Valuation of Ecosystem Services in Toronto’s Parks, Golf Courses, and Open Green Spaces

(Prepared for the Parks, Forestry and Recreation Division, City of Toronto)

Toronto and Region Conservation Authority

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EXECUTIVE SUMMARY

This report presents a quantitative account of key ecosystem services provided by city-owned and operated parks, golf courses, and open green spaces within the political boundary of the City of Toronto. These public green spaces play a major role in keeping the city livable for its inhabitants by mitigating the risk of urban flooding, purifying the air we breathe and the water we drink, removing carbon dioxide from the atmosphere, providing suitable habitat for a diversity of species, and mitigating extreme heat. They also provide the opportunity for people to exercise, to interact with one another and enhance their mental health, and to grow their food locally. These benefits are known as ecosystem services. These services can be measured and (sometimes) monetized to help inform land use planning and resource management on public green spaces in the city.

Toronto and Region Conservation Authority (TRCA) was commissioned by the City of Toronto to quantify, map, and monetize the benefits associated with key ecosystem services provided by City-owned and operated public green spaces and the network of natural assets (e.g., wetlands, trees, meadows, open water bodies, etc.) within these areas. These services are:

- Stormwater Retention and Water Quality Benefits
- Carbon Storage and Sequestration
- Air Quality Regulation
- Civic Contribution
- Food Provision
- Habitat Suitability
- Heat Mitigation (Temperature Regulation)
- Physical Health
- Mental Health

Results are presented as combined annual economic benefits for all services—except for habitat suitability and water quality benefits[1]—and aggregate service provision maps for stormwater retention, water quality indicators, and carbon storage and sequestration.

The total annual value of all monetized ecosystem services evaluated in this study is estimated to be $7.7 billion in 2022. This value should be interpreted as a conservative estimate since it is calculated based on specific modeling assumptions for some ecosystem services, does not reflect the value of all services considered in the study, and is adjusted for inflation based on a one-time Consumer Price Index (CPI) in May 2022 for a fixed basket of goods and services. The results show that $6.7 billion of this amount is provided by the stormwater retention service, highlighting the pivotal role that natural assets play in stormwater runoff reduction across public green spaces in the city. The ecosystem service provision maps in this report also show a greater concentration of aggregate service provision in and around public green spaces overlapping with the Toronto

[1] See sections 4.1 and 4.6 for more information

Ravine System and within natural land cover types such as wetlands, mature and successional forests, and meadows.

Insights from this report can help guide city-wide resource management strategies and land use planning policies concerning natural assets and public green spaces in several ways. These are:

- The results can be used to extract site-specific values for ecosystem services that are both mapped and monetized (i.e., stormwater retention, carbon storage, and carbon sequestration). This would help support the City's capacity for budget prioritization, funding applications, and public education purposes. However, the results should not be used to derive compensation values/tradeoffs.

- The results can be used to identify priority areas for natural asset (green infrastructure) investments based on service provision values for one or multiple services. One potential approach to identify investment priority areas is using a conservation/restoration lens for allocating funds. In this approach, investments should be allocated to restoration efforts in areas with lower service provision and to conservation efforts in areas with higher service provision.

- Findings of this report can be integrated into the City's broader asset management framework. For instance, the results can help inform service level measures for natural assets, which can be used along with information on asset condition and replacement costs to improve the sustainable management of these assets in City-owned and operated parks, golf courses, and open green spaces.

- Service-specific maps can be used in conjunction with the Ecosystem Services Provision Index (ESPI) values to augment the City's Parkland Strategy analyses (e.g., in reference to the Acquisition Priority Map).

- Where applicable, insights from this work can facilitate strategic resource allocation across the ravine system. For instance, service-specific or aggregate service provision maps can help guide resource management, investment, and stewardship strategies on sites overlapping with Priority Investment Areas (PIA) in the ravine system.

The methods presented in this work could also potentially be applied in the future to:

- map ecosystem service provision under multiple land use/cover scenarios. This could in turn inform city-wide land use planning and resource management decisions regarding natural assets under potential future scenarios.
- map stormwater retention and water quality benefits under different precipitation scenarios. This could help characterize and quantify potential stormwater retention and water quality benefits of the existing network of natural assets in the future. This is of strategic importance to the city, as stormwater retention benefits comprise a significant proportion of the annual economic benefits.
- monitor ecosystem service change over time.

Natural assets in Toronto are not limited to the public green spaces considered in this report. These assets are part of a broader green infrastructure network that exists in private lands, on rights of way, and across other green spaces within the city. The totality of these assets is critical to the provision of various ecosystem services that make Toronto a more livable place for all its inhabitants. Only a small proportion of these ecosystem services are analyzed in this study. Nevertheless, the results show that these services generate enormous economic benefits to the city on an annual basis. Protecting and enhancing the natural assets of public green spaces can ensure that these services and their economic benefits will continue in the future. This would in turn make Toronto a more livable city and save billions of dollars in municipal expenditure on engineered assets per year.

Table i. Summary of ecosystem service valuation for City-owned and operated parks, golf courses, and open green spaces

Ecosystem service	Indicator	Unit of measurement	Quantified service level	Estimated economic benefits ($ in 2022)
Stormwater retention	Retention volume (sum of interception, infiltration, and evapotranspiration)	m^3/year	55,360,841	6.7 billion
Avoided phosphorus	Water Quality: Total avoided load of phosphorus	kg/year	15,347	NA
Avoided suspended solids	Water Quality: Total avoided load of suspended solids	kg/year	2,575,673	NA
Carbon storage	The total carbon stocks in four carbon pools	tonne	810,228	817.7 million
Carbon sequestration	Annual carbon sequestration value per land cover	tonne/year	11,235	11.3 million
Air quality regulation	Tonnes of pollutants and particulate matter removed by forests and successional forests	tonne/year	162.3	7.2 million
Food provision	Fresh produce yield from community gardens and allotment garden sites	tonne/year	9.7	11,669
Civic contribution	Voluntary work	Hours worked	11,145.5	279,252
	Financial donations dedicated to parks and park programs	$ /year	112,069	112,069
Habitat suitability	Consolidated habitat suitability categories for nine functional traits of avian and amphibian species	NA	0 - 9	NA
Heat mitigation	Avoided cases of premature mortality	# of lives saved	15	133.5 million
	Avoided cases of emergency department visits	# of avoided visits	135	46,845
	Avoided cases of ambulance service calls	# of avoided calls	83	19,920
	Energy savings	gigawatts	1.4	158,200
	Increased worker productivity among those who are directly exposed to heat	# of days not classified as very hot	6	33 million
Physical health	Number of weekly park visitors that engage in 150 minutes or more of moderate to vigorous physical activity per week above the baseline rate	# of people meeting the physical activity threshold	29,732	10.8 million
Mental health	Number of weekly park visitors with reduced prevalence of mood disorders	# of people without mood disorders	9,546	21.1 million
			Total	**7.7 billion**

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READERS' GUIDE TO THIS REPORT

The purpose of this technical report is to provide decision-makers with information about the value and the geographic distribution of key ecosystem services and benefits provided by the City of Toronto's parks, golf courses, and open green spaces. Throughout the report, key concepts about ecosystem services are explained alongside the relevant technical information to equip readers with an in-depth understanding of the methods used to quantify each service category.

The report is organized into the following sections:

- **Introduction:** this section outlines the overall objectives of the project and provides the definition of natural assets (green infrastructure) in the context of the analysis.
- **Background:** this section provides background information on the project, defines the term "ecosystem goods and services", and explains what natural asset valuation is, how it complements ecosystem service quantification, and how valuation results should be interpreted.
- **Natural Asset Delineation:** this section presents the maps of public green spaces and natural assets within these areas. The section also lists all asset categories along with their descriptions and provides their area in hectares to provide a better understanding of the characteristics and geographic distribution of natural assets in the study area.
- **Quantification of Ecosystem Services:** this section provides background information for each ecosystem service and its importance to the city. The methods are then described for how each ecosystem service was quantified, monetized, and mapped (if applicable).
- **Aggregate Benefits:** this section describes the combined benefits of all service categories in two ways: the total economic benefits of all monetized services and the spatial distribution of mapped regulating services in the study area, informed by a framework that allows for multiple ecosystem services to be visualized together.
- **Summary and Recommendations:** this section provides a summary of the analyses and includes several recommendations to further improve key land use planning and natural resource management policies in the city.

Further information regarding data sources, methods, and findings of this study is provided in the Appendices.

1.0 INTRODUCTION

City-owned and operated parks, golf courses, and open green spaces in Toronto (hereafter the "study area") provide a wide range of ecosystem services for the city and its growing population. The network of natural assets in public green spaces contributes to a higher quality of urban life by regulating air temperature, sequestering and storing carbon from the atmosphere, reducing the risk of flooding and surface water contamination, and improving ambient air quality. Furthermore, spending time in these spaces improves the physical and mental health of individuals and gives them the opportunity to partake in community programs and activities. Also, urban agriculture plots within the study area are widely used by those who enjoy growing their own food. Finally, naturalized spaces within the study area serve as habitat for a variety of wildlife species, who in turn are essential for maintaining and supporting the health of the natural environment in a positive feedback cycle.

Ecosystem services are vital for maintaining and improving the quality of life in Toronto and should be integrated into key land use planning and resource management policies and decisions. To do so, these services can be quantified, monetized, and strategically managed along with the services provided by non-natural assets (e.g., engineered infrastructure) in the city.

This report is intended to inform decision-making on public green spaces in the city by quantifying, mapping, and estimating the economic value of key ecosystem services, using state-of-the-art valuation and mapping techniques. The ecosystem services analyzed in this study include:

- Stormwater Retention and Water Quality Benefits
- Carbon Storage and Sequestration
- Air Quality Regulation
- Civic Contribution
- Food Provision
- Habitat Suitability
- Heat Mitigation (Temperature Regulation)
- Physical Health
- Mental Health

For each ecosystem service, a full description is provided along with information on quantification, mapping, and valuation (where applicable). Quantifying the ecosystem services of natural assets can help inform levels of service for asset management purposes, which is critical for successful, long-term management of municipal natural assets.

The two major objectives of this study are:

1- Quantifying and, where applicable, monetizing the ecosystem services in the study area; and

2- Mapping the provision and geographic distribution of individual and multiple ecosystem services.

This study demonstrates the City of Toronto's continued commitment to advancing the science and application of ecosystem service valuation. The City published two studies in the past that quantify the economic value of different components of the natural assets system across public and private lands. The 2018 Ravine Ecosystem study focused on quantifying the ecosystem services of the ravines within the city. The 2018 Tree Canopy Study included an economic valuation of all the trees and shrubs located within the city. Both studies produced aggregate estimates of ecosystem services valuations without any spatial delineation. The current study differs from the past ecosystem service studies in two distinct ways. First, this study is focused on all natural assets within City-owned and operated (i.e., public) parks, golf courses, and open green spaces. Second, the results of this study include individual and aggregate service provision maps for some of the considered ecosystem services. This information can be used to inform land use planning and investment policies based on the magnitude and geographic distribution of the mapped ecosystem services. However, the economic value produced in this study cannot be simply added to or directly compared with the economic results reported in the previous studies due to partially overlapping study areas and updated methodologies.

The definition of natural assets[2] in this report is based on the definition of green infrastructure assets in Ontario Regulation 588/17, Asset Management Planning for Municipal Infrastructure (O.Reg.588/17). Accordingly, these assets are "natural or human-made elements that provide ecological and hydrological functions and processes and includes natural heritage features and systems, parklands, stormwater management systems, street trees, urban forests, natural channels, permeable surfaces and green roofs." The focus of this study is on the ecosystem services provided by the natural assets within City-owned and operated parks, golf courses, and open green spaces. Consequently, assets located outside of these areas are not included in the analysis. Green roofs, street trees, rights of way, and natural channels are also not considered in this report.

[2] The term natural asset is sometimes interchangeably used with the term Green Infrastructure (GI), but the latter typically refers to a broader spectrum of assets which also includes engineered infrastructure (such as stormwater ponds, raingardens, bioswales, etc.) designed to mimic natural processes in urban areas.

2.0 BACKGROUND

Sustainable management of land and natural resources has become an important consideration in municipal discussions on key land use planning and resource management decisions. With the cascading impacts of climate change and urbanization, more and more urban municipalities are prioritizing nature-based solutions to protect and enhance natural resources within public green spaces. Valuation of ecosystem services in urban green spaces is increasing in importance as an approach to justify and inform these decisions. Urban municipalities seek to maintain, and potentially improve, the quality of life in urban environments by protecting green spaces through informed land use planning and resource management.

Faced with multiple concurrent challenges including, but not limited to, population growth, urbanization, and a rapidly changing climate regime (Climate Atlas of Canada, 2022; Statistics Canada, 2022b; TRCA, 2021a), the City of Toronto is prioritizing the protection and enhancement of public green spaces across the city. Toronto's Parkland Strategy (City of Toronto, 2019a) highlights the role of urban parks as ecosystem service hubs and provides an in-depth analysis of park space provision across the City. According to the Parkland Strategy, due to pressures and constraints limiting expansion of the parkland system, the city-wide average parkland provision per resident is expected to drop by an average of 10% city-wide from the current rate of 28 m^2 of locally accessible parkland per person within the next ten years, with the decline being more pronounced in high-growth areas. Access to parkland is also highly uneven across the city. In high-growth and high-density areas of the city, parkland provision can be as low as 1 m^2 per person or less, far below the city-wide average of 28 m^2, while other areas of the city boast a parkland provision rate of well over 100 m^2 of parkland per person. This is a concerning trend for the utility of urban parks and for the equitable provision of services directly influencing Toronto residents (e.g., physical and mental health). In addition, excessive pressure on park spaces and limits to their expansion could negatively influence the provision of other ecosystem services required to contribute to the city's resilience, rendering parks less effective in the face of future environmental challenges. These findings reinforce the importance of undertaking an assessment of natural assets and ecosystem services in not just parks, but also golf courses and open green spaces.

2.1 Natural Assets (Capital) and their Ecosystem Goods and Services

Natural assets (capital) are the limited stocks of physical and biological resources in the biosphere (MNAI, 2017). These include the natural resources (e.g., land, water, air, and minerals) of Earth's ecosystems, as well as all living organisms (excluding humans) that inhabit them. These assets include some tangible products including clean air, food, water, soil, and fiber, which are commonly referred to as Ecosystem Goods. They also produce a range of benefits that sustain life across terrestrial and marine ecosystems through a web of complex physical, chemical, ecological, and biological processes. These fundamental, though less tangible, benefits are known as Ecosystem Services (ES). Hence, the term Ecosystem Goods and Services (EGS)[3].

[3] For planning and policy purposes, the term "ecosystem goods and services" is often interchangeably used with the term "ecosystem services".

These anthropocentric services can generally be categorized into four different groups (MA, 2005):

- Provisioning Services—the products provided by ecosystems to human societies, including a wide array of nutritional products derived from plants, animals, and microbes, as well as raw materials such as silk and hemp. Other examples include materials used for energy production (e.g., biological materials and wood), genetic resources, biochemicals (e.g., natural medicines and pharmaceuticals), and freshwater resources.
- Regulating Services—the benefits obtained from the regulation of ecosystem processes fundamental to keeping the biosphere habitable for all forms of life. Some examples include the role of natural land covers in flood control, water purification and waste treatment (through filtration and decomposition of organic waste), aquifer recharge, local and global climate regulation (by influencing precipitation, temperature, and the concentration of carbon dioxide in the atmosphere), erosion control, regulation of human diseases (by controlling the abundance of human pathogens, such as cholera, or disease vectors, such as mosquitoes), biological control (i.e., controlling the prevalence of crop or livestock pests), pollination, and protection against storms.
- Cultural Services—the nonmaterial benefits human societies obtain from ecosystems through spiritual enrichment, mental development, creation of social relations, reflection, recreation, ecotourism, and aesthetic experiences. These services are closely linked to social values, human behavior, and the political and economic structure of human institutions.
- Supporting Services— deemed essential for all other services, supporting services are different from other service categories in that their impacts on human societies are either indirect or occur over very long periods, whereas changes in other categories might have immediate and, sometimes, direct consequences on human societies. For example, soil formation can be categorized as a supporting service, as it has no direct use for humans, but a slight change in this process would have direct impacts on our food production capacities. Other examples of supporting services are nutrient cycling, production of atmospheric oxygen, erosion control over a long period, and the provisioning of suitable habitat for wildlife.

2.2 Ecosystem Goods and Service Valuation

Natural resources are typically exploited without regard to their value and the many benefits they provide for human societies. Many societies have failed to thoroughly appreciate the costliness and, in some instances, the improbability of replacing these services with engineered assets. Efforts to change this view have resulted in the emergence of the natural capital and EGS valuation framework. Accordingly, natural resources are seen as stocks, inventories, or capital that supply EGS to human societies (MNAI, 2017) and their valuation is intended to help sustain the flow of EGS into the future.

Valuation, in this context, should not be equated with putting a price on nature (thus privatizing EGS) and hoping for the best while the interactions between various forces in the market determine how and when natural resources and their ecosystem services should be traded as commodities (Sukhdev et al., 2014). Rather, valuation should be seen as a preemptive mechanism against the destruction of natural assets, one which makes their destruction a much less attractive strategic choice for private interests and supports land use planning policies and regulations that would protect these assets and their ecosystem services for social welfare.

