *development* is enabled.
- *Plant_tree_number_per_time*: A slider that determines the number of trees the greening agent plants upon visiting an eligible patch.
- *Max_trees_planted_number_per_patch*: A slider that determines the maximum number of new trees that can be planted in each patch throughout the model's run.
- *Tree_growth_rate*: A slider that sets the average natural growth rate of trees throughout the model's run. The growth rate refers to the increase in greenness per year due to the increasing canopy size of trees.
- *VSL*: A slider that sets the value of a statistical life (VSL) throughout the model's run. The VSL is multiplied by the deaths avoided to generate the economic value of tree planting in each tick.
- *Pop_growth*: A slider that sets the population growth of each patch. This increases the residential population in the model environment at the start of each tick. The population growth also increases the tree planting budget proportionally at the start of each tick.

- *Build_ratio*: A slider that sets the built ratio of commercial and industrial plots in the model environment. This determines the proportion of new commercial and industrial development that is subject to development charges. If *development* is disabled, this parameter does not contribute to the model's outputs.
- *Commercial_floor_factor*: A slider that sets the commercial development floor multiplier for new commercial development. The *commercial_floor_factor* is multiplied by the proportion of built commercial area (*build_ratio*) to yield gross floor area (GFA). The GFA is multiplied by the commercial development charge rate to determine the total amount of development charges. If *development* is disabled, this parameter does not contribute to the model's outputs.
- *Chance_of_development*: A slider that sets the chance of development occurring each time the developer agent visits an eligible patch. If eligible, the agent will develop the patch; if not, the agent will move to the next eligible patch. This parameter does not affect the model if *development* is switched off in the interface.
- *Development:* A switch that enables or disables residential and commercial development in the model. If enabled, the developer agent will operate in the patches of the model environment (see p. 28). The resulting development generates development charges, depending on the type of development and in which municipality it occurs, which contribute to the tree planting budget available to the greening agent in subsequent ticks. By default, the model allocates 50% of the total calculated development charges to the tree planting budget.

- *Carry_Forward_Balance*: A switch that enables or disables the carrying over of any remainder in the planting budget to the next tick. If enabled, the remainder is added to next tick's tree planting budget, thus increasing the amount of funds available to the greening agent.

Parameter	Min	Max	Default	Units
Cost_per_street_tree	50	2000	487.5	$
Initial_planting_budget	0	5000	175	$ thousands
Plant_tree_number_per_time	5	50	25	#
Max_trees_planted_number_per_patch:	25	200	75	#
Build_ratio	0.15	0.95	0.206	%
Commercial_floor_factor	1	5	1.5	#
VSL	8	8	8	$ millions
Pop_growth	0	0.1	0.0133	%
Development	FALSE	TRUE	TRUE	binary
Carry_Forward_Balance	FALSE	TRUE	FALSE	binary
Chance_of_development	0	1	0.25	%

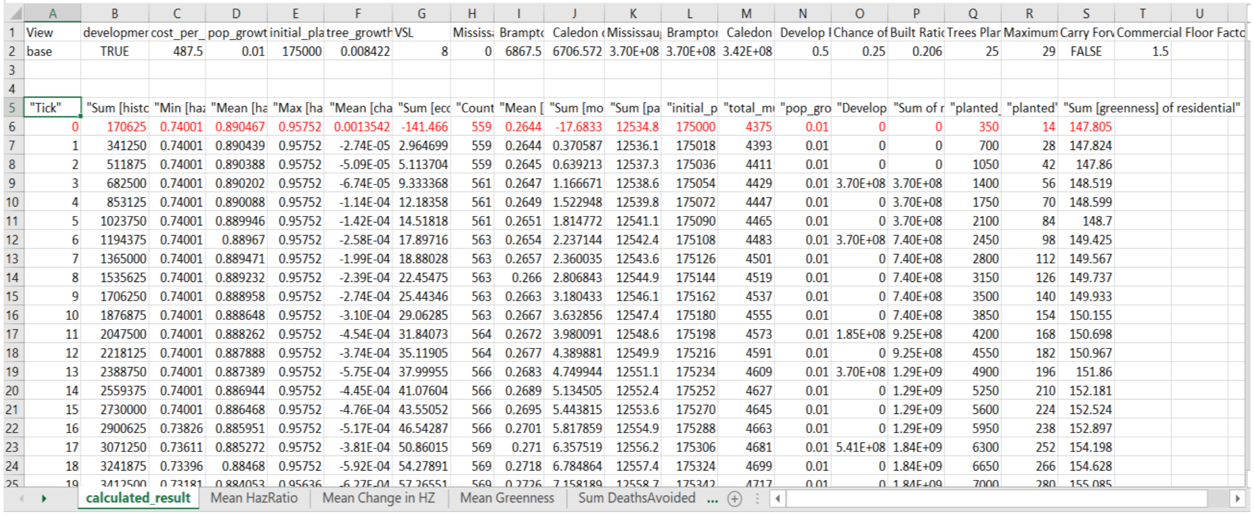
Table 2. The Range of Values Available for each Parameter in the User Interface. *The default values for each parameter are explained further in Chapter 4.*

5. The fields record the values of outputs throughout the model's run, including mean greenness, mean hazard ratio, number of avoided deaths, population, and the number of residential patches.

6. The view panel shows the model environment in the CRW. The panel shows the change in greenness and development across the patches. The greening agent and the developer agent, if enabled, are present and move throughout the environment over the 50-year run.
7. The *view* and *park_category* choosers modify the view panel to show the selected information.
8. The output plots show the change in outputs over the course of the model's run.

Model Outcomes

After each model run, the outputs are stored within a *results.csv* file (Figure 6). The file contains a summary of the initial parameter values used in each run. Each run has a duration of 51 ticks, and each tick has the outputs that were calculated during that time period. Tick 0 initializes some of the model's parameters, and therefore, is discarded from the subsequent analysis. Thus, the results data for each 50-year run starts at tick 1 and ends at tick 51. The *results.csv* file calculates summary statistics for the main outputs of the model which are used to generate graphs. The model interface also keeps track of the changes of several outputs throughout the run (Figure 7).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	View	developmer	cost_per_	pop_growt	initial_pla	tree_growth	VSL	Mississ:	Bramptc	Caledon c	Mississau	Bramptor	Caledon	Develop I	Chance of	Built Ratic	Trees Plar	Maximum	Carry Forv	Commercial Floor Factc	
2	base	TRUE	487.5	0.01	175000	0.008422	8	0	6867.5	6706.572	3.70E+08	3.70E+08	3.42E+08	0.5	0.25	0.206	25	29	FALSE	1.5	
3																					
4																					
5	"Tick"	"Sum [histc	"Min [haz	"Mean [ha	"Max [ha	"Mean [cha	"Sum [ecc	"Count	"Mean [	"Sum [mo	"Sum [pa	"initial_p	"total_mı	"pop_gro	"Develop	"Sum of r	"planted_	"planted"	"Sum [greenness] of residential"		
6	0	170625	0.74001	0.890467	0.95752	0.0013542	-141.466	559	0.2644	-17.6833	12534.8	175000	4375	0.01	0	0	350	14	147.805		
7	1	341250	0.74001	0.890439	0.95752	-2.74E-05	2.964699	559	0.2644	0.370587	12536.1	175018	4393	0.01	0	0	700	28	147.824		
8	2	511875	0.74001	0.890388	0.95752	-5.09E-05	5.113704	559	0.2645	0.639213	12537.3	175036	4411	0.01	0	0	1050	42	147.86		
9	3	682500	0.74001	0.890202	0.95752	-6.74E-05	9.333368	561	0.2647	1.166671	12538.6	175054	4429	0.01	3.70E+08	3.70E+08	1400	56	148.519		
10	4	853125	0.74001	0.890088	0.95752	-1.14E-04	12.18358	561	0.2649	1.522948	12539.8	175072	4447	0.01	0	3.70E+08	1750	70	148.599		
11	5	1023750	0.74001	0.889946	0.95752	-1.42E-04	14.51818	561	0.2651	1.814772	12541.1	175090	4465	0.01	0	3.70E+08	2100	84	148.7		
12	6	1194375	0.74001	0.88967	0.95752	-2.58E-04	17.89716	563	0.2654	2.237144	12542.4	175108	4483	0.01	3.70E+08	7.40E+08	2450	98	149.425		
13	7	1365000	0.74001	0.889471	0.95752	-1.99E-04	18.88028	563	0.2657	2.360035	12543.6	175126	4501	0.01	0	7.40E+08	2800	112	149.567		
14	8	1535625	0.74001	0.889232	0.95752	-2.39E-04	22.45475	563	0.266	2.806843	12544.9	175144	4519	0.01	0	7.40E+08	3150	126	149.737		
15	9	1706250	0.74001	0.888958	0.95752	-2.74E-04	25.44346	563	0.2663	3.180433	12546.1	175162	4537	0.01	0	7.40E+08	3500	140	149.933		
16	10	1876875	0.74001	0.888648	0.95752	-3.10E-04	29.06285	563	0.2667	3.632856	12547.4	175180	4555	0.01	0	7.40E+08	3850	154	150.155		
17	11	2047500	0.74001	0.888262	0.95752	-4.54E-04	31.84073	564	0.2672	3.980091	12548.6	175198	4573	0.01	1.85E+08	9.25E+08	4200	168	150.698		
18	12	2218125	0.74001	0.887888	0.95752	-3.74E-04	35.11905	564	0.2677	4.389881	12549.9	175216	4591	0.01	0	9.25E+08	4550	182	150.967		
19	13	2388750	0.74001	0.887389	0.95752	-5.75E-04	37.99955	566	0.2683	4.749944	12551.1	175234	4609	0.01	3.70E+08	1.29E+09	4900	196	151.86		
20	14	2559375	0.74001	0.886944	0.95752	-4.45E-04	41.07604	566	0.2689	5.134505	12552.4	175252	4627	0.01	0	1.29E+09	5250	210	152.181		
21	15	2730000	0.74001	0.886468	0.95752	-4.76E-04	43.55052	566	0.2695	5.443815	12553.6	175270	4645	0.01	0	1.29E+09	5600	224	152.524		
22	16	2900625	0.73826	0.885951	0.95752	-5.17E-04	46.54287	566	0.2701	5.817859	12554.9	175288	4663	0.01	0	1.29E+09	5950	238	152.897		
23	17	3071250	0.73611	0.885272	0.95752	-3.81E-04	50.86015	569	0.271	6.357519	12556.2	175306	4681	0.01	5.41E+08	1.84E+09	6300	252	154.198		
24	18	3241875	0.73396	0.88468	0.95752	-5.92E-04	54.27891	569	0.2718	6.784864	12557.4	175324	4699	0.01	0	1.84E+09	6650	266	154.628		
25	19	3412500	0.73181	0.884053	0.95636	-6.27E-04	57.26551	569	0.2726	7.158189	12558.7	175342	4717	0.01	0	1.84E+09	7000	280	155.085		