Like other assets, municipal natural assets should be managed efficiently to ensure that their value will not depreciate over time and that the benefits they provide to urban areas will flow sustainably into the future. EGS valuation can help municipal governments save unnecessary, and sometimes substantial additional costs that they would otherwise need to invest in expensive engineering alternatives to maintain the benefits of existing ecosystem services. Valuation of natural assets can therefore help municipalities understand their short-term economic gains and create strategies for potential future financial savings achieved through plans to maintain, enhance, or restore these assets within public green spaces. For instance, assessing ecosystem services using land use/cover information could provide strategic insights as to the provision of regulating ecosystem services under multiple future scenarios. These insights could be achieved by quantifying ecosystem service provision under alternative land use/cover scenarios, different environmental conditions (e.g., climate change), or any combination of the two.

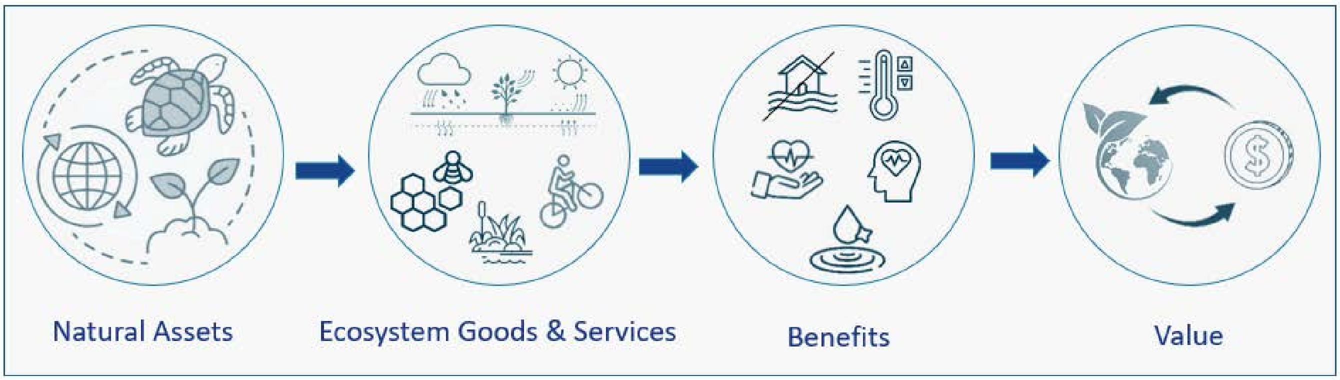

Figure 1. Conceptual illustration: from natural assets to valuation of the benefits derived from ecosystem goods and services

3.0 NATURAL ASSETS OF TORONTO'S PARKS, GOLF COURSES, AND OPEN GREEN SPACES

City-owned and operated parks (i.e., the park spaces of the Parkland Strategy which includes all existing parks as well as parks that are non-operational, proposed, or under construction), golf courses, and open green spaces (i.e., large tracts of lands with recreational, heritage, or significant ecological values) are illustrated in Figure 2.[4]

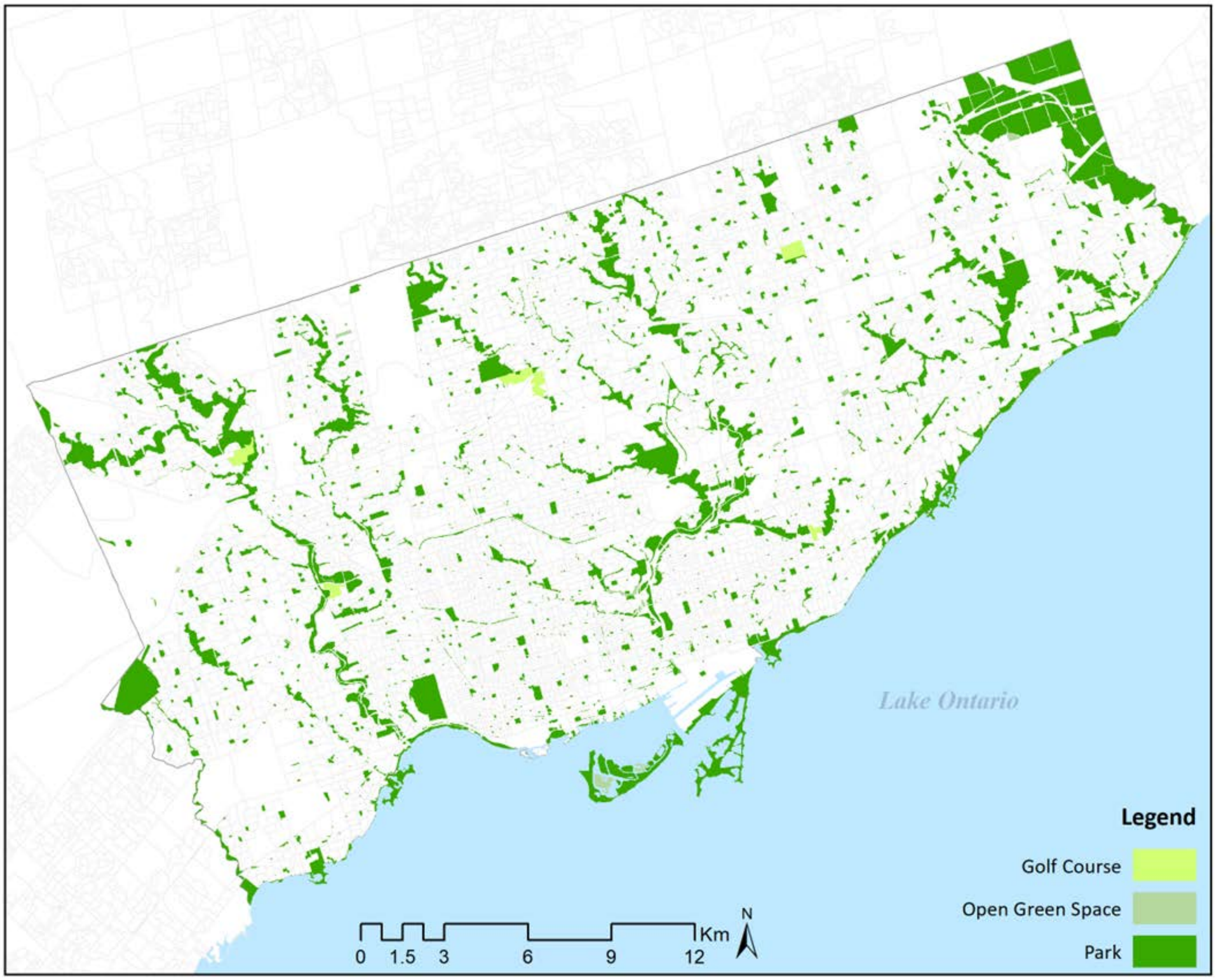

Figure 2. City-owned and operated parks, golf courses, and open green spaces in Toronto

These public green spaces cover approximately 13% of the land surface area in Toronto. The natural assets within these areas were delineated through a rigorous spatial analysis process, using the most recent spatial data sources available to TRCA and City of Toronto (CoT), including TRCA's 2017 land use/cover data layer and

[4] The maps used in this study are projected to *NAD_1983_UTM_Zone_17N* coordinate system.

CoT's urban agriculture sites. Table 1 includes a detailed description of these natural assets[5]. Figure 3 illustrates the map of all delineated natural assets in the study area.

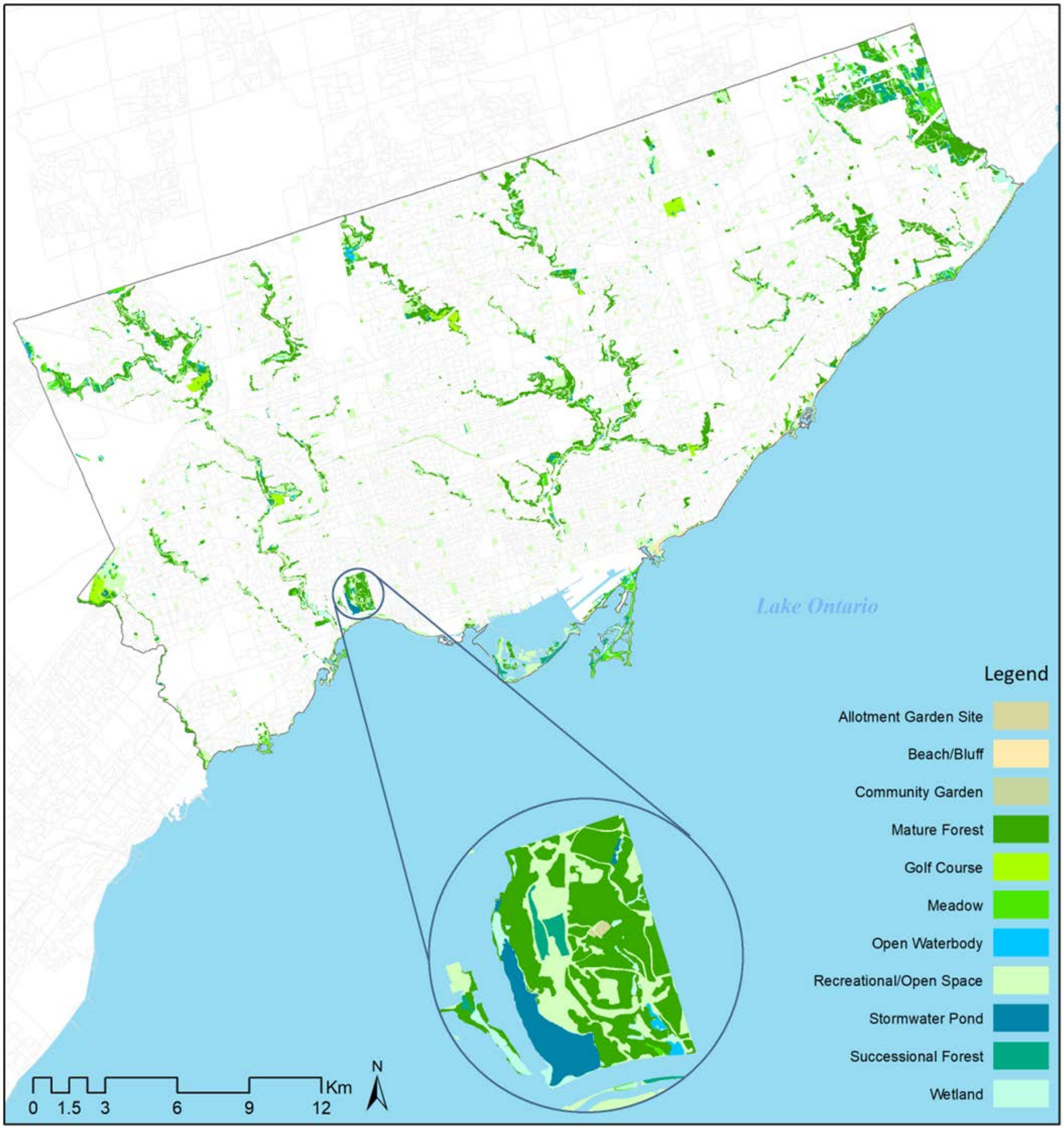

Figure 3. Natural assets of Toronto's parks, golf courses, and open green spaces (High Park is magnified to demonstrate classes)

[5] Despite having a great value to the public, privately held open green spaces are not included in this analysis.

Table 1. Type, definition, and area of natural assets in Toronto's parks, golf courses, and open green spaces

Asset	Definition	Area (ha)	Data Source
Mature Forest	Treed areas with greater than 60% tree cover (including all types of trees).	2820	TRCA
Successional Forest	Patches include non-manicured cultural woodlands and thickets that present a similar range of ecological values to that of forest patches. Features are identified by having a composition of 25% - 60% tree cover and 25% - 50% shrub cover. Trees can be a range of age classes but are sufficiently sparse and/or immature that no distinct canopy has been established as is representative of 'natural succession'.	466	TRCA
Wetland	Lands that are seasonally or permanently covered by shallow water, as well as lands where the water table is close to or at the surface. In either case the presence of abundant water has caused the formation of hydric soils and has favoured the dominance of either hydrophytic plants or water tolerant plants. The wetland assets were delineated according to TRCA's water resources systems dataset. The layer was produced by combining three different wetland datasets. These are: • TRCA 2017 Natural Cover layer • ELC wetland layer - extracted from Ecological Land Classification data. These data are collected on an annual basis from 1996 to 2019 in various locations by biologists according to the Ecological Land Classification System. • OMNRF wetlands - evaluated using the Ontario Wetland Evaluation System (OWES). The data collection date varies from 2000 to 2020.	553	TRCA
Allotment Garden Site	A predefined parcel of land comprised of gardening plots assigned to applicants.	10	CoT
Community Garden	A predefined area within a park utilized by volunteers for the purpose of growing vegetables and ornamental plants.	3	CoT
Open Waterbody	Included as part of TRCA's Inland Lakes and Littoral Zones layer, an open waterbody is defined as a permanent standing body of water, usually freshwater, larger than a pool or pond or a body of water filling a depression on the Earth's surface.	33	TRCA
Stormwater Management Pond	A stormwater management pond is an area designed for stormwater management purposes. This layer is also included in TRCA's Inland Lakes and Littoral Zones layer.	34	TRCA
Meadow	Comprised of patches with a minimum of 50% herbaceous (non-woody) cover, less than 25% tree cover, and less than 25% shrub cover, with the total coverage of trees and shrubs not exceeding 50%. Included features are natural tallgrass prairie, sand barren, and sometimes meadow marshes.	598	TRCA
Beach/Bluff	Natural barren coastal habitats not corresponding to other habitat types, including natural beach, coastal dunes, and bluffs. These are mainly areas with limited vegetation and exposed sandy substrate. Sparse shrubs and grasses comprise a total of less than 50% vegetated cover. Features in this class are limited to Lake Ontario waterfront and to steep ravine banks that fit this description.	107	TRCA
Recreational/ Open Space	This class is represented by land uses of manicured, semi-manicured, or maintained urban areas.	2544	TRCA
Golf Courses	This class includes driving ranges, practice greens, mini putts, and all manicured areas of golf courses (greens, fairways).	207	TRCA
	Total Area	**7376**	

Some of the areas identified as park spaces have a land use/cover type other than the natural assets listed in Table 1[6]. As such, these areas were excluded from the analysis. **The total area of all delineated natural assets in the study area is 7376 ha.**

[6] Examples include parking lots, recreation facilities, buildings, etc. This is either due to the area factor considered to delineate some of the natural assets in the study area or the 2017 land use/cover designation of these sites.

4.0 QUANTIFICATION OF ECOSYSTEM SERVICES

In this section of the report, different ecosystem services are explored. The quantification, mapping, and economic valuation methods associated with each ecosystem service are then outlined.

4.1 Stormwater Retention and Water Quality Benefits

Background

Permeable surfaces and natural assets, such as forests, wetlands, and meadows play an important role in reducing the risk of flooding, increasing water supplies and soil moisture, and improving water quality. Natural assets allow interception, infiltration, temporary storage, and often some degree of filtration of rainwater and runoff from surrounding areas. Replacing natural land covers with impervious surfaces such as asphalt and concrete results in increased risk of flooding and contamination of water resources by surface runoff and reduces the probability of groundwater recharge in the city (Locatelli et al., 2017; Wheeler et al., 2005). Added to these negative impacts, there is a changing climate regime that is sometimes characterized by severe storm events and at other times by extended droughts, increasing the likelihood for devastating flooding, further contamination of water resources, and significant loss of soil moisture (which leads to reduced soil permeability and increased risk of flooding), all of which has the potential to add extra social and financial burden to the city.

Protecting natural assets and permeable surfaces in public green spaces can help mitigate these negative consequences and reduce the City's reliance on engineered assets designed to provide a similar range of benefits. A review of stormwater and ecosystem service literature by Prudencio and Null (2018) found that most studies tend to focus on parcel-level quantification of these benefits during single storm events. While this approach is beneficial for comparing the contribution of different land use/cover classes towards site-specific stormwater retention and water quality regulation, it fails to capture the spatial and temporal requirements of a broader, city-wide assessment. It is this spatial and temporal understanding that supports large-scale planning capacities in the city.

Methods

To quantify the stormwater retention and water quality benefits (i.e., the avoided load of nutrients or pollutants to streams and lakes) provided by the existing network of natural assets, the InVEST Urban Stormwater Retention tool (Sharp, 2020) was used. This tool quantifies these ecosystem services on an annual basis for each pixel of the input land use/cover map. The annual estimation of the stormwater retention service is what makes this modeling framework different, and more practical for city managers, than models quantifying these benefits in the aftermath of a single storm event.

The water quality indicators considered for this analysis are the total avoided load of Phosphorus (P) and the total avoided load of Suspended Solids (SS)[7]. The economic value of the stormwater retention service can be

[7] These indicators are commonly considered in water quality studies. Excessive concentration of suspended solids is an indicator of turbidity and lack of sunlight, and excessive concentration of phosphorus is an indicator of reduction of dissolved oxygen in water, both considered critical to aquatic health.

calculated using the replacement cost approach whereby the unit cost of a new stormwater retention facility is multiplied by the total volume of water retained by the natural asset inventory[8]. The data used for this modeling study are listed in Table 2 along with their description, unit, and source of collection.