Figure 6. The results.csv File. *The results.csv file lists the parameter values that were used in each run (rows 1 and 2 of the spreadsheet). Each tick of the run has the outputs that were calculated during that period of time (rows 5 and onward of the spreadsheet). Tick 0 of each run is required to initialize feedback from certain parameters, specifically population growth and development charges, and is discarded from the dataset. Ticks 1 through 51 make up the 50-year run.*

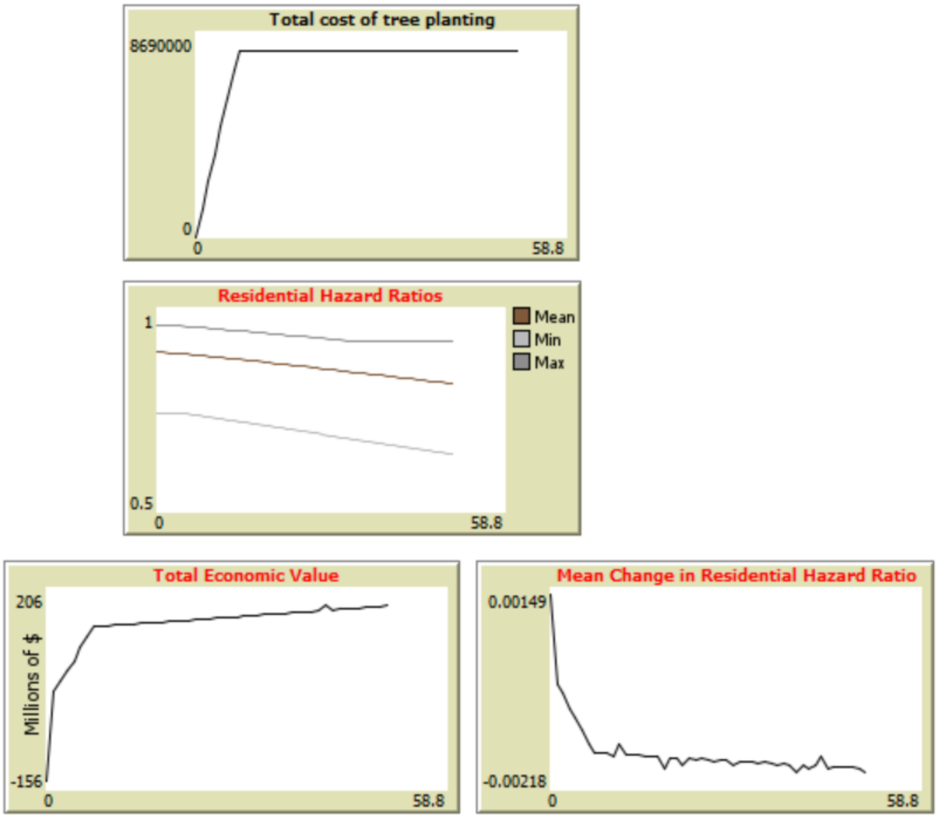
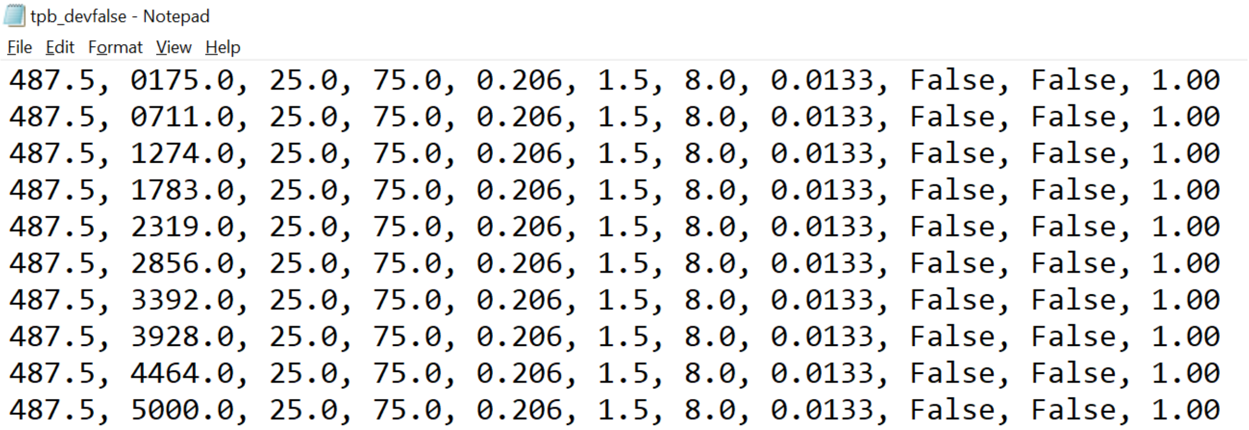


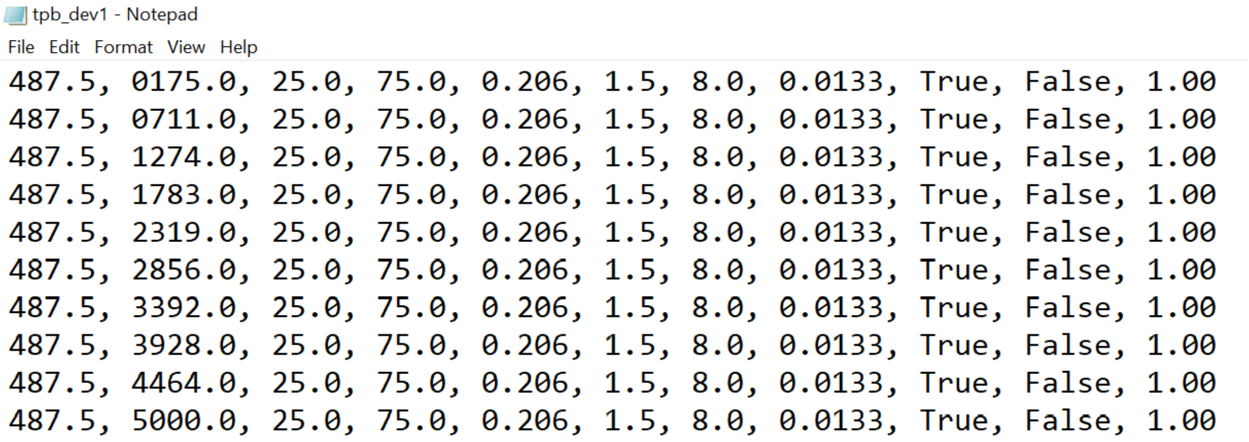
Figure 7. The Output Plots. *The plots in the NetLogo interface track the change in several outputs over the course of each run.*

Due to the number of parameters, there are many different scenarios can be set up and run in the NetLogo interface. I have included the results of two different sets of scenarios: increasing tree planting budgets with no development (Setup 1), and with development (Setup 2), to illustrate the range of results that the model can generate. The results also demonstrate the model behaviour with and without the feedback loop set up by the developer agent.



```
487.5, 0175.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 0711.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 1274.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 1783.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 2319.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 2856.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 3392.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 3928.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 4464.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
487.5, 5000.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, False, False, 1.00
```

Figure 8. Tree Planting Budget and No Development Batch File (Setup 1). *The parameter file with 10 scenarios of increasing tree planting budgets (column 2, in thousands). The tree planting budget values were chosen to meet the maximum possible value in the interface. Development is disabled in all 10 scenarios (column 9) and, therefore, the developer agent does not operate in the model environment.*



```
487.5, 0175.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 0711.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 1274.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 1783.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 2319.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 2856.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 3392.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 3928.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 4464.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
487.5, 5000.0, 25.0, 75.0, 0.206, 1.5, 8.0, 0.0133, True, False, 1.00
```

Figure 9. Tree Planting Budget and Development Batch File (Setup 2). *The parameter file with 10 scenarios of increasing tree planting budgets (column 2, in thousands). The tree planting budget values were chosen to meet the maximum value possible in the interface. Development is enabled in all 10 scenarios (column 9) and, therefore, the developer agent operates in the model environment. The chance of development is set to 1.00 (column 11) which means once the developer agent reaches an eligible patch, development will always occur.*