Table 2. Data requirements for modelling stormwater retention and water quality benefits in the InVEST tool

Data	Description	Unit	Source
Land use/cover map	The reclassified version of the updated TRCA's 2017 land use/cover layer. The layer was reclassified based on the runoff coefficient values for distinct land use/cover classes. It was then transformed to a raster data layer with a spatial resolution of 5 meters.	NA	(TRCA, 2021b)
Annual Precipitation	A raster layer produced based on the 30-year (1981-2010) average annual precipitation values reported for four Environment and Climate Change Canada stations in proximity of Toronto[9]. The city was divided into four zones based on the proximity of each zone to each station. Each zone was then assigned the average annual precipitation value of the closest climate station to it.	mm/ year	(Environment and Climate Change Canada, 2022)
Runoff Coefficient	The runoff coefficient is the proportion of precipitation that is converted to surface runoff. This parameter is determined based on the land use/cover class. It is then used to calculate the retention coefficient (i.e., the proportion of precipitation that is retained by the landscape) for each class of the input land use/cover map.	NA	(City of Toronto, 2009a; Ontario Ministry of Transportation, 1997)
Event Mean Concentration (EMC) of Pollutants	This is the water quality parameter of the model. It is the flow proportional concentration of pollutants in stormwater runoff. It was determined for phosphorus and total suspended solids based on recommended values reported in local as well as cognate studies.	mg/l	(Auger, 2016; Clary, 2020)
Road Centerlines	The centerline of all expressways, major and minor arterials, collector roads, local roads, access roads, and laneways in the city. When roads are considered as directly connected impervious surfaces, this layer is used to determine the adjusted retention coefficients for pixels located in a pre-determined distance (i.e., retention radius) from roads.	NA	(City of Toronto, 2022c)
Retention Radius	This parameter determines the distance from a pixel to the stormwater drainage network. It could be interpreted as the maximum overland distance that stormwater runoff might travel in an urban watershed before reaching a connected pavement or being infiltrated completely. This parameter was set to a recommended value of 20 m for medium to high density urban area.	m	(Sharp, 2020)
Replacement Cost	This parameter is used to determine the economic benefits of the stormwater retention service. It is equal to one-time unit cost of constructing a stormwater retention facility, such as a retention pond. The value of natural assets is assumed to be at least equal to the cost of replacing these assets with the engineered infrastructure capable of providing stormwater services.	$\$/m^3$	(EPA, 1999; Saini, 2018)

Modelling of stormwater retention and water quality regulation was carried out for the entire city, but the values reported herein are only representative of the contributions made by the study area. The land use/cover map used for the analysis is included in Appendix A.

[8] Water quality indicators are not monetized in this report. Unlike stormwater retention, there is no established replacement cost approach for these indicators.

[9] These stations are listed along with their 30-year average annual precipitation in Appendix A.

To estimate the retention capacity, the model first requires values of annual runoff coefficients for each land use/cover type (*RCx*). The runoff coefficients for different land use/cover types were determined based on the literature and are listed in Appendix A. For each land use/cover class, the retention coefficient is calculated from the runoff coefficient values as:

$$REx = 1 - RCx$$

where *REx* is the retention coefficient for land use/cover class x. Next, the model computes the retention volume (m^3/year) for each pixel i (*VREi*) as:

$$VREi = 0.001. Pi. REi. Pixel\ area$$

where *REi* is the retention coefficient for pixel i, *Pi* is the annual precipitation (mm/year), and the *Pixel area* is the area of each pixel (m^2).

When considered at an aggregate watershed scale, retention of a given pixel is influenced by retention (and runoff) in its surrounding upstream and downstream pixels. To account for the retention of runoff flowing from one pixel to its surrounding pixels, the stormwater model uses a simple modification to retention whereby the primary retention capacity for a given pixel is adjusted upwards based on the retention values of the pixels located in a certain radius from that pixel. The adjusted retention coefficient, *REi (adj)*, is calculated as:

$$REi\ (adj) = REi + (1 - REi). Ci$$

where *1-REi* is the runoff coefficient and *Ci* is the adjustment factor, which can either take a value of 0, if the pixel of interest is near a directly connected impervious area, or a value equal to the average retention coefficients of its neighboring pixels, if it is not located near a directly connected impervious surface. Simply put, if a pixel is located near a directly connected impervious area (e.g., roads and medium to high density residential sites), its retention capacity is considered equal to its primary retention coefficient, as these areas are considered directly connected to the drainage system. Otherwise, a pixel's retention capacity increases proportional to the runoff generated by its surrounding pixels. The "nearness" attribute is determined by a parameter known as the retention radius in the model, which is essentially the maximum distance that stormwater runoff travels overland before reaching a directly connected impervious surface or being percolated to the ground. This parameter was set to 20 m for this modeling study.

Runoff volume for each pixel i (*VRUi*) is also determined based on the adjusted retention volume and is calculated as:

$$VRUi = 0.001. Pi. RUi. Pixel\ area$$

where *RUi* is the adjusted runoff coefficient value for each pixel i.

To estimate the economic benefits of the stormwater retention service, the replacement cost of stormwater retention facilities is multiplied by the total volume of water retained in the study area ($VRE_{,total}$). For this analysis, an average unit capital cost of \$121.43/m^3 was used based on the adjusted[10] minimum and maximum

[10] All values in this study are adjusted for inflation considering Canada's Consumer Price Index (CPI) in May 2022 (Statistics Canada, 2022a). The CPI is a price index used to calculate inflation. It tracks how much an average household spends, and how this spending

reported replacement costs of wet stormwater management ponds (i.e., stormwater retention ponds) in the literature[11].

The water quality benefit of the stormwater retention service is determined as the amount of pollutant mass associated with retained stormwater. More specifically, this is equivalent to the total mass of pollutants that would otherwise get transported by stormwater runoff to streams and lakes. The model computes this avoided load in kg/year for each pixel as:

$$Avoided\ Load\ i = 0.001.VREi.EMC$$

where EMC is the event mean concentration of pollutants, measured in mg/l. The EMC values for phosphorus and suspended solids are listed in Appendix A. Similarly, the annual pollutant load due to surface runoff is calculated for each pixel as:

$$Load\ i = 0.001.VRUi.EMC$$

Results and Discussion

The results show that, at an aggregate level, the total volume of stormwater retention in Toronto is 198,803,385 m^3 per annum. **Of this, 55,642,202 m^3 (28%) is due to the retention capacity provided by natural assets in the study area. These assets also account for approximately 30% of the total prevented load of phosphorus and 19% of the total prevented load of suspended solids.**

Table 3. Stormwater retention and water quality improvements in parks, golf courses, and open green spaces

Service category	Unit	Land use	Value	Percentage of total (%)
Stormwater retention	m^3/year	Parks	53,695,841	96.51
		Open Green Spaces	472,185	0.84
		Golf Courses	1,474,176	2.65
Stormwater retention total			55,642,202	100.00
Water quality (P) - Prevented load of Phosphorus	Kg/year	Parks	14,735	96.01
		Open Green Spaces	157	1.03
		Golf Courses	457	2.96
Total avoided load of P			15,347	100.00
Water quality (SS) - Prevented load of suspended solids	Kg/year	Parks	2,424,405	94.13
		Open Green Spaces	22,383	0.87
		Golf Courses	128,885	5.00
Total avoided load of SS			2,575,673	100.00

The economic value of the stormwater retention service in the study area is estimated at $6.7 billion per year (Table 4). Since the replacement costs are determined based on the construction costs of stormwater management ponds, the estimated retention of the existing stormwater management ponds in the study area

changes over time. CPI is calculated for a fixed basket of goods and services including food, shelter, furniture, clothing, transportation, and recreation.

[11] The adjusted minimum and maximum capital costs associated with replacing a wet stormwater management facility are $39.14/ m^3 and 203.73/ m^3, respectively. The original costs were inflated using the inflation calculator of Bank of Canada (Bank of Canada, 2022).

was excluded from the economic valuation to avoid overestimation of the service value. It is also important to note that these values need to be interpreted as the annual, not the daily or storm-based, economic benefits associated with the stormwater retention service.

Table 4. The economic estimates for the stormwater retention service

Land use	Stormwater retention volume per year (m^3/year) (excluding the retention capacity provided by stormwater management ponds)	Estimated economic benefits of stormwater retention ($ in 2022)
Parks	53,431,814	6.6 billion
Open Green Spaces	472,185	57.3 million
Golf Courses	1,456,842	176.9 million
Total	**55,360,841**	**6.7 billion**

Stormwater retention in this context is considered as the sum of interception, infiltration, and evapotranspiration processes. This means that the economic benefits of the retention service should be seen as the replacement costs of all these underlying processes of the annual water cycle. Simply put, if the natural assets in the study area were replaced with impervious surfaces, the City would incur an average cost of $6.7 billion to collect 55,360,841 m^3 of stormwater and keep the water cycle in balance in the year of analysis.

Another key consideration for interpreting these results is the assumption that runoff coefficient values were solely associated with land use/cover classes. One of the factors influencing runoff coefficients in different land use/cover classes is the Hydrological Soil Group (HSG) that land use/cover class belongs to[12]. In the absence of data regarding runoff coefficient values per HSG class within Toronto, these coefficients were associated to the type of land use/cover class of each pixel. Including HSG classes in future analyses to determine runoff coefficients would increase the accuracy of results.

Finally, it is important to note that the results presented here are based on the average annual precipitation from 1981 to 2010[13]. A regional climate projection for the end of the century (TRCA, 2021a) shows that the average precipitation could increase dramatically (approximately by 200 mm/year) under business-as-usual and moderate greenhouse gas emission scenarios, putting many areas, including Toronto, at increased risk of flooding and water resources contamination. This analysis confirms the indispensable role of the natural assets within Toronto’s public green spaces in mitigating the negative repercussions of increased annual rainfall, thus providing significant financial savings that would otherwise need to be spent on stormwater control facilities. In addition, the analysis shows that the value of further enhancement and expansion of these natural assets can be quantified to assess how investments can improve Toronto's adaptive capacity in the future.

Figure 4 illustrates the distribution of stormwater retention and water quality improvement indicators in the study area. Sections of the Don Valley are magnified to highlight the level of detail available in the maps.

[12] Hydrological Soil Groups classify soils into 4 groups (A, B, C, and D) according to water run-off and infiltration rates.

[13] Average annual precipitation is generally calculated for 30-year periods. The 1981-2010 period was the most recent period with available data for the climate stations considered in the analysis.

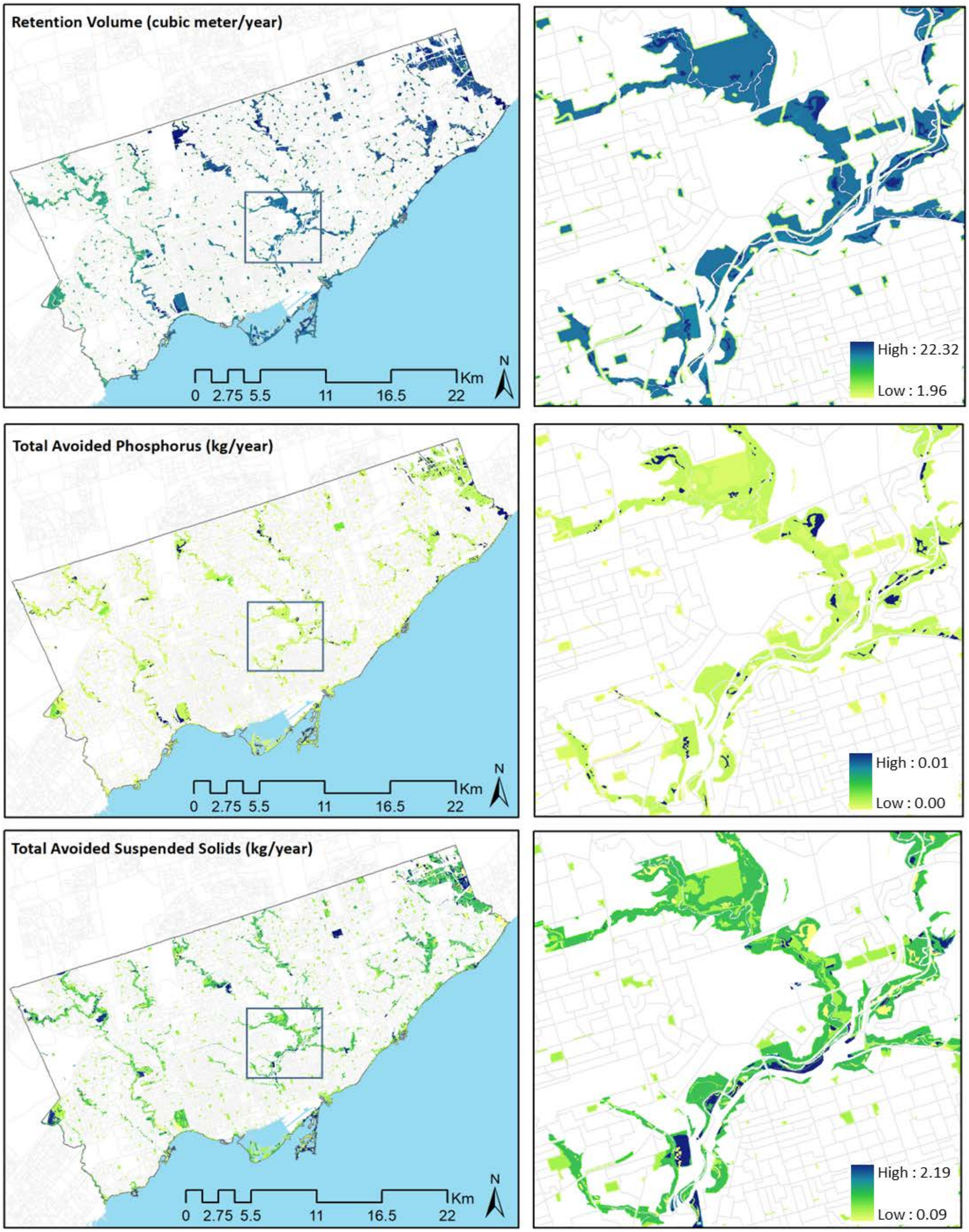

Figure 4. Stormwater retention and water quality benefits in the study area (left: city-wide scale, right: a zoomed-in portion of the Don Valley)

4.2 Carbon Storage and Sequestration

Background

Ecosystems play a fundamental role in regulating Earth's climate by adding and removing greenhouse gases such as carbon dioxide (CO_2) from the atmosphere (IPCC, 2006). Natural assets such as forests, grasslands, and wetlands collectively store much more carbon than the atmosphere. They do so by storing carbon in living plant materials (i.e., grass, herbaceous material, tree trunks, branches, leaves, and other woody understory), their root system (i.e., below-ground biomass), soil, and other organic matter such as plant litter and dead wood (Conte et al., 2011). Storage is not the only function of these natural systems; many continue to accumulate carbon in plants and soil over time, thereby sequestering additional carbon each year. While disturbing these systems through natural or anthropogenic perturbations can negatively impact their carbon storage and sequestration capacities, protecting and restoring these natural systems can maintain and potentially improve their carbon stocks over time. Therefore, the way ecosystems are managed has a significant impact on the climate and its changing patterns.

Given the growing interest in carbon markets and offset programs, particularly those applicable to urban areas, urban decision-makers need simple, practical, and reliable approaches to understanding how much carbon is stored in natural assets, where it is stored, and how much it is worth. Landscape-scale maps of carbon storage and sequestration provide this enhanced understanding (Sharp, 2020). Such maps can support a range of decisions by municipal governments. For instance, knowing which parts of a landscape store more carbon could help decision-makers efficiently target specific conservation programs that include carbon uptake as one of their management objectives. This could in turn increase the probability of protecting natural assets and help urban areas achieve net zero and net negative objectives.[14]

Methods

As part of this project, maps of carbon storage and sequestration were developed for forests, meadows, open spaces, and wetlands based on a detailed classification of land cover types in the city. The results were then extracted from the maps for these ecosystems. For meadows, the rates of carbon storage and sequestration were directly adopted from a local study (Wilson, 2008). For forests, wetlands, and open spaces, these values were determined based on the Natural Asset Carbon Assessment Guide and Toolbox (CVC, TRCA, and LSRCA, 2022), a database of locally applicable land cover-based carbon storage and sequestration rates. The database includes information on land cover classes, broken down into a detailed classification system using Ontario's Ecological Land Classification (ELC) codes, carbon sequestration and storage rates, and a ranking system illustrating the relevance of the reported rates to local jurisdictions (CVC, TRCA, and LSRCA, 2022).

To efficiently associate carbon storage and sequestration rates with forests, wetlands, and open spaces in Toronto, the map of delineated assets (Figure 3) was reclassified considering the land cover information in the database and the spatial overlap of both forest and wetland features with the ELC dataset.

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[14] Net zero refers to a situation where the economy removes as much CO_2 from the atmosphere as it emits to it, and net negative refers to a situation where the economy removes more CO_2 from the atmosphere than it emits to it.