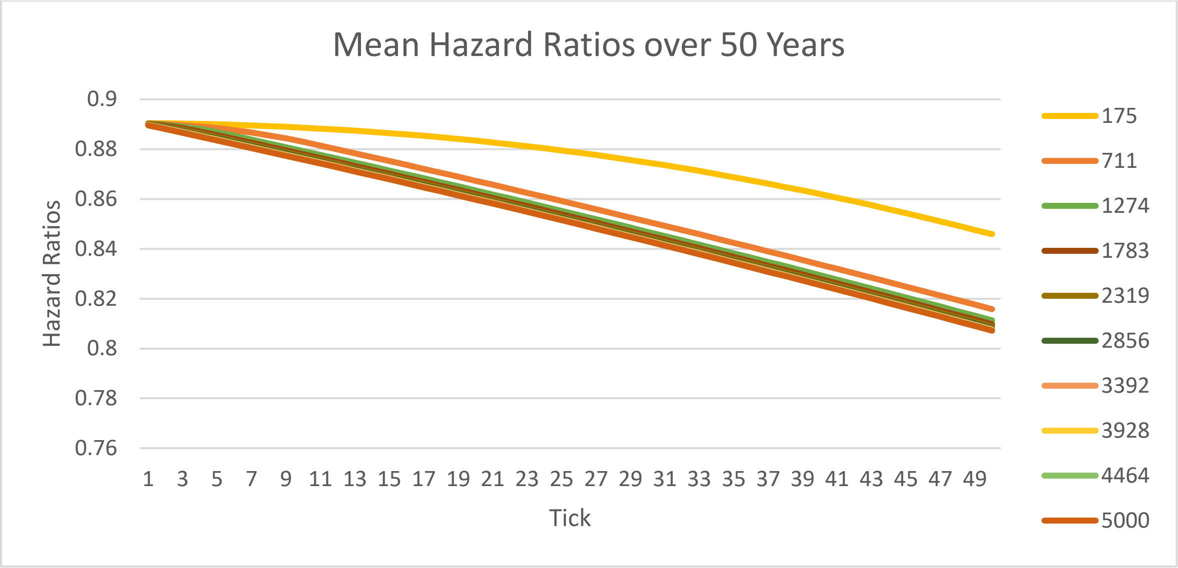


Figure 10. Setup 1 Mean Hazard Ratios. *Mean hazard ratios over 50 years for 10 scenarios with increasing tree planting budgets and no development (Figure 8). Each scenario is differentiated by the amount of initial tree planting budget (in thousands) as shown in the legend.*

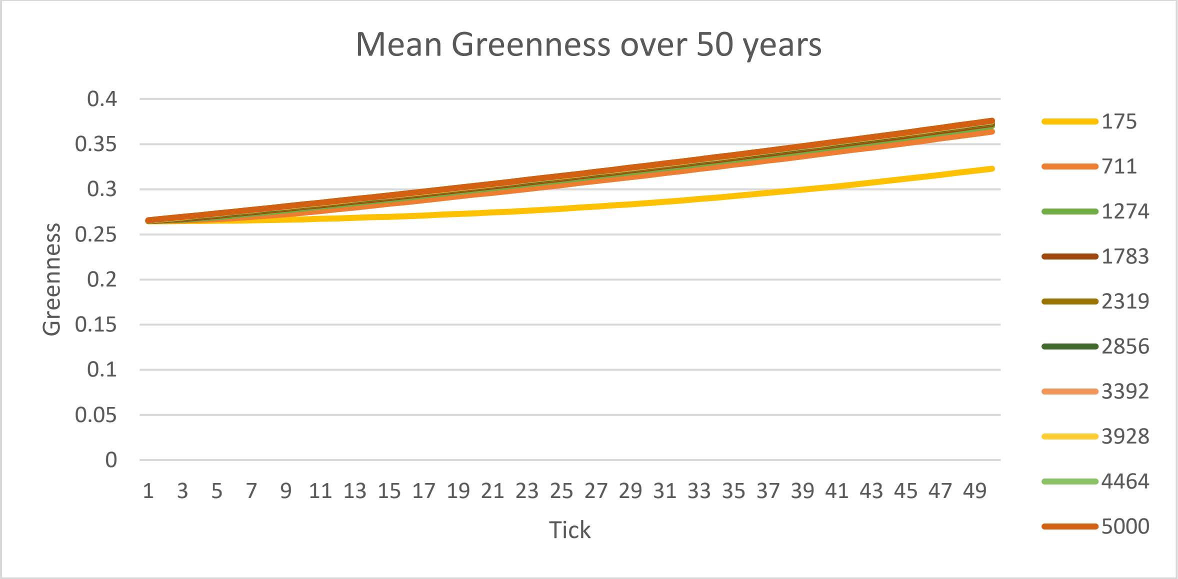


Figure 11. Setup 1 Mean Greenness. *Mean greenness values over 50 years for 10 scenarios with increasing tree planting budgets and no development (Figure 8). Each scenario is differentiated by the amount of initial tree planting budget (in thousands) as shown in the legend.*

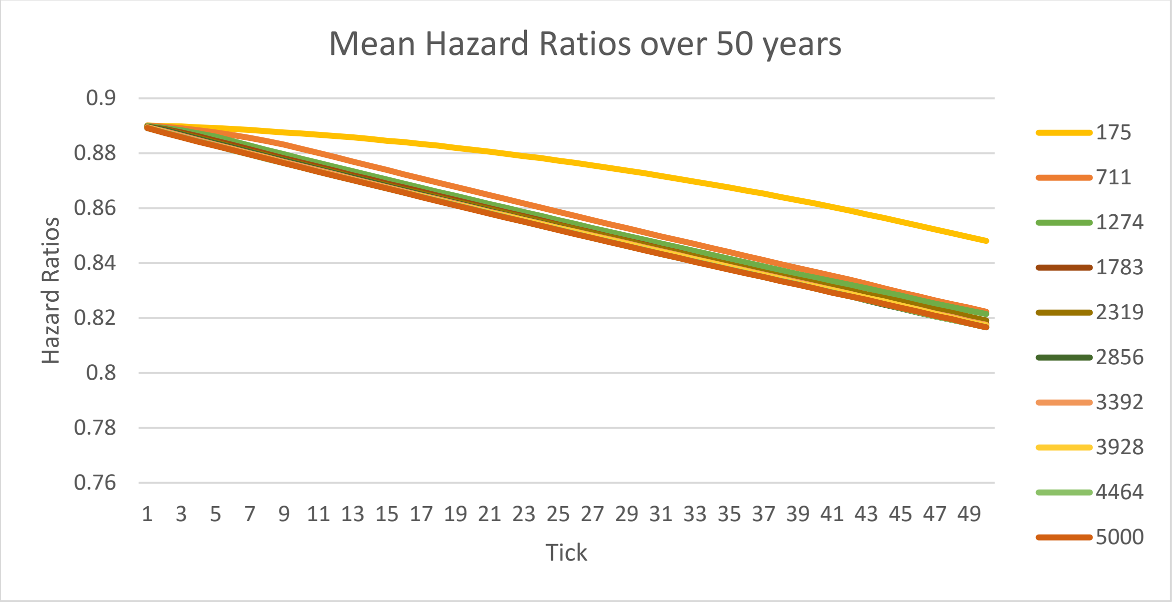


Figure 12. Setup 2 Mean Hazard Ratios. *Mean hazard ratios over 50 years for 10 scenarios with increasing tree planting budgets and full development (Figure 9). Each scenario is differentiated by the amount of initial tree planting budget (in thousands) as shown in the legend.*

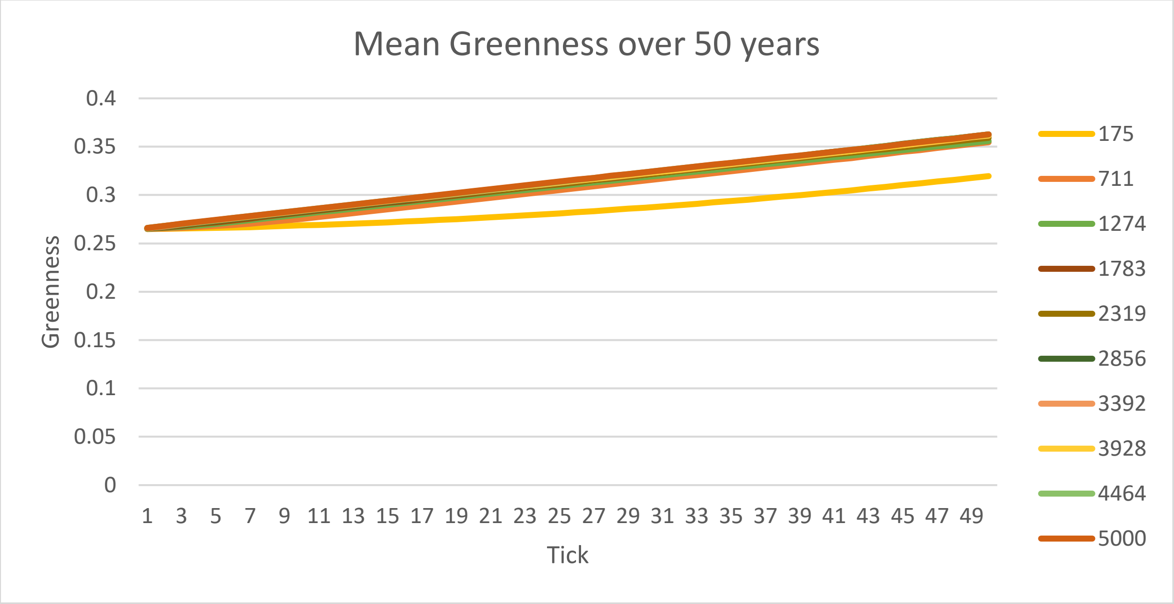


Figure 13. Setup 2 Mean Greenness. *Mean greenness values over 50 years for 10 scenarios with increasing tree planting budgets and full development (Figure 9). Each scenario is differentiated by the amount of initial tree planting budget (in thousands) as shown in the legend.*

Output	Setup 1: Tree Planting Budget + No Development	Setup 2: Tree Planting Budget + Development (CoD = 1.0)
Mean Hazard Ratio	0.854	0.856
Mean Greenness	0.312	0.310
Sum of Residential Greenness	205.639	251.196
Sum of Deaths Avoided	20.612	21.523
Economic Value ($ millions)	165	172

Table 3. Summary and Comparison of Results between both Sets of Scenarios.

In both sets of scenarios, runs with higher initial planting budgets led to higher mean greenness values and lower mean hazard ratios (Figures 4a – 5b). The budget available is the main limitation on the greening agent's ability to plant residential trees, and thus, more funds meant more trees were planted. Setup1 had a slightly lower mean hazard ratio and a higher mean greenness value than the scenario with development Setup 2 (Table 3). The developer agent in the model environment reduces the mean greenness value of the subwatershed due to the development of new residential neighbourhoods. It follows then that if development were absent from the model, the greenness values would increase unopposed. In Setup 2, however, there is a higher sum of residential greenness. This output is calculated by adding the greenness value of each patch in the subwatershed. While Setup 1 had a higher mean greenness in the subwatershed, residential neighbourhoods in Setup 2 had more exposure to greenness (i.e., more exposure to trees planted). This is primarily due to the developer agent which added more residential neighbourhoods, and thus, more eligible areas for the greening agent to visit due to their low greenness values. Finally, the sum of deaths avoided was higher in Setup 2, and thus, generated a higher economic value when multiplying by the VSL (Table 3).

Summary

This chapter provides an overview of the NetLogo software and its components. The chapter discusses the two agents of the model, the greening and the developer agents, and how they behave and interact. A breakdown of the user interface shows the elements with which users can interact, including the parameters that affect the model's outputs. Finally, the chapter provides some examples of results the model produces.

Chapter 4 describes in detail the parameters outlined in the user interface (see p. 28), including the data sources that were used to parameterize the model. This provides additional context for the parameters' default values in the CRW.

CHAPTER FOUR: MODEL PARAMETERIZATION

Introduction

This chapter describes the parameters used in the model, primarily the parameters in the user interface, outlined in Chapter 3. The chapter provides background information and context to familiarize the reader with each parameter. The chapter explains the data and logic used to parameterize the default values of each parameter. We use the best data available for the default values in order to create as close to a real-world scenario of tree planting in the CRW.

Tree Planting Budgets

Background

Tree planting budgets are allocated each year within the planning of fiscal year budgets for municipalities. Fiscal budgets are prepared following the discussion on municipality-wide goals, budgetary priorities and timelines, fiscal constraints, and a comparison to historical actuals for each municipal department. Fiscal budgets are divided into two categories:

- Operating budgets: Funds that provide the same level of service from a municipal department as the previous fiscal year (e.g., street tree replacements); and
- Capital budgets: Funds for infrastructure and asset projects that exceed one fiscal year (e.g., city-wide tree planting).

Funds for fiscal budgets primarily come from tax revenue, user fees, development charges, and other fines and payments. For example, Mississauga estimates that 57% of the City's 2022 fiscal budget will come from property tax revenue in 2021 (City of Mississauga, 2021b).

Tree planting budgets in Mississauga, Brampton, and Caledon have both operating and capital funding. For example, in 2020, Brampton had a $450,000 operating budget to fund street tree replacements and a $1,474,000 capital budget for new tree plantings in parks and the streetscape (W. Speirs, personal communication, March 11, 2021).

Parameterization

The tree planting budgets for Mississauga, Brampton, and Caledon in 2020 were used to calculate an initial planting budget for the model. Figures for operating and capital budgets, in addition to the average labour cost for each tree planted, were considered when determining the initial planting budget for the model. Based on 2020-21 tree planting budgets from municipalities in the Peel Region, an estimated budget of $1.827 million CAD was calculated; however, as the model focuses on residential tree planting, and due to patch-driven methodology of the model, a monetary figure per area was needed. This was calculated using the following:

$$Developed\ Tree\ Planting\ Budget\ (\frac{\$}{km^2}) = \frac{2020-21\ Tree\ Planting\ Budget\ (\$)}{Developed\ Area\ (km^2)}$$

$$= \frac{\$\ 1{,}827{,}000}{446.11\ km^2}$$

$$\cong \$\ 4{,}095.40/km^2$$

This value is the approximate tree planting budget for every square kilometer of residential land in the Peel Region.

As the model operates within the Fletcher’s Creek subwatershed of the CRW, the developed tree planting budget is multiplied by the area of the subwatershed.

$$Fletcher's\ Creek\ Subwatershed\ Tree\ Planting\ Budget$$

$$= \frac{\$\ 4{,}095.40}{km^2}\ x\ 42.7381345068\ km^2$$

$$\cong \$\ 175{,}000$$

Therefore, the initial planting budget of the model is \$175,000; however, the budget can be altered using the *initial_planting_budget* slider on the NetLogo user interface, or by modifying the parameter file if running the model using a batch file (see p. 28).

Upon running the model, the tree planting budget is set as the initial planting budget as defined in the NetLogo user interface. The initial planting budget is the parameter name for the tree planting budget during tick 0 of the model. At the start subsequent tick, the municipal planting budget will grow as the population grows using the following formula:

$$Municipal\ Planting\ Budget\ (t_x)$$

$$= Initial\ Planting\ Budget\ x\ (1 + \left(\frac{Population\ Growth}{100}\right))$$

In addition, the municipal planting budget will increase due to municipal development charges calculated in the previous tick if development is enabled in the interface (see p. 28)**.** This addition results in the total municipal planting budget for the tick.

$$Total\ Municipal\ Planting\ Budget\ (t_x)$$

$$= Municipal\ Planting\ Budget\ (t_x)$$

$$+ Proportion\ of Municipal\ Development\ Charge$$

Cost per Street Tree

Dozens of tree species are selected for municipal tree planting projects across the Peel Region. According to municipal planners and forestry officials in Mississauga, Caledon and Brampton, the cost of planting one tree ranges from $375 to $600 CAD (J. Johnson, personal communication, February 12, 2021; B. Reid, personal communication, May 7, 2021; W. Speirs, personal communication, March 11, 2021). The price includes the cost of the tree, costs associated with tree planting labour, and a two-year maintenance warranty with the contractor. We use the average of this range, or $487.50, as the average cost per tree in the model. This is the default value of the parameter, but it can be changed using the *cost_per_street_tree* slider in the NetLogo interface or by modifying the parameter file if running the model using a batch file (see p. 28).

Carry Forward Balance

Finally, the calculation of tree planting budget can further be modified by the Carry Forward Balance parameter. The Carry Forward Balance adds the remainder of the previous tick's municipal planting budget (i.e., any funds not used by greening agent to plant trees) to the municipal planting budget in the current tick. By default, Carry Forward Balance is turned off, but can turned on using the *carry_forward_balance* switch in the NetLogo interface or by modifying the parameter file if running the model using a batch file (see p. 28).

The Carry Forward Balance is disabled by default due to the nature of municipal budget planning. Each year, fiscal budgets are calculated for services where previous allocations are considered.

Operational budgets are calculated for one fiscal year, and any remaining funds are not typically carried forward. As municipal tree planting budgets in the model combine both operational and capital funds, the model assumes no carry forward balance to reflect the realities of municipal budgeting process.

Development Charges

Background

Following the passing of the *Development Charges Act* in 1997, the councils of municipalities in Ontario gained the ability to implement by-laws for development charges to fund the increased needs for services arising from new developments. The Act details the services applicable to development charges and include water supply, storm water drainage, waste diversion, policing, fire protection, and ambulance (Development Charges Act, 1997).

Peel Region passed the *Development Charges By-Law 77-2020* which came into effect on January 22, 2021. The By-Law establishes development charges against any lands that are developed for a non-agricultural use if the development requires:

- The passing of a By-Law or amendment for a zoning By-Law under Section 34 of the *Planning Act;*
- The approval of a minor variance under Section 45 of the *Planning Act*;
- The approval of a plan or subdivision under Section 51 of the *Planning Act;*
- The completion of a building permit under the *Building Code Act*. (Region of Peel, 2020a).

The development charge rates for Peel Region are adjusted semi-annually, as outlined in the *Development Charges Act,* using latest information from Statistics Canada Quarterly and Non-Residential Building Construction Price Index (Region of Peel, 2020a). The municipalities of Mississauga, Brampton, and Caledon all have separate calculated development charge rates for residential, commercial and industrial developments. According to the *Development Charges Act,* municipalities are required to perform background studies to inform the development of by-laws.

Parameterization

The development charges used in the model are taken from the most recent rates (February 1, 2021) from the major municipalities in the Region of Peel (Table 4).

Region of Peel	**Brampton**[1]		**Mississauga**[2]		**Caledon**[3]	
Land Use	Dev. Charge/unit	Dev. Charge/ m2	Dev. Charge/unit	Dev. charge/ m2	Dev. Charge/ unit	Dev. Charge/ m2
Non-Residential						
Industrial/Commercial	-	$ 248.85	-	$ 272.36	-	$ 243.02
Residential						
Single/Semi-Detached/Duplex Dwelling	$105,166.33	-	$104,335.30	-	$96,909.64	-
Row (Townhouse & Other Multiples) Dwelling	$ 82,376.45	-	$ 83,168.41	-	$76,854.64	-
Apartment Dwelling (> 750 sq. ft.)	$ 72,659.42	-	$ 75,248.42	-	$66,974.57	-
Apartment Dwelling (< = 750 sq. ft.)	$ 41,693.79	-	$ 42,364.11	-	$38,637.76	-

1. City of Brampton. (2021). *Current Development Charges.* Retrieved from the City of Brampton website: https://www.brampton.ca/EN/Business/planning-development/development_charges/Pages/Amended-Rates.aspx
2. City of Mississauga. (2021a). *Development charges by-laws and rates.* Retrieved from the City of Mississauga website: https://www.mississauga.ca/services-and-programs/building-and-renovating/development-charges/development-charges-by-laws-and-rates/
3. Town of Caledon. (2021). *Development Charges.* Retrieved from the Town of Caledon website: https://www.caledon.ca/en/town-services/development-charges.aspx

Table 4. Schedule of Development Charges. *Schedule of development charge rates effective February 1, 2021 for non-residential and residential land use in Brampton, Mississauga, and Caledon. The rates are valid until July 31,*

2021. Residential development charges are calculated per unit and type of residential dwelling. Non-residential development charges are calculated using the total floor area of the development (Region of Peel, 2020b).