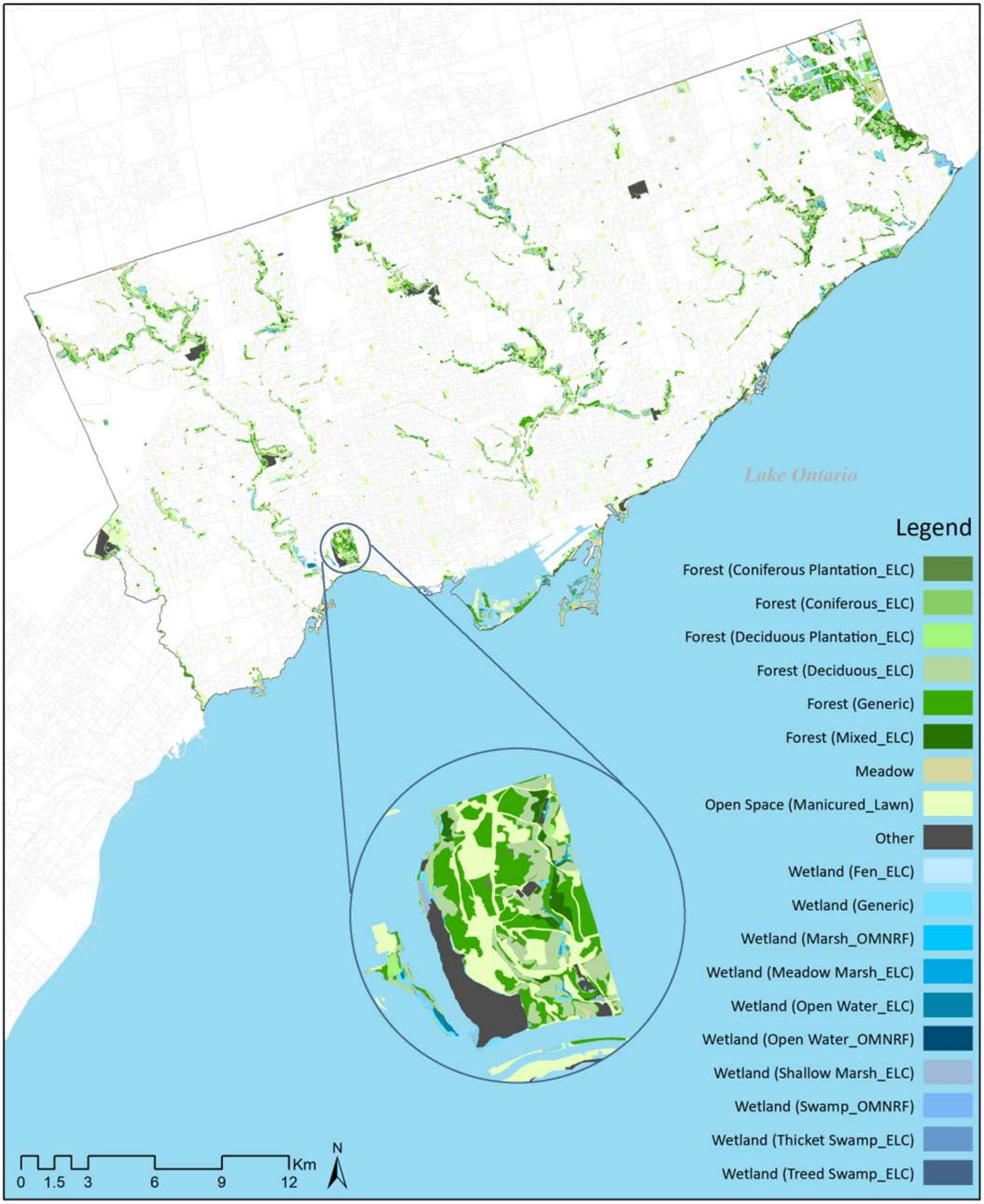

Figure 5. Detailed classification of natural assets for carbon accounting (High Park is magnified to demonstrate classes)

For wetlands, a more detailed classification is provided based on the spatial overlap of the wetland features not categorized by ELC and those classified by Ontario Ministry of Natural Resources and Forestry (OMNRF). All the other land cover types (except meadows whose rates were adopted from a different study) were reclassified as "other" and assigned a value of zero for sequestration and storage. Figure 5 illustrates the reclassified map of natural assets for carbon accounting. The areas associated with land cover classes of this map are listed in Appendix B.

Each land cover type was assigned sequestration and storage rates based on a set of pre-determined criteria (further information is available in Appendix B). In this approach, the carbon storage density in a land cover class is equated to the sum of carbon stocks in above-ground biomass, below-ground biomass, soil, and the dead organic matter in that land cover class. Carbon sequestration in a land cover class is considered as the Annual Net Primary Production (ANPP) of biomass in that class. In other words, the ANPP is equal to the annual amount of net carbon uptake by vegetation in a single land cover class. The land cover classes along with their associated sequestration and storage densities for the study area are listed in Table 5. Figure 6 illustrates the maps of storage and sequestration.

Land cover class	Carbon sequestration (tonne/ha/year)	Soil carbon (tonne/ha) [depth of measurement]	Aboveground biomass (tonne/ha)	Belowground biomass (tonne/ha)	Dead organic matter (wood) (tonne/ha)
Forest (Generic)	2.19	97.2 [70]	50.62	14.88	7.42
Forest (Coniferous Plantation_ELC)	3.96	64.6 [100]	87.75	14.36	5.70
Forest (Coniferous_ELC)	3.96	64.6 [100]	87.75	14.36	5.70
Forest (Deciduous_ELC)	1.99	97.2 [70]	56.95	14.2	6.39
Forest (Deciduous Plantation_ELC)	1.99	70.2 [100]	33.2	14.2	6.39
Forest (Mixed_ELC)	2.63	52.5 [60]	18.85	18.95	13.95
Wetland (Generic)	5.08	125.11 [NA]	10.62	17.01	0
Wetland (Marsh_OMNRF)	6.21	116.21 [NA]	13.25	21.37	0
Wetland (Meadow Marsh_ELC)	4.17	130 [average of 20 and 16]	10.3	12.8	0
Wetland (Open Water_ELC)	2.38	95 [22]	5.9	6.7	0
Wetland (Open Water_OMNRF)	2.38	95 [22]	5.9	6.7	0
Wetland (Shallow Marsh_ELC)	8.55	110 [average of 15 and 21]	17	30.9	0
Wetland (Treed Swamp_ELC)	2.94	87 [average of 14 and 18]	7.2	4.1	0
Wetland (Thicket Swamp_ELC)	1.99	170 [average of 21 and 24]	2.8	6	0
Wetland (Fen_ELC)	2.77	71 [17]	11.7	2.7	0
Wetland (Swamp_OMNRF)	2.15	155.97	3.54	5.67	0
Meadow	0.5	105 [100]	0	0	0
Open Space (Manicured Lawn)	0.34	49.76 [15]	0	0	0
Other	0	0	0	0	0

Table 5. Carbon sequestration and storage densities per land cover type

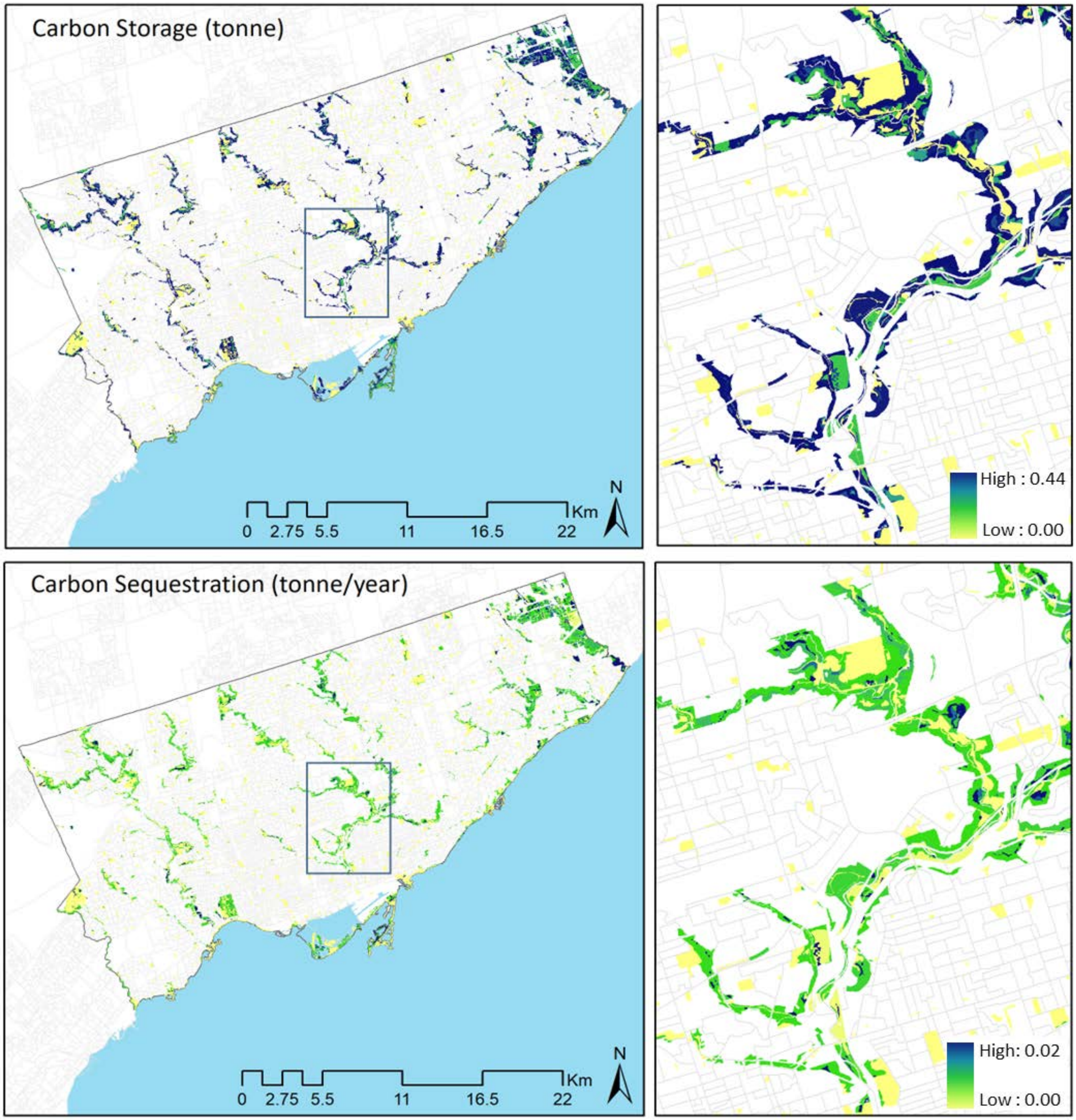

Figure 6. Maps of carbon storage and sequestration (left: city-wide scale, right: a zoomed-in portion of the Don Valley)

The economic benefits of carbon sequestration and storage services were determined using the recommended social cost of carbon in Canada[15] (Government of Canada, 2023). The social cost of carbon is the economic

[15] The adjusted value is equal to \$275/t CO_2 in 2022. This number was calculated based on the value of \$256/t CO_2 in 2022 (reported in 2021 dollars).

damage caused by emitting an additional tonne of CO_2 into the atmosphere (Nordhaus, 2017; Stern, 2007). When applied to carbon storage, this is equivalent to the cost of releasing the existing carbon stocks into the atmosphere through natural or anthropogenic disturbances (e.g., fire, deforestation, land conversion, etc.) or the benefits associated with preventing that from happening. When applied to sequestration, it is equal to the economic damage avoided by every additional sequestered tonne of carbon. Since the social cost of carbon is applied to CO_2 emissions, tonnes of carbon storage and sequestration were converted to equivalent tonnes of CO_2, using 3.67 as the conversion multiplier (Allen et al., 2009). That is, each tonne of carbon is equal to 3.67 tonnes of CO_2 (the CO_2 equivalent of total carbon densities is written as CO_2e).

Results and Discussion

The results of the analysis show that **Toronto's forests, wetlands, meadows, and open spaces have a total carbon stock of approximately 1,410,900 tonnes, of which 810,228 tonnes (57.4%) are stored in the natural assets in City-owned and operated public green spaces. Natural assets also collectively sequester 17,695 tonnes of carbon per year in the city, of which 11,235 tonnes (63.5%) are annually sequestered in the study area.** Approximately 98% of the total carbon storage and sequestration in the study area is provided by the natural assets within city parks while the aggregate contribution of golf courses and open green spaces to each of these services is approximately 2%. Table 6 lists the total storage and sequestration values in parks, golf courses, and open green spaces.

Table 6.Total carbon storage and sequestration by land use type

Land use	Total sequestration (ANPP) (tonne /year)	Total storage (tonne)	Sequestration (%)	Storage (%)
Parks	11,015	794,923	98.00	98.12
Open Green Spaces	118	7,633	1.05	0.94
Golf Courses	102	7,672	0.95	0.94
Total	**11,235**	**810,228**	**100**	**100**

The economic estimates of the storage and sequestration services are listed in Table 7. (Please note that for valuation purposes, only CO_2 equivalent values are listed in this table). **The total economic benefits of carbon sequestration and storage services are estimated as $11.3 million and $817.7 million, respectively.**

Table 7. The carbon dioxide equivalent and the economic benefits associated with carbon sequestration and storage services

Land use	CO_2e of total Sequestration (tonne /year)	CO_2e of total storage (tonne)	Social cost of carbon ($ /t CO_2e)	Estimated value of sequestration ($ in 2022)	Estimated value of storage ($ in 2022)
Park	40,425	2,917,367	275	11.1 million	802.3 million
Open Green Space	433	28,013		119,075	7.7 million
Golf Courses	374	28,156		102,850	7.7 million
Total	**41,237**	**2,973,540**		**11.3 million**	**817.7 million**

Carbon storage and sequestration are dynamic phenomena influenced by factors such as soil typology, altitude, temperature, species, age, soil nutrient levels, and concentration of atmospheric CO_2 (Congreves et al., 2017; Coursolle et al., 2012; Terrer et al., 2021). The analysis portrays the total land cover-based carbon stock and sequestration values at a single point in time and does not reflect fluxes of carbon due to variations in the aforementioned factors. However, it does provide essential baseline estimates as well as key information on where, and to what extent, carbon storage and sequestration services are distributed across the study area. Considering these baseline estimates, Appendix C provides a detailed description of applying the social cost of carbon in the future.

4.3 Air Quality Regulation

Background

Poor or below-standard Ambient Air Quality (AAQ) has been identified as a significant contributing factor to increased health problems, such as acute and chronic respiratory and cardiovascular diseases and different types of cancer, as well as hospitalization and premature mortality in cities around the world (Manisalidis et al., 2020) and in Canada (Health Canada, 2021). Referencing 2014 data, ambient air pollution from all sources in Toronto resulted, on average, in 1,300 cases of premature death and 3,550 cases of hospitalization per year (Toronto Public Health, 2014). The description of the key pollutants in urban areas and their associated health risks is provided in Table 8.

Table 8. Pollutants commonly considered in air quality studies and their associated health risk (World Health Organization, 2021)

Pollutant	Description	Health risks
Particulate matter ($PM_{2.5}$)	The major components of PM are sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water. It consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. Particles with a diameter of equal or smaller than 10 microns and bigger than 2.5 microns are classified as PM_{10} and those with a diameter of equal to or smaller than 2.5 microns are classified as $PM_{2.5.}$	Chronic exposure to particles contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer.
Ozone (O_3)	Ozone at ground level is a major constituent of photochemical smog. It is formed by the reaction with sunlight (photochemical reaction) of pollutants such as nitrogen oxides (NO_x) from vehicle and industry emissions and volatile organic compounds (VOCs) emitted by vehicles, solvents, and industry. The highest levels of ozone pollution occur during periods of sunny weather.	Increased occurrence of breathing problems, asthma, and lung diseases are the major health risks associated with exposure to ozone.
Nitrogen Dioxide (NO_2)	NO_2 is the main source of nitrate aerosols, which form an important fraction of $PM_{2.5}$ and of ozone (in the presence of ultraviolet light). NO_2 is produced through combustion processes, such as heating, power generation, and engines in vehicles and ships.	Symptoms of bronchitis in asthmatic children increase in association with long-term exposure to NO_2.
Sulfur Dioxide (SO_2)	A colorless gas, SO_2 is produced from the burning of fossil fuels (coal and oil) and the smelting of mineral ores that contain sulfur.	Negatively affects respiratory system and results in the aggravation of asthma and chronic bronchitis. Exposure also causes eye irritation.

Urban forests can play a pivotal role in air quality improvement. Trees and shrubs remove air pollution by intercepting particulate matter on plant surfaces and absorbing gaseous pollutants through small openings in their leaves' structure (Nowak et al., 2014). Air quality improvement could help mitigate the existing rates of mortality and hospitalization in Toronto. Therefore, understanding the benefits associated with improved air quality provided by trees and shrubs is of paramount importance for municipal decision-makers.

Methods

To understand the benefits in the forested areas of the study area, the results of the i-Tree Eco analysis in Toronto's most recent tree canopy assessment (KBM Resources Group et al., 2018) were used. The 2018 Tree Canopy Report is an update to the previous tree canopy study, conducted in 2009 (City of Toronto, 2009b). The estimation provided by the i-Tree Eco model is based on computing the annual gas exchange and particulate matter interception by trees and shrubs for carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter less than 2.5 microns ($PM_{2.5}$), and sulfur dioxide (SO_2). More specifically, the model estimates the hourly dry deposition of these pollutant gases and particulate matter on tree and shrub cover based on locally collected data on different species as well as hourly weather and pollutant concentration data. The model also estimates the economic benefits of gas regulation based on avoided health-care expenses (i.e., cost of illness), productivity losses associated with specific adverse health events, and the value of preventing mortality[16] (Nowak, 2021). To determine how much of the total gas regulation benefits are due to the tree and shrub cover in the study area, the weighted sum of tree and shrub cover in each land use type was multiplied by the city-wide economic benefits. The weighting factors were determined by calculating the proportion of the total area of mature and successional forest categories to the total area of tree and shrub cover as reported in the 2018 land cover data (City of Toronto, 2020).

Results and Discussion

In 2018, trees and shrubs removed 972 tonnes of pollutants and particulate matter with an estimated value of \$37.9 million, which is equivalent to \$43.1 million in 2022 (Bank of Canada, 2022). Since mature and successional forests in the study area have a total area of 3,286 ha, which is equivalent to approximately 16.7% of the total tree and shrub canopy cover in Toronto, it is plausible to postulate that **162.3 tonnes of annual pollution removal can be attributed to these assets. Therefore, the adjusted economic value of this pollution removal service in the study area is approximately \$7.2 million** (Table 10).

Table 9. Estimated annual air quality benefits in Toronto

Pollutant/particulate matter	Annual removal of pollutants and particulate matter (calculated based on average monthly tonnes removed by trees and shrubs)	Estimated economic benefits (\$ in 2018)
CO	3.6	5,364
O_3	607.8	12.9 million
NO_2	240.5	762,385
SO_2	87.4	101,384
$PM_{2.5}$	32.7	24.1 million
Total	**972**	**37.9 million**

Table 10. Estimated air quality regulation benefits of mature and successional forest in the study area

Land use	Proportion of city-wide tree and shrub cover in the study area (%)	Estimated total pollutants removed (tonnes/year)	Estimated economic benefits (\$ in 2022)
Parks	16.33	158.7	7 million
Open Green Spaces	0.15	1.4	64,650
Golf Courses	0.23	2.2	99,130
Total	**16.71**	**162.3**	**7.2 million**

The values presented here should be seen as conservative estimates of air quality regulation benefits, as mature and successional forests were the only categories considered for the analysis. Individual trees are found in other classes of natural assets in the study area, such as manicured lawns, but these features only comprise a very

[16] These benefits were estimated in 2018 as \$0.00149/g CO, \$0.02124/g O_3, \$0.00317/g NO_2, \$0.00116/g SO_2, and \$0.73728/g $PM_{2.5}$ removed from the atmosphere.

small proportion of the land surface area in these classes. As such, their contribution towards air quality regulation was not included in these estimates.

4.4 Food Provision

Background

Harvesting urban agriculture products is considered a major source of food provision in cities. But the benefits associated with urban agriculture activities go beyond nutritional values of the products being harvested. To many communities the most important benefit is the avoided costs associated with store purchases of fresh produce. Collecting locally grown food also improves the physical and mental health of individuals and plays an indispensable role in community cohesion (Armstrong, 2000; Ober Allen et al., 2008). Furthermore, due to reduced reliance on conventional means of transportation, such as cars and trucks, local food collection can result in significant cost savings, reduced greenhouse gas emissions, and other environmental benefits (Okvat & Zautra, 2011). Finally, many locally grown products have medicinal values and could be used to relieve symptoms of various illnesses (Guarrera & Savo, 2013).

Since food collection is considered as a provisioning ecosystem service in this report, the economic value of this service was estimated considering only the market costs of the locally grown fresh produce in City-owned and operated urban agriculture sites. This conservative estimation method, therefore, excludes the potential mental, physical, transportation, and community cohesion benefits derived from collecting locally grown food.

Methods

The supply of community garden fresh produce to 25 community agencies in the city (City of Toronto, 2021) was used as a proxy to estimate the food provision benefits in the study area. The total production capacity of urban agriculture sites was calculated based on the area and production capacity of fresh produce per hectare of community gardens in the city. The production capacity of community gardens was estimated as 0.73 tonnes per hectare. It was then assumed that allotment garden sites have the same production capacity. The economic benefit associated with food production was then determined based on the adjusted market cost of a similar basket of locally grown food in Toronto (Green Analytics, 2018)[17].

Results and Discussion

The economic value of locally grown fresh produce in community gardens and allotment garden sites in the study area is estimated to be $11,669, of which $4,932 (almost 42.2%) is attributable to food production in parks and $6,737 (almost 57.8%) to food production in open green spaces[18].

[17] The original value was reported as $1,033 per tonne in 2017. This is equal to $1,203 per tonne in 2022 (Bank of Canada, 2022).

[18] There were no production sites within or near golf courses considered in the analysis.

Table 11. The economic benefits of locally grown fresh produce in urban agriculture sites in the study area

Land use	Growing space (ha)	Estimated production capacity of fresh produce (tonnes)	Estimated economic benefits ($ in 2022)
Park	5.50	4.1	4,932
Open Green spaces	7.50	5.6	6,737
Total	**13.00**	**9.7**	**11,669**

It is important to note that food provision was estimated based on the assumption that the production capacity across each hectare of urban agriculture sites in the study area is a fixed number. The real production capacity in these sites is probably higher than the estimated numbers, which are based on the amount of produce supplied to community organizations, as these areas are also used for household food production. Furthermore, food price hikes in 2022 were almost twice as much as the overall CPI used to adjust for inflation in this study (Statistics Canada, 2022a). Therefore, the results presented herein should only be seen as conservative estimates of the food provision service.

4.5 Civic Contribution

Background

Resources that are available to communities through social interactions, reciprocity, and mutual trust are commonly referred to as social capital (Bourdieu, 1986). Social capital in an urban setting is materialized through social cohesion, which occurs when urban spaces are used to promote shared values, cooperation, and interaction among citizens (Forrest & Kearns, 2001). It is therefore plausible to posit that social gathering spaces such as public parks are essential to building cohesive communities (Peters et al., 2010). Regardless of their size, urban parks can improve the health and subjective well-being of people and offer them numerous opportunities to interact, learn, and feel more involved in their communities (Baur & Tynon, 2010; Kim & Jin, 2018). Social cohesion in parks may be achieved when people visit these spaces or participate in park-related activities. Dedicating voluntary work or financial resources to maintain, renew, and improve parks and the range of recreational, educational, and cultural programs offered in parks are two ways in which a society can help improve social cohesion in urban areas (Harnik et al., 2017). These activities can be referred to as "civic contribution" and were used as a proxy to estimate contributions made by the society to keep parks and park-related programs cohesive.

Methods

To calculate civic contribution, the number of volunteer hours dedicated to parks and their programs was monetized, using the minimum hourly wage rate of $15 in Ontario (Government of Ontario, 2022). This number was then added to the adjusted average value of financial donations dedicated to parks and park-related programs in 2017 and 2018[19]. Table 12 shows the name and the number of volunteer hours dedicated to the Natural Environment and Community Programs (NECP) unit of the Parks, Forestry and Recreation Division (PFR) of the City of Toronto in 2019.

[19] Total financial contributions to parks were obtained through email correspondence with city staff. This value was $116,000 in 2017 and $77,000 in 2018. These values were respectively adjusted to $136,015 and $88,123 in 2022 (Bank of Canada, 2022).

Table 12. Park programs, volunteer hours, and associated economic values

Park Program	Volunteer hours	Estimated value ($ in 2022)
Planting Events	6,485	97,275
Stewardship Events	664	9,960
Community Stewardship Program	3,829	57,435
Tree Planting Captain Program	76.5	1,148
Don Valley Brickworks Ambassador Program	91	1,365
Total	**11,145.5**	**167,183**

Results and Discussion

The total value of civic contribution is estimated as $279,252. Table 13 lists total civic contribution based on the values of the volunteer hours and donations to parks and their programs.

Table 13. Estimated civic contribution to City-owned and operated parks in Toronto

Civic contribution category	Estimated Civic Contribution ($ in 2022)
Volunteer hours	167,183
Average adjusted financial donations based on 2017 and 2018 donation data	112,069
Total	**279,252**

Civic contribution should not be equated with social cohesion or social capital. Quantifying civic contribution may even seem inconsistent with how ecosystem services are evaluated. For instance, the question could be asked why a cultural service (in this case the benefits of social relations to community) should be measured through the contributions made by people to parks and their programs and not through what these spaces and programs provide for the community. This is a valid question, however, there is no established method for quantifying this sub-category of cultural services. Furthermore, there are no established methods for disaggregating its potential overlap with the mental health benefits provided by the creation of social interaction in park spaces. Another equally important consideration is that the ability of communities to participate in formal volunteer programs is typically constrained in several ways, including the lack of resources at the City to promote or host sanctioned volunteer programs, and the lack of resources in many communities to participate in unpaid volunteer opportunities. Therefore, in this context, civic contribution should only be seen as the minimum amount of time and financial donations that the community is willing to invest—under certain limitations—in parks and park-related programs to keep these areas cohesive and capable of creating the social capital, which is the actual cultural service provided by park spaces.

4.6 Habitat Suitability

Background

There is a reinforcing causal relationship between the health of ecosystems and the biological diversity that inhabits them (Duffy, 2009). This simply means that the health of ecosystems, and the amount of goods and services they provide, depend largely on the population and persistence of thriving biological diversity, and that the existence of different groups of species hinges upon the array of physical and biotic resources that support their survival and reproduction (Alsterberg et al., 2022). The latter relationship can be characterized by the extent, diversity, suitability, and connectivity of habitat patches in a landscape.

These biodiversity indicators have been negatively influenced by the anthropogenic activities of the present and the past (Cardinale et al., 2012), particularly in urban areas. Over the past two decades, cities have doubled in size, resulting in massive loss of biological diversity in urban areas and in transition zones between cities and rural areas (IPBES, 2019). An expanding urban area requires new infrastructure for transportation and energy, new lands for industrial manufacturing, commercial use, food production, employment, housing, and recreation, and new areas to dispose of waste that is generated in other land uses. These land uses have altogether transformed what once used to be suitable habitat patches for different groups of species into fragmented landscapes with reduced habitat extent, suitability, diversity, and connectivity. Nevertheless, conservation measures in these smaller patches could help maintain the remaining critical biological diversity (Wintle et al., 2019) in cities. Therefore, these areas should also be prioritized for conservation and restoration purposes.

In Ontario, a response to this loss and fragmentation of habitat has long been integrated into the natural heritage and Natural Heritage System (NHS) policies of the Provincial Policy Statement (PPS). These policies outline restoration and conservation measures and development restrictions across the NHS to maintain biological diversity and to improve the connectivity and quality of natural components within the NHS. The City of Toronto has strong protection and enhancement policies within the Official Plan and other planning documents, including the Biodiversity Strategy (City of Toronto, 2019b) which outlines several actions that can be taken to protect, enhance, and manage biodiversity within the city.

Methods

TRCA completed an update to its target regional Natural Heritage System (NHS) spatial layer in 2021. The purpose of this layer is to strategically delineate areas for protection, restoration, and enhancement in key natural heritage features and areas that are important for terrestrial and aquatic ecosystem health across the landscape (Shrestha & Chin, 2022). This extensive work was carried out using an advanced optimization process applied to 28 distinct spatial data layers to describe aquatic functions, terrestrial functions, and municipal NHS areas in the TRCA's jurisdiction. The results of this optimization process were then combined with the spatial data layers representing the existing natural features in the jurisdiction to delineate priority areas for protection, restoration, and enhancement in the NHS.

Habitat suitability maps for functional trait[20] groups of avian and amphibian species are among the spatial datasets used in the NHS update. These data layers were produced by linking species presence data to various predictor variables, such as the amount of broad natural cover types and vegetation communities, land use types, various natural cover quality attributes (e.g., perimeter-to-area ratio, largest patch in proximity), habitat connectivity, and urban forest canopy. Habitat suitability was calculated for nine functional traits of species including wetland, woodland, swamp, and arboreal amphibians as well as aerial insectivore, forest canopy, forest insectivore, grassland, and ground-nesting avian species at a spatial resolution of 100 m (TRCA, 2022).

Results and Discussion

To portray a holistic view of habitat suitability across the study area, the consolidated map of habitat suitability for these functional trait groups was considered (Figure 7). This map was generated by combining the top 30% of habitat suitability scores for each functional trait group of species. This scoring illustrates a gradient of habitat suitability values which contribute to regional biodiversity. It is important to note that habitat suitability was calculated considering a set of environmental factors influencing species occurrence at a spatial resolution of

[20] Functional traits are those that define species in terms of their ecological roles - how they interact with the environment and with other species (e.g., diet - carnivorous or herbivorous, habitat selection - forest, grassland, or aquatic, etc.).

100 m. Therefore, this layer was excluded from the final overlay analysis to avoid ecological fallacy[21].

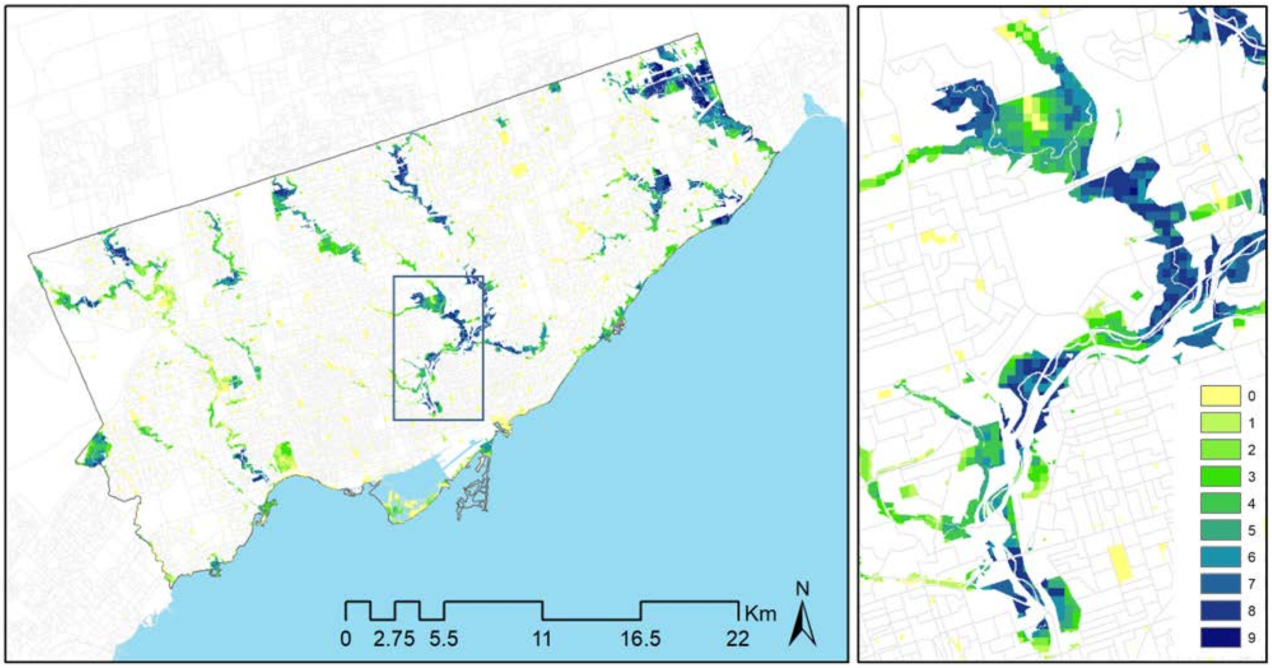

Figure 7. The consolidated habitat suitability scores for functional trait groups of avian and amphibian species. The value of 0 shows areas that are not suitable for any functional trait groups, and the value of 9 represents ideal habitat patches for all considered functional trait groups.

Habitat suitability, which is used as a proxy for biodiversity, is not monetized in this study as its value is typically determined through contingent valuation (Nunes & van den Bergh, 2001)[22], which is opinion-based and considered a highly subjective economic assessment approach for estimating the non-use values of the environment (Kahneman & Ritov, 1994).

4.7 Heat Mitigation (Temperature Regulation)

Background

The consequences of the Urban Heat Island (UHI) effect and the frequency and duration of heat waves are becoming more evident in cities around the world. Urban dwellers, particularly vulnerable groups such as socially disadvantaged and elderly people, are experiencing more heat-related stress, illnesses, and mortality due to the combined impacts of climate change, heat wave events, and UHIs (Benmarhnia et al., 2015; Jandaghian & Akbari, 2018). The severe impacts of heat waves are closely associated with the regional climate characteristics of multi-day heat stress, warm nights, and increased relative humidity. In the Greater Toronto Area (GTA), 60 heat warnings and 37 extended heat warnings were issued during the last 20 years (City of

[21] Ecological fallacy is a logical fallacy where inference is made on individual components based on the aggregate data on all components. It would be the case in this study, if the habitat suitability scores in Figure 6 were assumed to be valid at a finer spatial resolution (e.g., at 5 m, which is the spatial resolution used to map some of ecosystem services in this study).