Development charges generated from residential and commercial/industrial development in the current tick are applied to the next tick's total municipal planting budgets. Thus, development charges are not included in the budget until tick 1. The model accommodates this by running the model for 51 ticks, and excluding tick 0 from the reported results.

The model calculates average residential development charges in each municipality using the effective residential rates and the land use portion of each residential type (Table 4). Average commercial/industrial development charges use the effective rates, the land use portion of commercial/industrial development, the built ratio of commercial/industrial development, and a commercial floor factor. The calculation results in six average development charges: one for residential and one for non-residential in each of Mississauga, Brampton, and Caledon.

When the developer agent initiates new development in the model, the average residential or commercial/industrial rate is applied depending on the type and in which municipal jurisdiction the development occurs.

Built Ratio and Commercial Floor Factor

Background

The model requires the calculation of development charges (DC) from residential and non-residential (i.e., commercial and industrial) units. Residential DCs have a price designated per unit type (e.g., single or apartment), and non-residential units (i.e., commercial and industrial) are charged per squared meter of gross floor area (GFA). In the CRW, DCs are made up of municipal rates, Region of Peel rates (Region Bylaw 77-2020), and GO Transit rates for residential units only (Region of Peel, 2020b).

The built area refers to the proportion of commercial and industrial land parcels that are developed (i.e., buildings). This figure is needed in order to calculate a built ratio: the area of buildings compared to the area of commercial and industrial parcels. Using the built ratio, the proportion of new commercial and industrial developments that are subject to development charges was integrated into the model. The values were calculated using georectification guidelines as built ratios are not fully documented by planners in the Region of Peel (A. Lalingo, personal communication, March 12, 2021).

Georectification Guidelines and Land Use Sampling

The built area ratio of commercial and industrial land use in the CRW was calculated using land use classification in ArcGIS. Commercial and industrial polygons were selected and the watershed was divided into quadrants. According to georectification guidelines, each quadrant must contain at least 20% sample control points of the data set, and each data point must be separated by a distance of at least 10% of the watershed's diagonal. The diagonal was calculated using the following formula:

$$\frac{Length\ of\ watershed\ (m) + Width\ of\ watershed\ (m)}{2} \times 0.1$$

$$= \frac{62{,}885.37 + 17{,}058.29}{2} \times 0.1$$

$$\cong 3{,}997\ m$$

The length was taken from the top of the watershed to Lake Ontario in the most direct manner. The width of the watershed was taken at its widest point. The length and width were perpendicular to each other. The diagonal was multiplied by a factor of 0.1 to determine the minimum distance by which data points should be separated as per georectification guidelines outlined above.

Selection of Data Points

A total of 40 commercial and industrial polygons were chosen within the boundaries of the CRW. A minimum of 20% (eight polygons) of the data was selected in each quadrant. The centroids of each polygon were calculated to determine the distance between selected points. Polygons were chosen non-randomly, ensuring centroids were separated by a distance of at least 3,997 meters (i.e., 10% of the diagonal of the watershed). Due to the uneven and clustered distribution of commercial and industrial land use, particularly in the northern half of the watershed, not all data points met georectification rules. As a caveat in the northern quadrants, points were selected as far as possible from each other and adhered to the 10% ruling as much as possible.

Calculation of the Built Ratio

The total commercial and industrial area (m^2) was recorded from the land use data. For each of the 40 data points, the built area was calculated by summing the footprint of each building within the polygon. The ratio was then calculated by dividing the sum of built floor space with the total area of the polygon. An average, built area ratio of 0.206 was calculated for the CRW and is the default value in the NetLogo model. This can be altered using the *build_ratio* slider in the user interface or by modifying the parameter file if running the model using a batch file (see p. 28).

Commercial Floor Factor

The built ratio estimates the proportion of building floor space to total commercial and industrial land use area. As development charges for commercial and industrial units are calculated using a price rate per square meter, the gross floor area (GFA) is required. However, municipalities do not track the average number of floors for commercial and industrial units consistently. Due to insufficient data, the model assumes a floor factor of 1.5 by default. The user can use the *commercial_floor_factor* slider in the interface to change the value in the model. The value can be modified in the parameter file if running the model using a batch file (see p. 28).

Population Growth

Background

The Region of Peel monitors population growth to guide planning policy and decisions concerning housing development, employment opportunities, and access to services and amenities for residents. Census data, gathered every five years, is used to assess current population trends for use *The Growth Plan for the Greater Golden Horseshoe* (Region of Peel, 2019).

The Region of Peel uses provincially approved forecast numbers found within *The Growth Plan for the Greater Golden Horseshoe* and aligns with the *Peel Regional Official Plan ROPA 24* (Region of Peel, 2020c). The population figures are derived using Census 2006 data and includes projections every five years up to 2031 (Region of Peel, 2020c). The dataset is listed as official, but is insufficient for the purposes of the model due to its lack of predictive power up to 2071.

Parameterization

The data used for the model was prepared by Hemson Consulting in 2018 for the Region of Peel. The dataset provides draft population projections, employment and housing unit forecasts for the Community Planning Area using Census data in 5-year intervals from 2016 to 2041. The forecast has no formal planning status, but are proposed changes to the Regional Official Plan and are being undertaken through Municipal Comprehensive Review. Projected population values include an undercount correction (Region of Peel, 2020d).

Mississauga

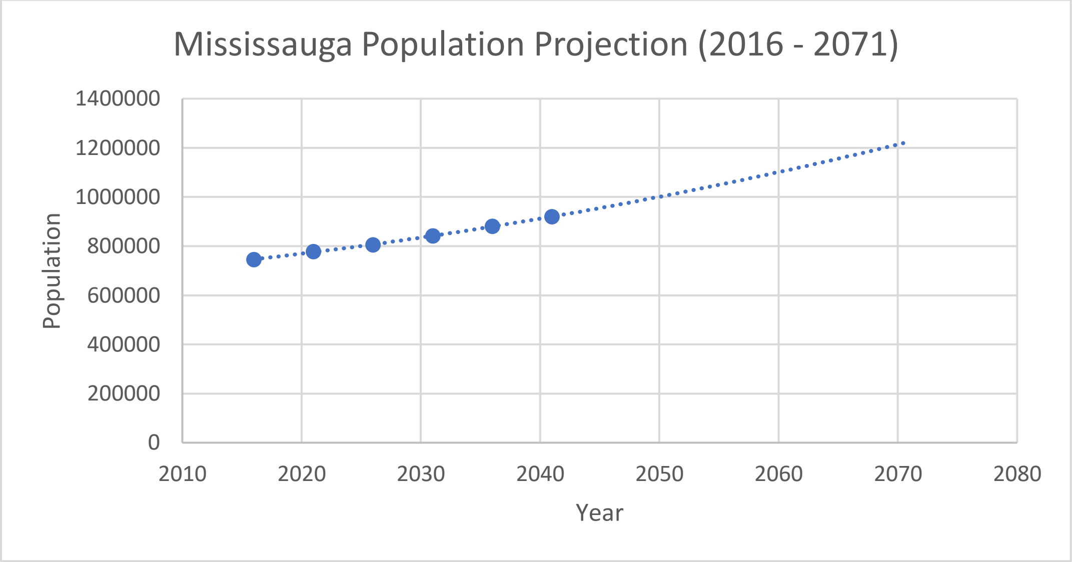


Figure 14. Mississauga Population Estimates. *Population estimates were calculated in 5-year intervals from 2016 to 2041 by Hemson Consulting. Population trendline was projected until 2071 in Microsoft Excel using a polynomial (n=2) trendline (R^2 = 0.9995).*

Brampton

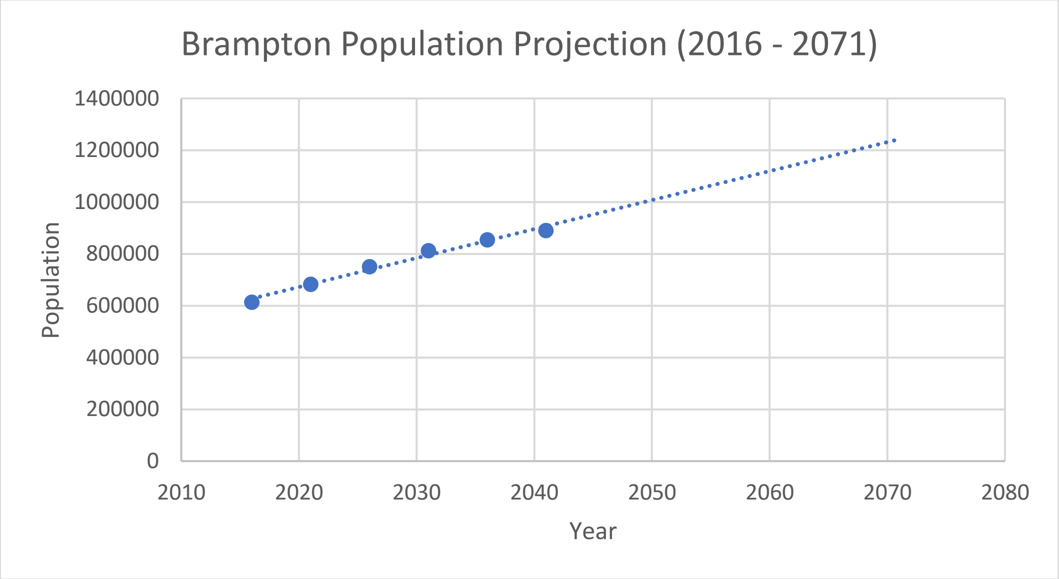


Figure 15. Brampton Population Estimates. *Population estimates were calculated in 5-year intervals from 2016 to 2041 by Hemson Consulting. Population trendline was projected until 2071 in Microsoft Excel using a linear trendline (R^2 = 0.9840).*