[22] Contingent valuation, which is also known as stated preference, is a method for assessment of ecosystem services that involves directly asking people, in a survey, how much they would be willing to pay for a specific ecosystem service under hypothetical situations.

Toronto, 2022b). A heat warning is issued in southern Ontario when there is a forecast of two or more consecutive days with daytime maximum temperatures of 31°C or warmer, the nighttime minimum temperatures of 20°C or warmer, or a forecast of two or more consecutive days with humidex values of at least 40 (City of Toronto, 2022b). By 2050, the number of days with a maximum temperature above 30 ˚C is expected to reach 66 days per year in the GTA (City of Toronto, 2022b). This projection would significantly increase the number of heat-related deaths (Pengelly et al., 2007).

Preserving and enhancing natural assets in public green spaces is one approach to respond to this growing challenge. In Toronto, preserving tree canopy was proven to be an effective solution to mitigating the UHI effect and increasing ambient thermal comfort (Wang et al., 2016). Given the existing climate projections, it is imperative to evaluate the role of natural vegetative cover, aquatic features, and tree canopy in mitigating extreme ambient heat parameters and their associated health indicators.

Methods

An integrated health-heat framework was employed to estimate the impacts of the blue-green natural assets (i.e., shrubs, grass, water bodies, and tree canopy cover) on hot ambient temperature and associated health impacts. The applied framework combines statistical analysis with microclimate simulations to investigate the cooling impact of the blue-green assets on urban microclimate and heat-related community health responses. More specifically, the analysis uses a predictive model to compare current conditions with a scenario of no parks, open green spaces, and golf courses to estimate the role of these areas in mitigating the impacts of hot temperatures. The results were then used to estimate the economic benefits of heat mitigation in terms of the number of lives saved, reduced emergency department visits and ambulance service calls, reduced energy consumption, and increased worker productivity. A detailed description of the statistical models used in the analysis is provided in Appendix D.

Microclimate simulations were conducted using an updated version of the Urban Weather Generator (Dardir & Berardi, 2021), a simulation tool that predicts the cooling effect of blue-green assets based on evaporation cooling and realistic provision of shading. Two periods were considered to assess the cooling impacts: i) a forecasted two-week high temperature period[23] (June 18 – July 2); and ii) a typical summer season which extends from May to September. In addition, the simulations were performed for two different scenarios: the existing condition and an alternative "no-park" scenario where tree canopy and aquatic features are removed, and vegetative cover is reduced by 30% across the study area[24]. Table 14 lists the percentage of different cover types within parks and urban areas in the two described scenarios.

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[23] This scenario was developed by Environment and Climate Change Canada (ECCC) as an expected weather scenario for southern Ontario in 2030.

[24] These changes reflect a hypothetical urban development scenario whereby natural land cover categories are replaced by pavements and solid surfaces. Not only do these changes influence the percentage of blue-green natural assets within parks, but they also alter the overall percentage of these assets in the city—Parks are part of the urban fabric. These changes are reflected under the No-Park Scenario column for both park spaces and the entire city.

Table 14. Cover types within parks and urban areas in two scenario simulation runs

	Current Condition			No-Park Scenario		
	Vegetative cover (%)	Tree canopy (%)	Water (%)	Vegetative cover (%)	Tree canopy (%)	Water (%)
City-wide	23.5	25.9	1.3	17.1	14.2	0.7
Parks	80	80	5	50	0	0

Table 15 lists the results of the simulation for the extreme heat and typical summer conditions. The table shows the average and maximum values of temperature ("Temp_avr" and "Temp_max", respectively), and humidex

Table 15. Variations of Heat-related and energy parameters under the two scenarios and simulation periods

<table>
<tr><th colspan="2"></th><th colspan="5">During an extreme heat event</th><th colspan="5">During a typical summer season</th></tr>
<tr><th colspan="2"></th><th>Temp_avr (°C)</th><th>Temp_max (°C)</th><th>E_use (MW)</th><th>Hmdx_avr</th><th>Hmdx_max</th><th>Temp_avr (°C)</th><th>Temp_max (°C)</th><th>E_use (MW)</th><th>Hmdx_avr</th><th>Hmdx_max</th></tr>
<tr><td rowspan="4">City-wide</td><td>Current</td><td>23.3</td><td>36.3</td><td>267.5</td><td>29.7</td><td>52.3</td><td>16.5</td><td>31.9</td><td>185.7</td><td>18.8</td><td>40.6</td></tr>
<tr><td rowspan="3">No-park scenario</td><td>24.3</td><td>37.9</td><td>272.0</td><td>30.7</td><td>53.9</td><td>17.2</td><td>33.0</td><td>194.9</td><td>19.5</td><td>41.7</td></tr>
<tr><td colspan="10">Percent Change</td></tr>
<tr><td>4.3%</td><td>4.4%</td><td>1.7%</td><td>3.4%</td><td>3.1%</td><td>4.2%</td><td>3.4%</td><td>5.0%</td><td>3.7%</td><td>2.7%</td></tr>
<tr><td rowspan="4">Inside park</td><td>Current</td><td>17.8</td><td>28.6</td><td>0.15</td><td>24.4</td><td>40.8</td><td>9.9</td><td>24.9</td><td>0.16</td><td>12.3</td><td>31.4</td></tr>
<tr><td rowspan="3">No-park scenario</td><td>22.3</td><td>33.9</td><td>0.28</td><td>28.7</td><td>49.9</td><td>14.0</td><td>29.3</td><td>0.20</td><td>16.3</td><td>38.1</td></tr>
<tr><td colspan="10">Percent Change</td></tr>
<tr><td>25.3%</td><td>18.5%</td><td>86.7%</td><td>17.6%</td><td>22.3%</td><td>41.4%</td><td>17.7%</td><td>25.0%</td><td>32.5%</td><td>21.3%</td></tr>
</table>

("Hmdx_avr" and "Hmdx_max", respectively), along with the average daily energy consumption ("E_use", a reflection of changes in energy used for cooling buildings) under both considered scenarios in urban areas as well as within parks. The results clearly show the impact of the blue-green cover in creating thermal comfort and reducing energy consumption. Figures 8 and 9 illustrate the results of the analysis for humidex and ambient temperature for the two scenarios in Toronto’s parks, golf courses, and open green spaces. As shown in these time-series plots, the blue-green assets help mitigate extreme temperature and humidex condition, particularly during days of maximum heat stress.[25]

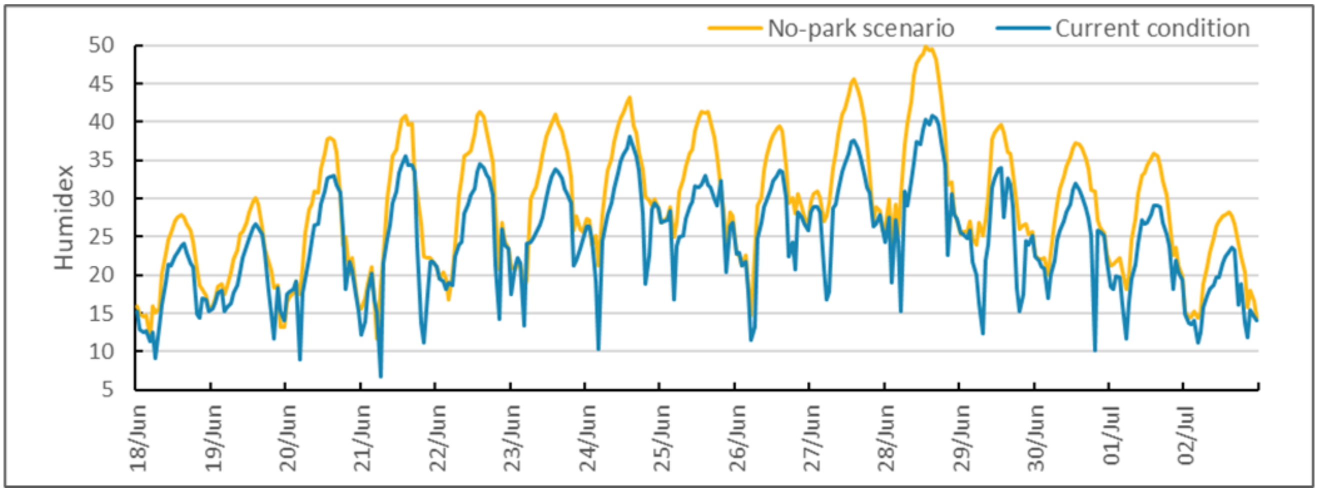

Figure 8. Variations of humidex under two scenarios during an extreme heat event

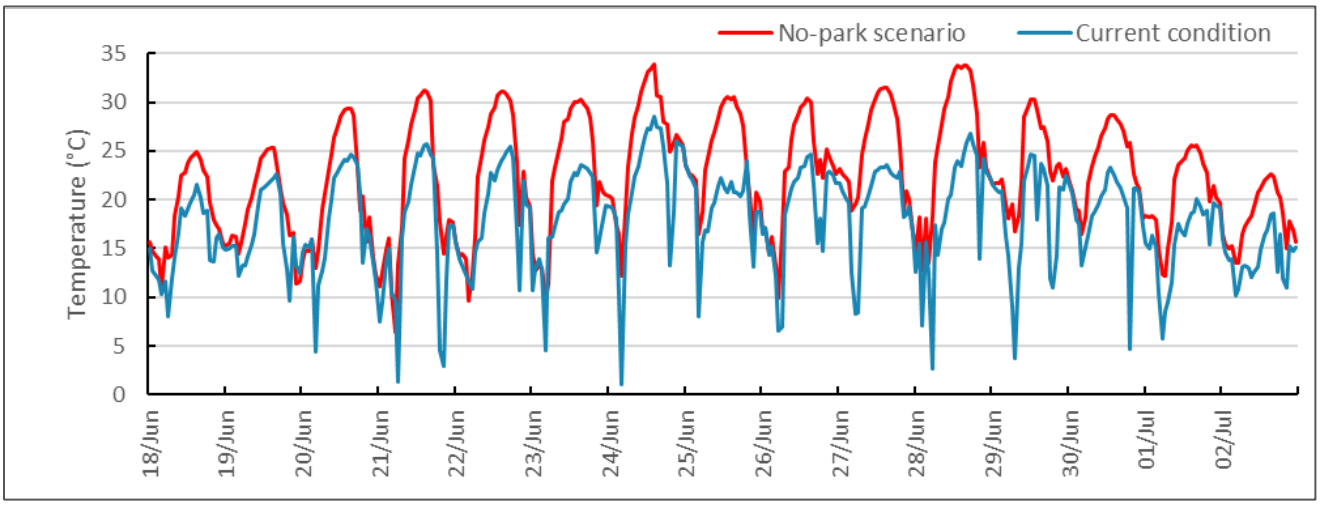

Figure 9. Variations of ambient temperature under two scenarios during an extreme heat event

Results and Discussion

The results described in Table 16 show that the heat regulation provided by the blue-green assets contribute to a reduction in mortality and the use of health services such as ambulance calls and emergency department visits. When extended to an average annual basis, the heat mitigation service during a typical summer season saves 15 lives (all-cause mortality), reduces emergency department visits by 135, and results in 83 fewer ambulance calls. Mitigating the impacts of extreme heat provides direct economic benefits in terms of avoided premature mortality, avoided costs of emergency department visits, avoided costs of ambulance service calls,

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[25] These time-series plots represent daily fluctuations in ambient temperature and humidex. During nighttime and early morning hours and due to the cooling effect of vegetation, the temperature within the park can exceptionally drop to a very low level (for a few hours) compared to daytime temperatures. More specifically, with no heating sources, traffic, or anthropogenic activities, and with radiative cooling to the night sky, the nighttime and early morning temperature has the potential to fall significantly in the study area.

lower energy use, carbon emission reduction, and increased worker productivity. **The analysis shows that the total economic benefit of the heat mitigation service is $166.7 million** (Table 17). The breakdown of results is described in the following sections.

Table 16. Daily community health response to hot temperature under different scenarios

		MOR_ all_avr*	MOR_ all_max*	EMR_ all_avr*	EMR_ all_max*	Amb_ Calls*
Extreme heat event	Current	48.6	50.8	433.8	464.0	194.9
	No-park scenario	48.7	51.0	435.2	466.3	277.8
		Percent Change Values				
		0.2%	0.4%	0.3%	0.5%	42.5%
Typical summer season	Current	49.1	51.3	427.0	455.8	194.9
	No-park scenario	49.2	51.4	427.9	457.3	277.8
		Percent Change Values				
		0.2%	0.2%	0.2%	0.3%	42.5%

*Variables legend:
MOR_all_avr: Daily average all-cause (total) mortality
MOR_all_max: Daily maximum all-cause (total) mortality
EMR_all_avr: Daily average all-cause (total) emergency visits
EMR_all_max: Daily maximum all-cause (total) emergency visits
Amb_Calls: Daily calls for ambulatory services

Table 17. The economic benefits of heat mitigation

Economic benefit category	Economic benefits ($ in 2022)
Avoided costs of premature mortality	133.5 million
Avoided costs of emergency department visits	46,845
Avoided costs of ambulance service calls	19,920
Energy savings	158,200
Increased worker productivity	33 million
Total	**166.7 million**

Avoided Costs of Premature Mortality

The economic cost of avoided premature death in 2022 was estimated at $8.9 million, as adopted from Health Canada's analysis of health impacts of air pollution ($7.7 million in 2016). This value is the recommended estimate for policy analysis in Canada (OECD, 2021); it is based on a review of Canadian studies (Chestnut & Civita, 2009), which examines Canadians' willingness to pay to reduce the risk of premature death by 1 out of 100,000. As clearly noted by Health Canada, the value is not "equivalent to the economic worth of an identified person's life, but rather an aggregation of individual values people are willing to pay for small changes in risk," (Health Canada, 2021). **The annual economic benefit of reduced early mortality attributed to heat mitigation in a typical summer season is $133.5 million** (15 avoided premature deaths multiplied by $8.9 million).

Avoided Costs of Emergency Department Visits

According to the Canadian Institute for Health Information, Canadian Management Information System (MIS) database (Canadian Institute for Health Information, 2022a), the average cost of an emergency department visit in 2018 was $304, which is equivalent to $347 in 2022. **The annual economic benefit of fewer emergency department visits attributed to heat mitigation in a typical summer season is $46,845** (135 avoided emergency department visits multiplied by $347).

Avoided Costs of Ambulance Service Calls

The average cost of each land ambulance service call in Ontario is $240 in 2022 (Ontario Ministry of Health, 2022). Based on the modeling, the heat mitigation service provided by the blue-green cover in the study area results in 83 fewer ambulance calls. **The annual economic benefit of avoided ambulance service calls is therefore $19,920** (83 avoided ambulance service calls multiplied by $240).

Energy Savings

The heat mitigation service reduces the energy consumption of air conditioning systems and other cooling technologies. During a typical summer season, energy consumption is reduced by 1.4 gigawatts as compared with the modelled no-parks scenario. Based on Ontario Energy Board 2022 summer pricing system, a mid-peak rate of 11.3 cents per kilowatt hour is applied to monetize the estimate energy saving. Accordingly, **the economic value of energy savings due to heat mitigation is $158,200** (1.4 million kwh multiplied by $0.113).

Increased Worker Productivity

During a typical summer season, outdoor workers lose on average 22 hours of work time due to increased breaks attributed to heat exposure (Canadian Institute for Health Information, 2022b). This number is equivalent to approximately 1% of the total hours worked in a year. Considering the hourly mean wage of $33.86 in 2022 in Ontario's labour market, the average lost worktime can be equated to an economic loss of $744.92 per outdoor worker per year (or $37.25 per hot day, assuming 20 hot days per summer season). The analysis shows that the cooling effect provided by blue-green assets reduces the number of days that would normally qualify as very hot by 6 days. **This is equivalent to $223.50 in avoided productivity losses per outdoor worker during a typical summer season**.

In Ontario, 8.8% of the labour force work in professions that have dangerous exposure to solar ultraviolet (UV) radiation (Peters et al., 2015). According to Toronto Economic Dashboard statistics, Toronto had 1,674,400 people in the labour force at the end of August 2022 (City of Toronto, 2022d). Assuming the percentage of Toronto's labour force working in professions with exposure to solar radiation is identical to that of Ontario's average, an estimated 147,347 people in Toronto's labour force are in professions that put them at risk of exposure to UV solar radiation. **Therefore, the annual economic benefit of increased worker productivity due to heat mitigation services is approximately $33 million** (147,347 multiplied by $223.50).

4.8 Physical Health

Introduction

Parks contribute to the health of the population by attracting people to spend time outdoors and by providing places for physical activity. The most studied link between park use and improved health outcomes is the role of parks in increasing physical activity in a population (Astell-Burt et al., 2013; Hartig et al., 2014; Lee et al., 2012; McCormack et al., 2010; WHO, 2016). The evidence shows that physical activity reduces the risk of several diseases and other adverse health outcomes, such as cardiovascular disease, diabetes, cancer, hypertension, obesity, depression, osteoporosis, and premature death (Lee et al., 2012; Toftager et al., 2011; Warburton et al., 2006).

Research has consistently found a positive association between parks and increased physical activity, most often measured by whether individuals meet the recommended dose of daily physical activity (Chaix et al., 2014; E. A.

Richardson et al., 2013; Schipperijn et al., 2017; Sugiyama et al., 2008). Studies of park use among North American parks in urban settings have found that the percentage of park users that engage in moderate to vigorous physical activity ranges from 18%-62% (Cohen et al., 2006; Hamilton et al., 2017; Holliday et al., 2017). Factors influencing the intensity, duration, and frequency of physical activities in a park include neighbourhood demographics, socio-economic conditions, park proximity, park sizes, facilities, amenities, and features (Kaczynski et al., 2009; Schipperijn et al., 2013).

Methods

The analysis assumed a park versus no-park scenario (or health benefit attributed to park presence) and combines three datasets: MobileScapes and CommunityHealth from Environics Analytics, and a 2022 survey on how Torontonians use parks conducted by Ipsos (City of Toronto, 2022a). The health benefit of physical activity attributed to park presence was based on the difference between the percent of weekly park users that engage in physical activity at or above the recommended level of physical activity per week according to the Canadian Physical Activity Guidelines (CPAG) and the population-wide rate for Toronto. The recommended guideline is 150 minutes or more of moderate to vigorous physical activity per week.

The percentage of park users physically active at or above the recommended level from CPAG was derived from the Environics Analytics MobileScapes and CommunityHealth datasets. Extracts of park visitors were compiled from MobileScapes for the City of Toronto for the year 2021. MobileScapes is a mobile movement dataset derived from mobile device users that give permission to share their latitude/longitude location with a collection of trusted applications. The raw mobile data allows Environics Analytics to identify devices observed within a defined area, such as a park, for a given date and time range. These devices are used as a sample of visitors. The sample excluded devices that spent less than 1 minute or greater than 5 hours within the park, devices that are likely to be employees, and devices from foreign countries (including the U.S.A.). Environics Analytics uses modeling to scale up the sample to a representative estimate of visits and visitors. Visitor characteristics can be estimated based on the characteristics of the population where they most likely live (the device's common evening location). Environics Analytics profiled Toronto park visitors based on their CommunityHealth dataset, which was derived from the Canadian Community Health Survey (CCHS) administered by Statistics Canada in 2017-2018 and modeled to 2021 population estimates. The percentage of 2021 park visitors physically active at or above the level recommended by CPAG was 54.82% compared to the city-wide rate of 52.94%.

The base number of Torontonians using parks at least once per week was taken from a 2021-2022 survey by Ipsos on how Torontonians use parks (City of Toronto, 2022a). The survey had a representative sample of n=1,619 Toronto residents 18 years of age and older. The survey was fielded between December 15, 2021 and January 6, 2022 and conducted online. The survey found that 56% of respondents visited a park at least once a week in 2021.

Results and Discussion

The economic value of physical activity due to park presence is estimated based on the avoided direct health care costs of physical inactivity derived by Krueger and colleagues (2014) estimated at $367 per person in 2022, when adjusted for inflation. This number was multiplied by the number of weekly park users that engage in 150 minutes or more of moderate to vigorous physical activity per week above the baseline rate to determine the avoided direct health care costs of physical inactivity among physically active park users. **The physical health**

benefit attributed to park presence is estimated at approximately $10.8 million in 2022. A breakdown of this calculation is presented below.

Table 18. Data input summary table for physical health

Variable	Result	Source
Population, Toronto Census Subdivision	2,794,356	Census 2021
Percent of park users 18 years + at or above the recommended physical activity level from CPAG	54.82%	MobileScapes park visitors (Environics Analytics 2022a); CommunityHealth (Environics Analytics 2022 b)
Toronto-wide rate of people 18 years + at or above the recommended physical activity level from CPAG	52.94%	CommunityHealth (Environics Analytics 2022 b)
Percent of Torontonians 18 years + visiting a park one or more times per week	56%	Park use survey (City of Toronto 2022a)

Calculation Breakdown

- Number of Torontonians (2,794,356) visiting a park at least once per week (56%) = 1,564,839
- Physical health improvement attributed to park presence, based on the difference between the prevalence of meeting the CPAG recommendation among park visitors (54.82%) and the city-wide prevalence rate (52.94%) = 1.88%
- Increased population meeting physical activity recommendations (i.e. the number of Torontonians visiting a park at least once per week (1,564,839) multiplied by the difference between prevalence of meeting the CPAG recommendation among park visitors and the city-wide prevalence rate (1.88%)) = **29,418 people**
- Avoided direct health care costs of physical inactivity per person = **$367** (in 2022)
- **Economic value of physical activity health benefit of park presence = (29,418 multiplied by 367) = $10.8 million in 2022.**

The analysis presented in this study does not investigate the impact of confounding variables such as park quality or median income distribution on park usership. The result indicates that park use is positively correlated with people meeting the physical health threshold considered in the analysis. This does not imply causality; in the absence of these spaces (no-park scenario), people may find alternative locations to exercise, for example, walking or jogging on the sidewalk as opposed to a park or playing sports in local gyms or community centres as opposed to fields. While park visitors are meeting the physical activity guidelines at a higher rate than the population-wide rate, they are not necessarily engaging in 150 minutes or more of moderate to vigorous physical activity per week in parks. Exercise may be occurring in other locations as well.

4.9 Mental Health

Background

Studies have consistently linked exposure to green space and time spent in green space to lower levels of stress, depression, anxiety, and frustration, improved cognitive function, and higher sense of personal wellbeing and self-esteem (Beyer et al., 2014; Hartig et al., 2014; Maas et al., 2009; Nutsford et al., 2013; Triguero-Mas et al., 2015). While explanatory pathways are not well understood, studies consistently find that parks positively contribute to mental wellbeing (Engemann et al., 2019). Shanahan et al (2016) found that depression, high blood pressure, and social cohesion were linked to both the duration and frequency of green space visits. The longer the green space visit, the lower the rates of depression and high blood pressure, and those who visited more frequently reported greater social cohesion. A dose-response analysis for depression and high blood pressure suggests that visits to outdoor green spaces of 30 minutes or more per week could reduce the population prevalence of these illnesses by up to 7% and 9%, respectively (Shanahan et al., 2016; WHO, 2016).

Methods

This analysis assumed a park versus no-park scenario. The mental health benefit was based on the difference in prevalence of mood disorders (depression and bipolar disorder) among Toronto park users and the city-wide prevalence rate. The rate of mood disorders was derived from the Environics Analytics MobileScapes and CommunityHealth datasets, as described in section 4.8. Accordingly, the percentage of park users with mood disorders was 7.70% compared to the city-wide prevalence rate of 8.31%.

Results and Discussion

The annual mental health benefits attributed to park presence equals approximately $21.1 million in 2022. A breakdown of the calculation is presented below.

Table 19. Data input summary table for mental health

Variable	Result	Source
Population, Toronto Census Subdivision	2,794,356	Census 2021
Prevalence of mood disorder among park visitors in Toronto	7.70%	MobileScapes park visitors (Environics Analytics 2022a); CommunityHealth (Environics Analytics 2022 b)
Toronto-wide prevalence of mood disorder	8.31%	CommunityHealth (Environics Analytics 2022 b)
Percent of Torontonians 18 years + visiting a park one or more times per week	56%	Park use survey (City of Toronto 2022a)

Calculation Breakdown

- Number of Torontonians (2,794,356) visiting a park at least once per week (56%) = 1,564,839
- Mental health improvement attributed to park presence based on the difference between prevalence of mood disorders among park visitors in Toronto (7.70%) and the city-wide prevalence rate (8.31%) = 0.61%
- Reduced population experiencing mood disorder (i.e., the number of Torontonians visiting a park at least once per week (1,564,839) multiplied by the difference between prevalence of mood disorders among park visitors in Toronto and the city-wide prevalence rate (0.61%) = **9,546 people**
- Avoided economic burden of mental illness per person = **$2,212** in 2022[26]

[26] The value was adjusted for inflation based on the population-based figure reported by Lim et al. (2008)

- **Economic value of health benefit related to improved mental health condition (9,546 multiplied by 2,212) = $21.1 million in 2022**

The result indicates that park use is correlated with lower prevalence of mood disorders. This does not imply causality. Multiple factors influence mental wellbeing including biological, social, and environmental factors. This result reports the health benefit of improved mental health by spending time in parks. In the absence of these spaces (no-park scenario), people may find alternative locations for respite, relaxation, and social interaction.

5.0 AGGREGATE BENEFITS

5.1 Total Economic Benefits

Table 19 provides a summary of all ecosystem service categories along with the indicators used to quantify each service, the units considered for quantification, the quantified service level, and the economic values associated with monetized services (where applicable).

Table 20. Summary of ecosystem service valuation for City-owned and operated parks, golf courses, and open green space

Ecosystem service	Indicator	Unit of measurement	Quantified service level	Estimated economic benefits ($ in 2022)
Stormwater retention	Retention volume (sum of interception, infiltration, and evapotranspiration)	m^3/year	55,360,841	6.7 billion
Avoided phosphorus	Total avoided load of phosphorus	kg/year	15,347	NA
Avoided suspended solids	Total avoided load of suspended solids	kg/year	2,575,673	NA
Carbon storage	The total carbon stocks in four carbon pools	tonne	810,228	817.7 million
Carbon sequestration	Annual carbon sequestration value per land cover	tonne/year	11,235	11.3 million
Air quality regulation	Tonnes of pollutants and particulate matter removed by forests and successional forests	tonne/year	162.3	7.2 million
Food provision	Fresh produce yield from community gardens and allotment garden sites	tonne/year	9.7	11,669
Civic contribution	Voluntary work	Hours worked	11,145.5	279,252
	Financial donations dedicated to parks and park programs	$ /year	112,069	112,069
Habitat suitability	Consolidated habitat suitability categories for nine functional traits of avian and amphibian species	NA	0 - 9	NA
Heat mitigation	Avoided cases of premature mortality	# of lives saved	15	133.5 million
	Avoided cases of emergency department visits	# of avoided visits	135	46,845
	Avoided cases of ambulance service calls	# of avoided calls	83	19,920
	Energy savings	gigawatts	1.4	158,200
	Increased worker productivity among those who are directly exposed to heat	# of days not classified as very hot	6	33 million
Physical health	Number of weekly park visitors that engage in 150 minutes or more of moderate to vigorous physical activity per week above the baseline rate	# of people meeting the physical activity threshold	29,732	10.8 million
Mental health	Number of weekly park visitors with reduced prevalence of mood disorders	# of people without mood disorders	9,546	21.1 million
			Total	**7.7 billion**

Accordingly, **the total annual value of all monetized ecosystem services is estimated to be $7.7 billion in 2022.** This value should be interpreted as a conservative estimate since it is calculated based on specific modeling assumptions for some ecosystem services, does not reflect the value of all services considered in the study, and is adjusted for inflation based on a one-time CPI value reported in May 2022 for a fixed basket of goods and services including food, shelter, furniture, clothing, transportation, and recreation.

5.2 Ecosystem Service Provision Index

To measure the aggregate provision of all mapped regulating services, the Ecosystem Service Provision Index (ESPI) was developed using a fuzzy overlay analysis[27]. Fuzzy overlay refers to a set of aggregation methods developed based on the principles of fuzzy logic[28]. Fuzzy overlay methods are used to reduce inaccuracies associated with spatial data classification in multi-criteria analysis (ESRI, n.d.). To generate the ESPI, all mapped regulating services were transformed into a gradient of values between 0 and 1 based on a series of data-driven fuzzy linear membership functions, so that they could all be jointly analyzed. These fuzzified maps were then overlaid using the fuzzy γ (Gamma) operator (Figure 10).

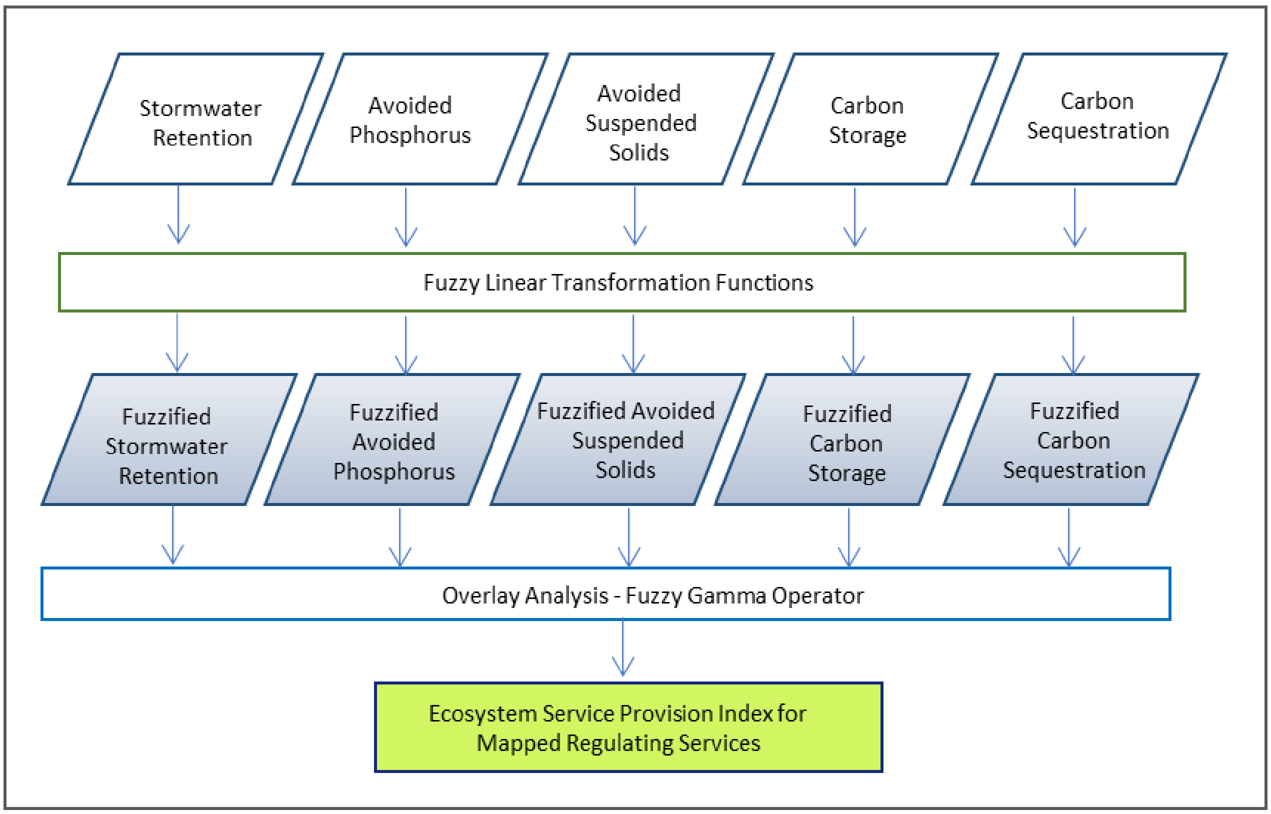

Figure 10. The fuzzy overlay analysis undertaken to produce the Ecosystem Service Provision Index for all mapped regulating ecosystem services

[27] The fuzzy overlay method used in this study is a modified version of the fuzzy overlay analysis employed in a site suitability study in southwestern Ontario (Mirnasl et al., 2022). This method is briefly explained in Appendix E.

[28] The fuzzy logic is a mathematical approach to addressing uncertainty in decision analysis situations. It is a widely used approach when decisions need to be made under complex situations requiring simultaneous assessment of multiple criteria.

Figure 11 illustrates the ESPI map of the study area.