Caledon

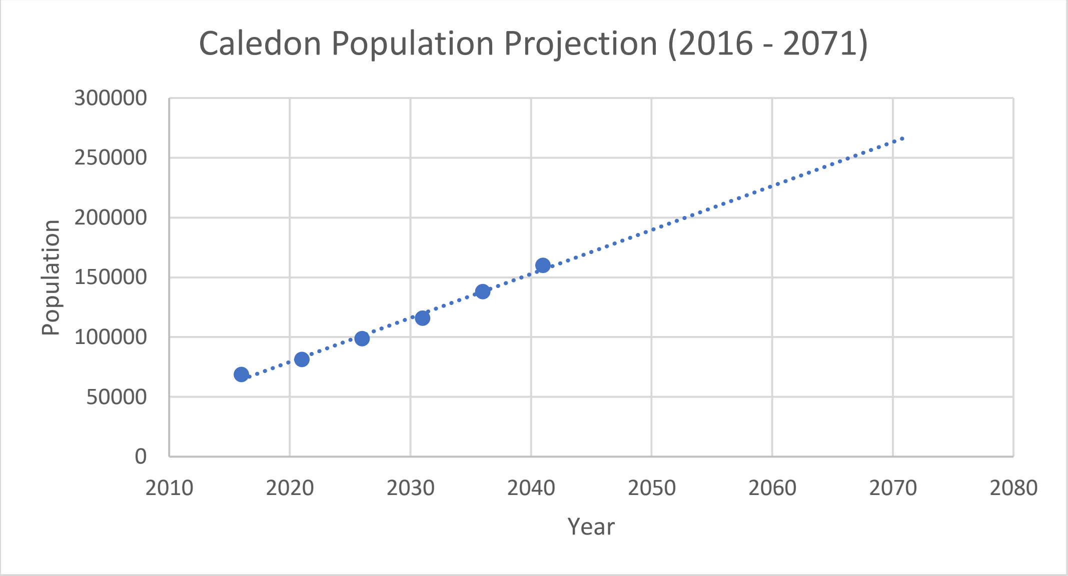


Figure 16. Caledon Population Estimates. *Population estimates were calculated in 5-year intervals from 2016 to 2041 by Hemson Consulting. Population trendline was projected until 2071 in Microsoft Excel using a linear trendline (R^2 = 0.9909).*

Peel Region

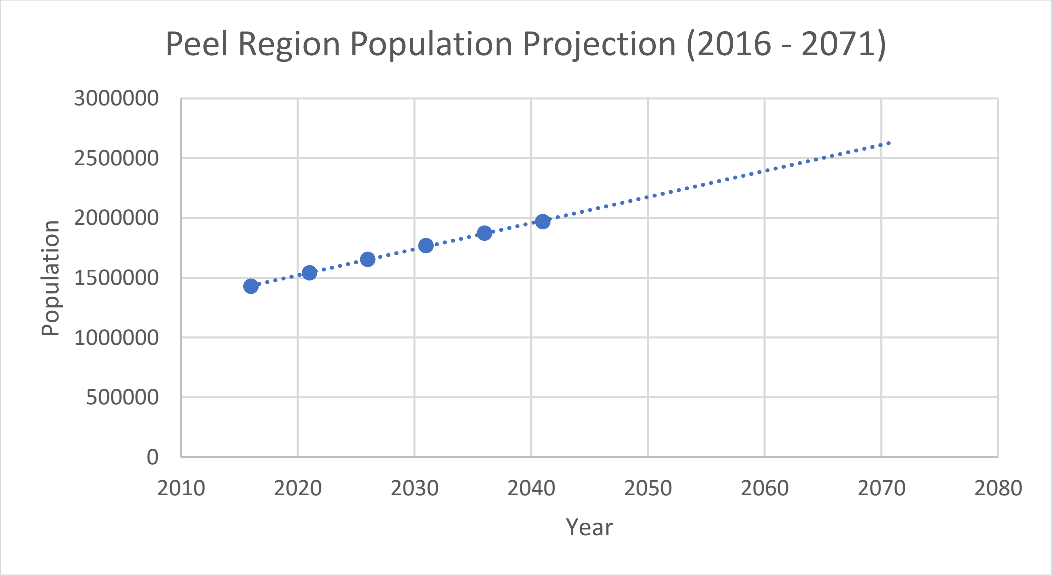


Figure 17. Peel Region Population Estimates. *Population estimates were calculated in 5-year intervals from 2016 to 2041 by Hemson Consulting. Population trendline was projected until 2071 in Microsoft Excel using a linear trendline (R^2 = 0.9990).*

The data from the Peel Region Population Projection (Figure 4) gives an average population growth rate of 1.33% or 0.0133 per year. This is the default value of the model and can be altered using the *pop_growth* slider in the interface or by modifying the parameter file if running the model using a batch file (see p. 28).

Normalized Difference Vegetation Index (NDVI)

Background

Normalized Difference Vegetation Index (NDVI) is an indicator of the quantity of green vegetation on the ground. It is derived using remote sensing satellite data and has range of values from -1 to 1. Negative values represent water surfaces, value near 0 represent bare soil, and positive values represent green vegetation. NDVI quantifies differences in vegetation based on albedo; near-infrared wavelength for vegetation that strongly reflects light and red light for vegetation that strongly absorbs light. NDVI is commonly used as a measure for exposure to greenness (i.e., vegetation cover and/or green spaces) in studies related to human health and wellbeing (Crouse et al., 2017).

Parameterization

The NDVI values are used to calculate a greenness index which is the average NDVI within 250 m of each patch in the model. For each patch, the initial greenness calculation is dependent on the surrounding 2019 Peel Region land use data, 2016 Ecological Land Classification (ELC) data derived by 2013-2015 orthophotos and curated by the Credit Valley Conservation Authority (CVC), Google Earth satellite imagery, and NDVI data derived from July 2014 remote sensing imagery. The calculated greenness values for each patch are essential to define the ruleset for agents within the model.

The NDVI values were added to the model using an ArcMap raster layer using Landsat 8 Bands 4 (B4) and 5 (B5). The B4 captures red light (0.636 – 0.673 µm wavelength) and B5 captures near infrared light (NIR) (0.851 – 0.879 µm wavelength) which vegetation absorbs and strongly reflects, respectively (Barsi et al., 2014). An NDVI value is the quotient of the difference and sum of red and NIR wavelengths:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

The B4 and B5 raster layers store a range of values from ± 3.402823466e+38. We used the Raster Calculator in ArcMap to calculate NDVI values, but the division results were integers. To ensure the NDVI values were non-integers, we used the “Float” algebraic expression.

Initial greenness of the model, prior to any tree planting by the greening agent, is calculated using NDVI values of the CRW. Greenness is initialized in the model using the following command:

$$ask\ mask\ [set\ greenness\ mean\ [patch\ NDVI]\ of\ mask\ in-radius\ 5],$$

where *mask* refers to the watershed. The initial greenness value is the mean of all patch NDVI values within a radius of 250 metres. *Radius 5* refers to the radius of five patches (i.e., each patch has a radius of 50 metres).

The greening agent prioritizes patches with low greenness values when considering where to plant trees, and only does so in those with suitable conditions. Greenness values for the patch will increase over time, based on the user-defined growth rate for trees (see p. 58).

The change in greenness is calculated using the following equation:

$$Change\ in\ greenness = 1 + growth\ rate\ x\ \frac{plant\ tree\ number\ per\ time}{\max trees\ planted\ number\ per\ patch},$$

where *growth rate* is the natural growth rate of trees in the model. *Plant tree number per time* refers to how many trees are planted per patch by the greening agent. The *max trees planted number per patch* refers to the maximum number of trees that can be planted in each patch over the model's run. Both these parameters can be altered in the NetLogo interface (see p. 28).

The model's greenness value only changes with the trees planted and their growth rates. Through this assumption, the background growth rate of naturally-occurring trees in the patches, and any additional tree plantings by citizens, are not considered.

Growth Rate of Street Trees

The model focuses on changes in the watershed's greenness values due to street tree planting. The main assumption is that residential street tree planting will increase greenness over time because older trees have larger forest canopies. Older neighbourhoods have a higher greenness value because they have "fuller" tree canopies compared to newer neighbourhoods with younger trees (i.e., saplings). Using this assumption, three residential neighbourhoods in the CRW were selected to compare greenness (i.e., NDVI) values: Lorne Park and Streetsville in Mississauga, and Mount Pleasant/Lundy Village/Spring Valley in Brampton. Satellite data of each neighbourhood was compared to vectorized land use data to confirm the spatial boundaries in the GIS data, then overlaid with NDVI values to perform statistical analysis (Figures 8a, 9a, and 10a). We plotted the distributions of NDVI values in each neighbourhood (Figures 8b, 9b, and 10b). The summary statistics of NDVI values for each neighbourhood in Table 2.

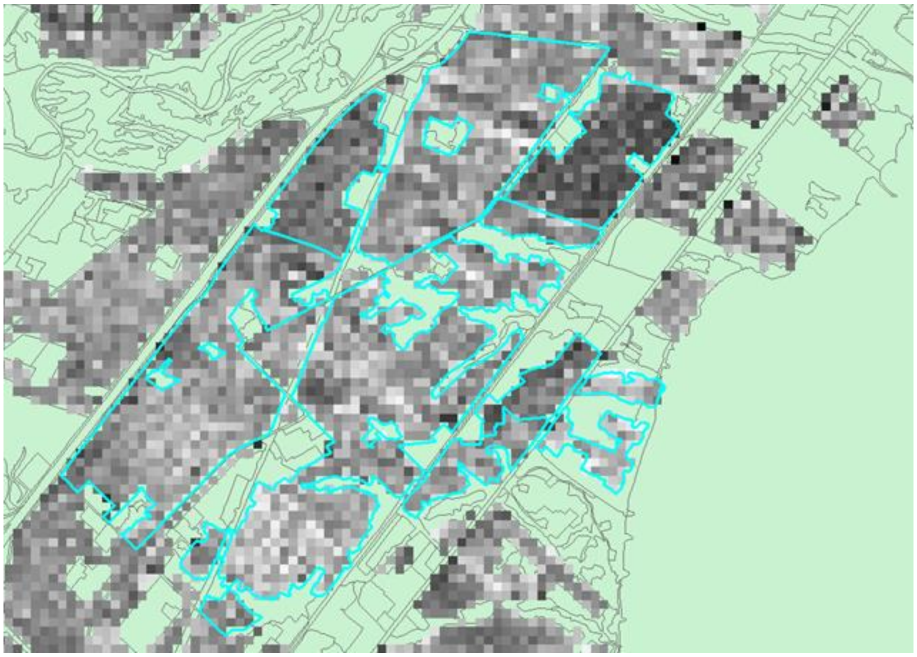


Figure 18. Lorne Park NDVI Data. *The NDVI raster data in the residential areas of the Lorne Park neighbourhood (blue highlight) in Mississauga, opened in ArcMap.*

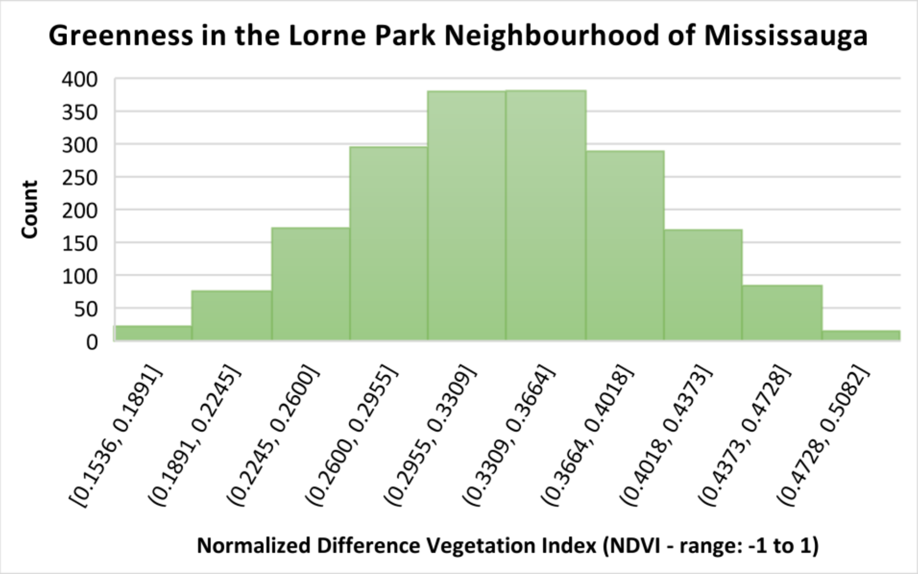


Figure 19. The Distribution of NDVI Values in Lorne Park, Mississauga. *The data was plotted using Microsoft Excel.*

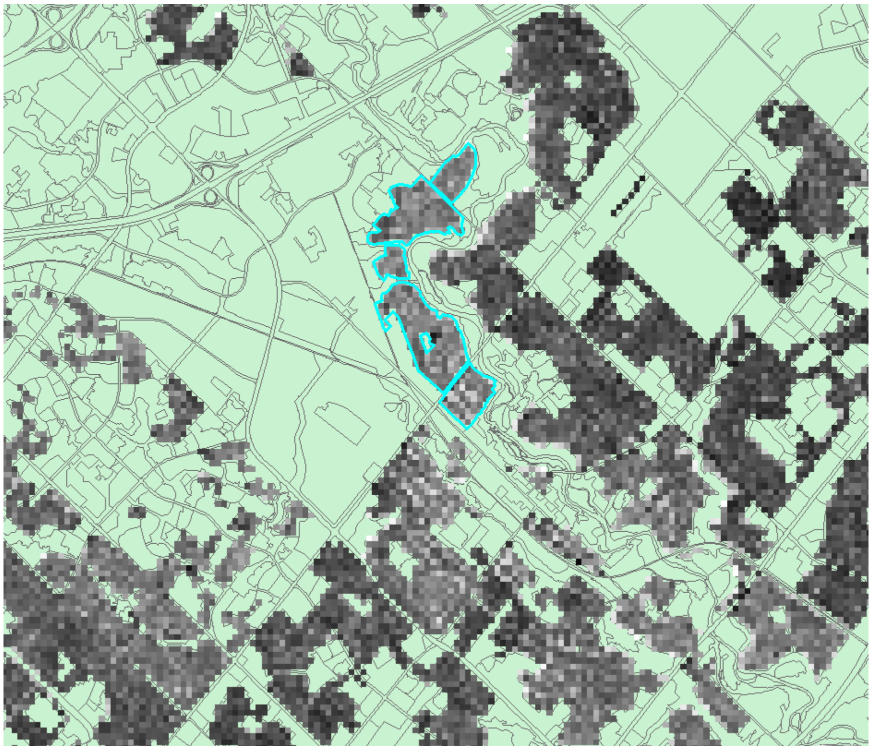


Figure 20. Streetsville NDVI Data. *The NDVI raster data in the residential areas of the Streetsville neighbourhood (blue highlight) in Mississauga, opened in ArcMap.*

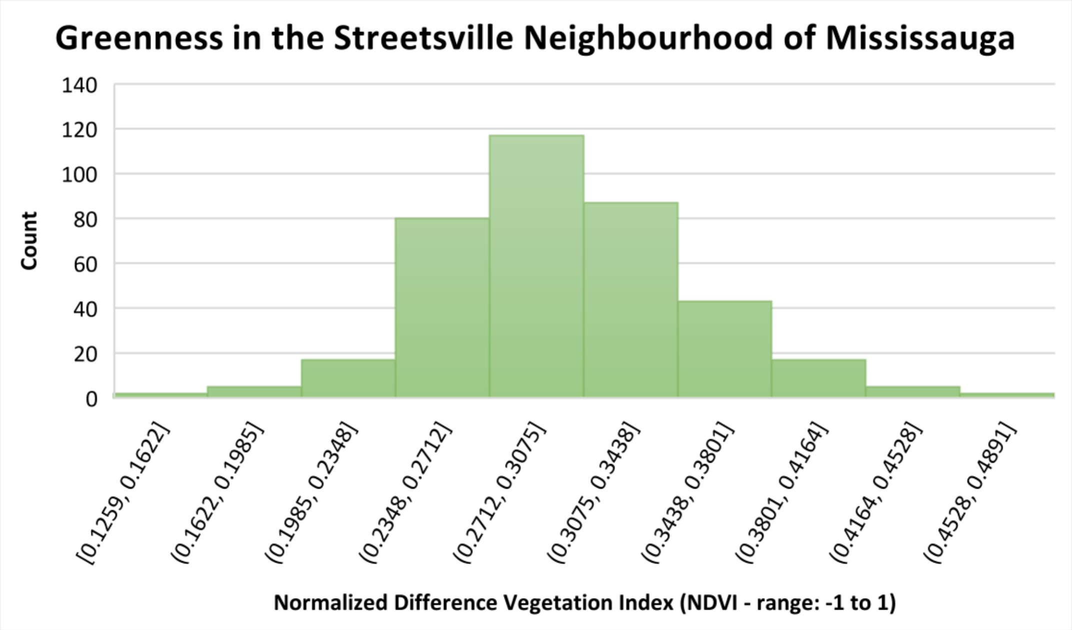


Figure 21. The Distribution of NDVI Values in Streetsville, Mississauga. *The data was plotted using Microsoft Excel.*

Figure 22. Lundy Village/Spring Valley NDVI Data. *The NDVI raster data in the residential areas of the Lundy Village/Spring Valley neighbourhood (blue highlight) in Brampton, opened in ArcMap.*

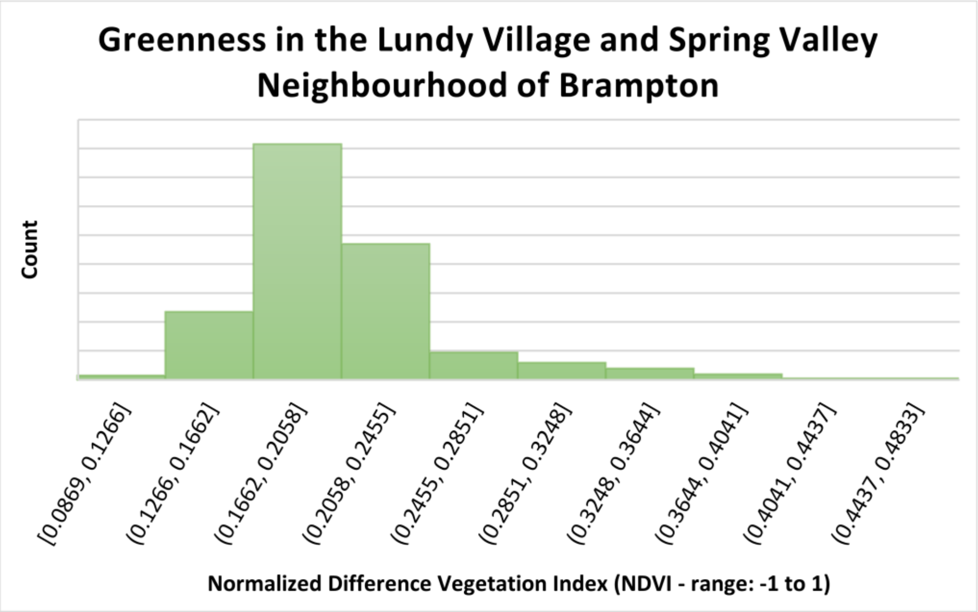


Figure 23. The Distribution of NDVI Values in Lundy Village/Spring Valley, Brampton. *The data was plotted using Microsoft Excel.*

Name of Neighbourhood	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Lorne Park	0.1536	0.5082	0.3303	0.0647
Streetsville	0.1259	0.4891	0.2991	0.0498
Lundy Village and Spring Valley	0.0869	0.4833	0.2050	0.0500

Table 5. A Comparison of Normalized Difference Vegetation Index (NDVI) Statistics between Old and New Neighbourhoods in the CRW.

The difference between the maximum NDVI of old neighbourhoods (i.e., 0.5082 in Lorne Park) and the minimum NDVI of new neighbourhoods (i.e., 0.0869 in Lundy Village and Spring Valley) is 0.42. This value is then divided by 50 years (i.e., the duration of the model). This calculation provides a growth rate of 0.00842% in greenness per year which is the default in the model. Essentially, the default growth rate in the model, over the 50-year run, indicates approximately the time it takes for a sapling to grow into a mature tree and therefore maximize its greenness value in the watershed. The growth rate can be altered by the user using the *tree_growth_rate* slider in the NetLogo interface (see p. 28).

Hazard Ratio

Background

A hazard ratio is a measure of association widely used in studies to compare the relative risk of an exposed population to a non-exposed population. The hazard ratio is the chance of an event occurring in the treatment population over the chance of the event occurring in the control. Thus, a hazard ratio of 1 signifies no association between the treatment and control populations. A value greater than 1 suggests an increased risk in the treatment population while a value less than 1 suggest a smaller risk (Cox, 1972).

Parameterization

Crouse et al. (2017) used Cox proportional hazard models to measure the association between residential greenness, a continuous variable derived from NDVI satellite data, and mortality. Hazard ratios were stratified by age groups (ages 25 to 89), by sex, and by metropolitan area. Hazard models were constructed for six common causes of mortality: all non-accidental causes, cardiovascular disease plus diabetes, cardiovascular diseases, ischaemic heart disease, cerebrovascular disease, and non-malignant respiratory diseases.

The hazard ratio relationship from Crouse et al. (2017) was adapted for the model's calculation of hazard ratio (Figure 11). The following equation is used to calculate hazard ratios in the watershed:

$$Hazard\ Ratio = 0.4251x^2 - 1.0264x + 1.1315,$$

where *x* refers to greenness. Hazard ratio is initialized using initial greenness values (see p. 56). At each subsequent tick, a new hazard ratio is calculated using greenness after tree planting (set as *hr_t1*) and compared to the previous tick's hazard ratio (set as *hr_t0*). The change in residential hazard ratio is the difference between *hr_t1* and *hr_t0.* Afterwards, deaths avoided due to tree planting is calculated using the following equation:

$$Deaths\ Avoided = \ -1(patch\ pop \times change\ HR),$$

Where *patch pop* is the population of the patch and *change HR* is the difference between *hr_t1* and *hr_t0.* The equation is multiplied by -1 to yield positive values. At the end of each tick, the equation calculates deaths avoided and adds the value to a running total of cumulative deaths avoided. The economic value output is calculated at the end of each tick by multiplying the deaths avoided value by the VSL.

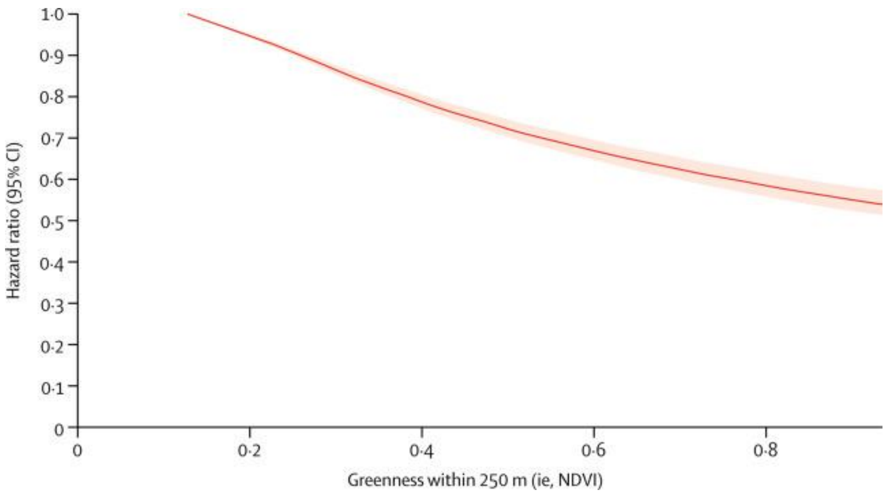


Figure 24. Relationship between Mortality Hazard Ratio and Greenness in Residential Neighbourhoods. *Adapted from 'Urban greenness and mortality in Canada's largest cities: a national cohort study, by Crouse et al., 2017, Lancet Planet Health 1: e295.*

Value of Statistical Life (VSL)

Background

Health and safety policy makers seek to implement regulations that reduce mortality risks. The Government of Canada uses the value of statistical life (VSL) to determine the monetary value associated with a reduction in mortality risk (Treasury Board of Canada Secretariat, 2018). VSL is an aggregate measure of each individual's willingness to pay for a reduction in mortality risk. Willingness to pay (WTP) is a method of economic valuation that calculates an individual's maximum payment to obtain a benefit if a transaction were feasible. (Chestnut & De Civita, 2009). Estimates for WTP are generated from studies which examine people's preferences regarding trade-offs between using resources to reduce mortality risk versus other uses of those resources. Consequently, WTP estimates cannot be used outside the valuation context, and therefore, may vary for the same amount of risk reduction in other contexts (Chestnut & De Civita, 2009).

According to the Treasury Board of Canada Secretariat (2019), the Government of Canada uses the VSL estimate specified in the Cost-Benefit Analysis Guide for Regulatory Purposes. The document uses the average Canadian VSL of $6.5 million (2007 CAD) updated from a meta-analysis completed by Chestnut et al. (1999). The average VSL is expressed in dollars of the desired price year using Statistics Canada's Consumer Price Index. In addition, other VSL values may be used for sensitivity analysis. (Treasury Board of Canada Secretariat, 2018).

To clarify, VSL is not a monetary value for an individual life, but an aggregate value of individual preferences for marginal changes in risk (Treasury Board of Canada Secretariat, 2019).

Example of VSL Calculation using WTP

Regulators seek to estimate the WTP of an affected population to reduce the risk of dying from the consumption of contaminated meat. The reduction in mortality risk is expressed annually in dying due to contaminated meat from 3 in 100,000 to 2 in 100,000. The study calculates an average WTP of $60 from the population; or, put another way, each individual is willing to pay $60 to experience a 1 in 100,000 reduction in mortality risk. The sum of the population's average WTP (i.e., $60 multiplied by 100,000 people) provides the estimate for VSL (i.e., $6 million). The VSL is the aggregate WTP for the population to prevent one death from contaminated meat (Chestnut & De Civita, 2009).

Parameterization

We used the Chestnut et al. (2009) Canadian VSL estimate, and the methodology outlined by the Treasury Board of Canada in the *Canada's Cost-Benefit Analysis Guide for Regulatory Proposals.* The values for Consumer Price Indices (CPIs) were obtained from Statistics Canada's Consumer Price Index Data Visualization Tool (Statistics Canada, 2021). The parameterization uses annual averages for CPIs taken from the most recent full year (2020), and the year the Treasury Board's VSL benchmark was calculated (2007).

$$\text{Value in 2020 CAD dollars} = \text{Value in 2007 CAD Dollars x } \left(\frac{CPI\ 2020}{CPI\ 2007}\right)$$

$$= 6{,}500{,}000 \text{ x } \left(\frac{137.0}{111.5}\right)$$

$$= \$\ 7{,}986{,}547.09 \text{ 2020 CAD}$$

The Canadian VSL estimate is used in our model as the best estimate for the aggregate WTP for reduction of risk. The default value is \$8.0 million CAD and can be altered using the *VSL* slider in the interface or by modifying the parameter file if running the model using a batch file (see p. 28).

Summary

This chapter provided detailed descriptions of the parameters used to calibrate the model, including the definition of the parameter, the context in which the parameters are used, and the data used to parameterize the default values. The parameters that can be altered by the user in the interface are mentioned.

CHAPTER FIVE: MODEL IMPLICATIONS FOR PLANNING

Overall, the model results suggest that larger tree planting budgets and residential development both contribute positively to human health (i.e., hazard ratios and deaths avoided) and economic metrics (p. 40). The results demonstrate the utility in considering human health and well-being when planning urban development. For planners, the model provides an opportunity to explore the impacts of policies and initiatives on ecosystem health, human health, economic development, and all the connections therein. This is possible through NetLogo's use of agent-based modeling and geosimulation. The model allows planners to conduct spatial analyses of their jurisdictions using real-world data and figures, to explore how economic, social and natural phenomena interact and produce patterns, and to investigate how public policies and decisions can affect desired outcomes.

The model demonstrates that municipal planners operate within a complex environment where new approaches are required to solve challenges for both people and the environment. These approaches create an opportunity for planners to adopt an interdisciplinary role and collaborate with public health institutions, conservation authorities, and economists. For example, the model's usage of VSL highlights the importance of incorporating economic valuation techniques into urban planning and decision-making. Economic valuation provides planners with another tool in assessing the impacts of decisions (e.g., residential tree planting) on health and economic metrics (e.g., deaths avoided). A push towards expanding the economic literacy of planners can provide additional information for or add context to addressing planning challenges and opportunities. At the very least, the inclusion of economic valuation of ecosystem services can stimulate new approaches to planning practices or offer different perspectives to governments, institutions, and the public.

Finally, the model, based on the findings of Crouse et al. (2017), highlight the importance of prioritizing tree planting in residential neighbourhoods with fewer street trees and canopy cover. Environmental planners and urban foresters should target these residential neighbourhoods to increase the residents’ exposure to surrounding tree cover and the corresponding benefits to both human health and well-being. This is especially vital in dense, urban areas with limited access to surrounding open or recreational green spaces.

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