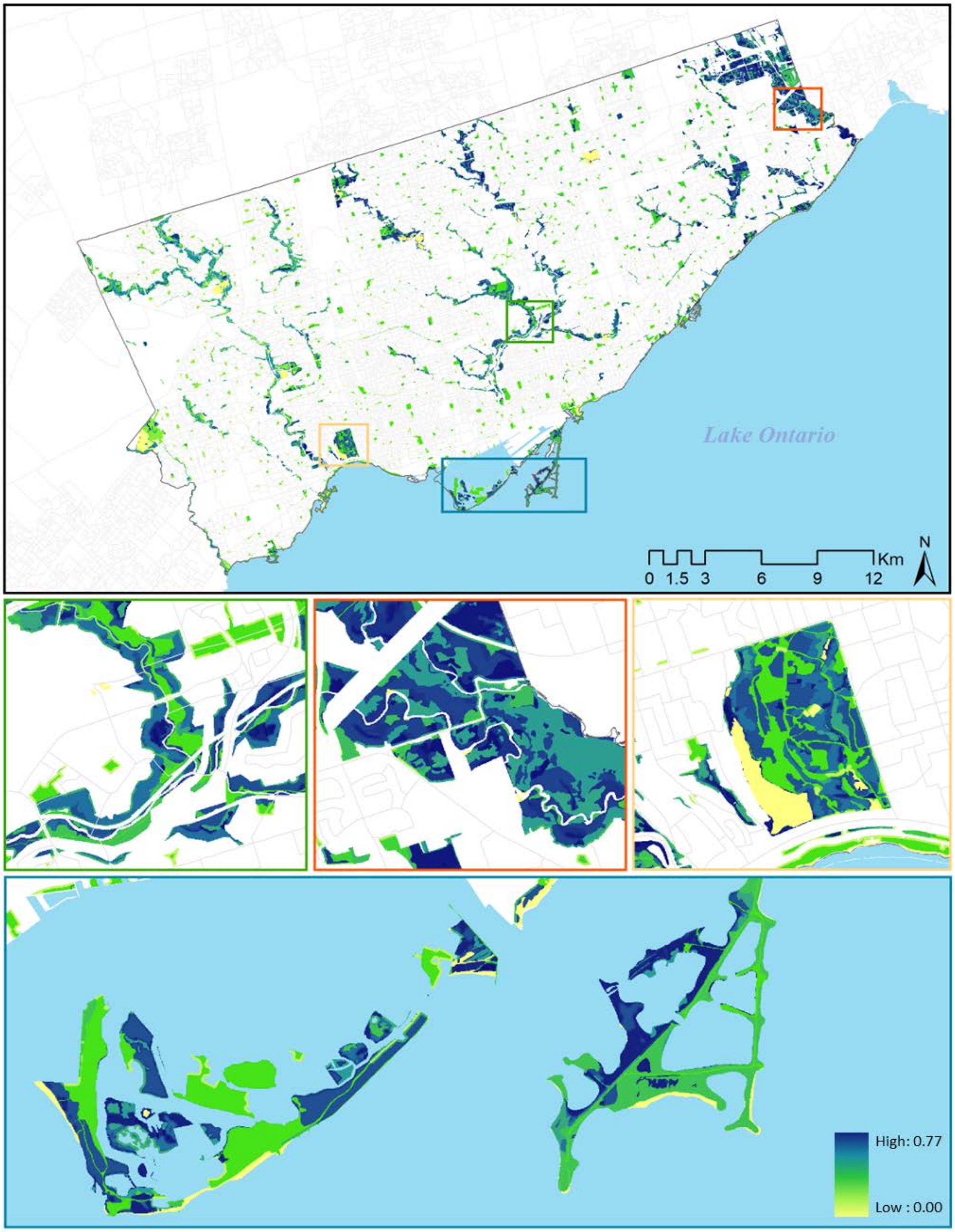

Figure 11. The map of Ecosystem Service Provision Index (ESPI) for the study area (parts of the Rouge National Urban Park, Don Valley, High Park, Toronto Island Park and Tommy Thompson Park are magnified to show the geographic distribution of ESPI)

Figure 11 shows the geographic distribution of regulating ecosystem service provision at an aggregate level for stormwater retention, water quality improvements, and carbon storage and sequestration categories. More specifically, the ESPI value for each pixel in this map shows that pixel's ecosystem service provision capacity when all mapped regulating services are simultaneously considered. ESPI values range between 0 and 0.77, with higher values showing greater service provision level. These values, and thus multiple regulating services, are higher for natural assets such as wetlands, mature and successional forests, and meadows than for assets such as recreational/open space, stormwater management ponds, and beach/bluff. Also, areas that spatially overlap with the ravine system have higher ESPI values than areas located outside of this system. This means that Toronto's ravines play a key role in the provision of regulating ecosystem services.

To distinguish between the hydrologic ecosystem services and carbon-related services, provision indices were also generated separately for each service group. Maps of Ecosystem Service Provision Index for Water (ESPI-W) and Ecosystem Service Provision Index for Carbon (ESPI-C) are included in Appendix F. These maps can be used to determine high/low service provision areas when land use planning or resource management decisions need to be made by considering closely associated ecosystem services[29]. For instance, if decision-makers need to compare site-specific hydrologic service provision to determine investment priority areas (e.g., for asset enhancement), the ESPI-W map can provide insights as to where investments should be directed. Similarly, if management decisions require information on the magnitude and geographic distribution of carbon storage and sequestration services, the ESPI-C map can provide that critical information.

[29] ESPI-W and ESPI-C values are different than the ESPI values, as each index was developed based on a different combination of the mapped regulating ecosystem services.

6.0 SUMMARY AND RECOMMENDATIONS

This study provides an in-depth assessment of key ecosystem services associated with City-owned and operated parks, golf courses, and open green spaces in Toronto. The results are presented as total annual economic benefits of the monetized services and the service provision maps for all and closely associated (thematic) regulating services. **The annual economic value of ecosystem services in the study area is estimated as $7.7 billion in 2022. While this number should be seen as a conservative estimate, it is a considerable figure, as it is derived from only 13% of the City's land surface area.** The economic benefits provided by each ecosystem service can help justify future investments for protecting Toronto's public green spaces and the network of natural assets within these areas. The Ecosystem Service Provision Index (ESPI) and the thematic service provision maps for water (ESPI-W) and carbon (ESPI-C) can help formulate informed land use polices and natural resource management decisions. These maps can help guide site-specific interventions to improve the aggregate service provision score with reference to all or thematic regulating services.

The findings of this report can be used in several ways to further improve key land use planning decisions regarding natural assets found in public green spaces. Some suggestions include the following:

- The results presented in this report can be used to extract site-specific values for ecosystem services that are both mapped and monetized (i.e., stormwater retention, carbon storage, and carbon sequestration). This would help support the City's capacity for budget prioritization, funding applications, and public education purposes.
- The results can be used to identify priority areas for natural asset (green infrastructure) investments based on service provision values for one or multiple services. One potential approach to identify investment priority areas is using a conservation/restoration lens for allocating funds. In this approach, investments should be allocated to restoration efforts in areas with lower service provision and to conservation efforts in areas with higher service provision.
- The results can be integrated into the City's broader asset management framework. For instance, the findings can help inform service level measures for natural assets which can be used along with information on asset condition and replacement costs to improve the sustainable management of these assets.
- Service-specific maps can be used in conjunction with the ESPI values to augment the City's Parkland Strategy analyses (e.g., in reference to the Acquisition Priority Map).
- The findings of this report are in line with the guiding principles and the recommended actions of Toronto's Ravine Strategy (City of Toronto, 2017). Where applicable, insights from this work can facilitate strategic resource allocation across the ravine system. For instance, service-specific maps, ESPI, ESPI-W, and ESPI-C values can help guide resource management, investment, and stewardship strategies across areas that overlap with Priority Investment Areas (PIA) in the ravine system.
- The methods presented in this report can be used to map ecosystem service provision under multiple land use/cover scenarios. This could inform city-wide land use planning and resource management decisions regarding natural assets under potential future scenarios.

The methods presented in this work could also potentially be applied in the future to:

- Facilitate funding applications and budget discussions to help inform how further investment in natural assets could translate into improved ecosystem service provision.
- Map stormwater retention and water quality benefits under different precipitation scenarios, considering future climate projections for the region (Climate Atlas of Canada, 2022; TRCA, 2021a). This would help characterize and quantify potential stormwater retention and water quality benefits of the existing network of natural assets in the future. This is of strategic importance to the City, as stormwater retention benefits comprise a significant proportion of the annual economic benefits.
- Monitor ecosystem service change over time. Future studies should consider a more detailed classification of natural assets. They can also consider other ecosystem services not analyzed in this report to paint a more holistic picture of aggregate ecosystem service provision.

Natural assets in Toronto are not limited to the public green spaces considered in this report. These assets are part of a broader green infrastructure network that exists in private lands, on streets, and other public green spaces within the city. The totality of these assets is critical to the provision of various ecosystem services that make Toronto a more livable place for all its inhabitants. Only a small proportion of these ecosystem services are analyzed in this study. Nevertheless, the results show that these services generate enormous economic benefits to the city on an annual basis. Protecting and enhancing the natural assets of public green spaces can ensure that these services and their economic benefits continue.

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APPENDICES

In this section, further information is provided regarding the methods and data layers used in the analysis.

Appendix A - Supplementary information on stormwater retention and water quality analysis

Figure 1A illustrates the input land use/cover map of Toronto used to quantify the stormwater retention and water quality benefits. The original land use/cover map was reclassified according to the runoff coefficient values found in the literature.

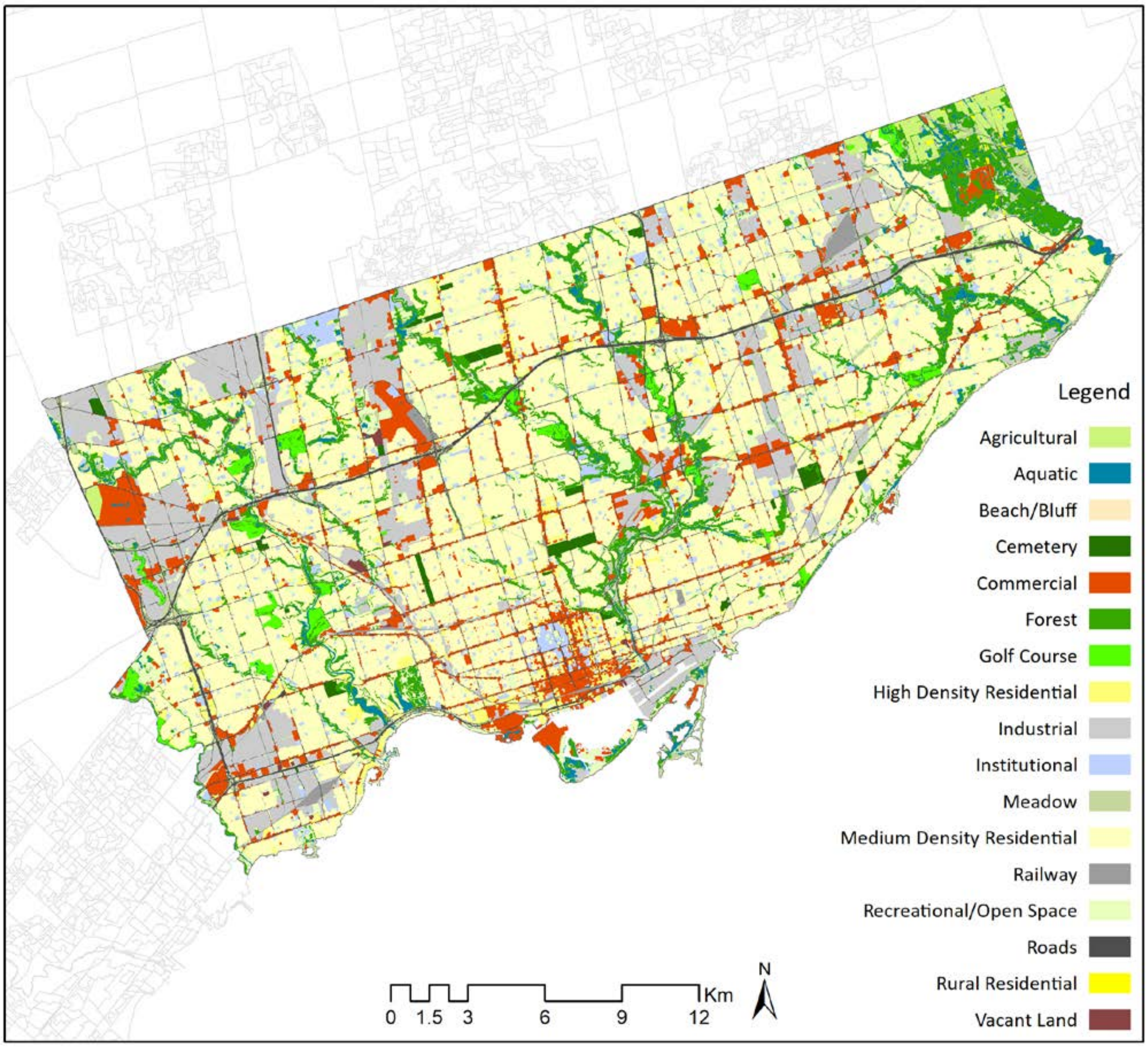

Figure 1A. The land use/cover map used to quantify the stormwater water retention and quality benefits in Toronto

Table 1A lists the primary and reclassified land use/cover classes used for the analysis. It also includes information about the runoff coefficients and Event Mean Concentration (EMC) values associated with the reclassified land use/cover types.

Table 1A. Runoff coefficients and EMC values associated with each land use/cover classes in the input map of the study area

Primary land use/cover	Reclassified land use/cover	Runoff Coefficient	EMC_P (mg/l)	EMC_TSS (mg/l)
Agricultural	Agricultural	0.35	0.23	100
Airport	Commercial	0.9	0.23	90
Allotment Garden Site	Agricultural	0.35	0.23	100
Beach/Bluff	Beach/Bluff	0.25	0.2	27
Cemetery	Cemetery	0.25	0.32	100
Commercial	Commercial	0.9	0.23	90
Community Garden	Agricultural	0.35	0.23	100
Forest	Forest	0.25	0.23	55
Golf Course	Golf Course	0.25	0.32	100
High Density Residential	High Density Residential	0.85	0.23	90
Industrial	Industrial	0.85	0.23	90
Institutional	Institutional	0.75	0.23	90
Lacustrine	Aquatic	0.05	0.81	13
Meadow	Meadow	0.28	0.23	100
Medium Density Residential	Medium Density Residential	0.75	0.23	90
Mixed Commercial Entertainment	Commercial	0.9	0.23	90
Open Waterbody	Aquatic	0.05	0.81	13
Railway	Railway	0.35	0.23	90
Recreational/Open Space	Recreational/Open Space	0.25	0.2	27
Riverine	Aquatic	0.05	0.81	13
Roads	Roads	0.9	0.23	90
Rural Residential	Rural Residential	0.65	0.23	90
Stormwater Pond	Aquatic	0.05	0.81	13
Successional Forest	Forest	0.25	0.23	55
Vacant Land	Vacant Land	0.30	0.09	7.00
Wetland	Aquatic	0.05	0.81	13

The 30-year average annual precipitation data (1981-2010) were derived for four Environment and Climate Change Canada stations (Table 2A). This information was then used to produce the precipitation raster for four different zones in Toronto. Each zone was assigned a precipitation value equal to that of the closest station to it.

Table 2A. ECCC climate stations and 30-year average annual precipitation used for the analysis

Station	ID	30-Year Average Annual Precipitation (mm)
Toronto	6158350	831.1
Pearson Airport	6158733	785.9
Toronto Buttonville A station	615HMAX	852.9
Richmond Hill	6157012	895.2

Appendix B - Supplementary information on carbon storage and sequestration analysis

Table 3A lists the areas associated with each land cover category in the reclassified map of natural assets for carbon accounting.

Table 3A. Area of each land cover type in the reclassified map of natural assets for carbon accounting

Asset_Type	Area (ha)	Percentage (%)
Forest (Coniferous Plantation_ELC)	67	0.9
Forest (Coniferous_ELC)	55	0.8
Forest (Deciduous Plantation_ELC)	239	3.2
Forest (Deciduous_ELC)	1350	18.3
Forest (Generic)	1292	17.5
Forest (Mixed_ELC)	283	3.8
Meadow	598	8.1
Open Space (Manicured_Lawn)	2543	34.5
Other	395	5.3
Wetland (Fen_ELC)	0	0.0
Wetland (Generic)	353	4.8
Wetland (Marsh_OMNRF)	8	0.1
Wetland (Meadow Marsh_ELC)	49	0.7
Wetland (Open Water_ELC)	16	0.2
Wetland (Open Water_OMNRF)	3	0.0
Wetland (Shallow Marsh_ELC)	78	1.1
Wetland (Swamp_OMNRF)	4	0.1
Wetland (Thicket Swamp_ELC)	39	0.5
Wetland (Treed Swamp_ELC)	4	0.1
Total	**7376**	**100.0**

The criteria used to determine carbon storage and sequestration rates based on the Natural Asset Carbon Assessment Guide and Toolbox are as follows:

- Rates that are local, transferable to southern Ontario, or have a high confidence ranking were prioritized over non-local rates with medium confidence level.
- Where rates are from non-local or outdated studies, the rates were determined according to the rates reported for the most relevant land cover class.
- Forests and wetlands not overlapping with ELC or Ontario Ministry of Natural Resources and Forestry (OMNRF) datasets were identified as generic landcover types. These features were assigned carbon storage and sequestration rates equivalent to the weighted average of these rates in the other forest and wetland categories. The weighting factor was determined considering the relative frequency (of surface area) of the rest of the forest and wetland classes.
- Since soil carbon rates are reported at different depths, rates at identical or closer depths are prioritized in the analysis.
- Only rates for mature species were considered for forests.

- The Forest (Generic) class was assigned a soil carbon storage equal to that of the most frequently occurring forest class (i.e., Forest [Deciduous_ELC]).
- Carbon storage rates are measured in tonne/ha. The database sometimes includes average soil carbon rates calculated for a very long period (e.g., 100 years), and thus measured in tonne/ha/year. To keep the rates consistent among all land cover classes, the average values reported for long periods were multiplied by the number of years over which they were calculated, assuming that the soil carbon stocks in these land cover types have remained constant over the reported period, and that these rates are accurate for the year of analysis.
- Sequestration and storage rates for OMNRF marshes and swamps were determined based on the weighted average of these rates for ELC marshes and swamps.
- Carbon sequestration and storage rates for Manicured Open Spaces are reported for bluegrass establishments younger and older than 25 years. The rates included in the analysis were determined by calculating the weighted average of the reported rates, assuming a maximum age of 100 years for these features.

Appendix C - A step-by-step guide to monetizing carbon storage and sequestration in the future.

The future economic value of carbon storage should be based on future carbon stocks. Assuming no change in the natural assets used in quantifying carbon storage and sequestration and a constant annual sequestration rate (ANPP), the carbon storage number for a site needs to be updated by adding its annual sequestration rate to its carbon stocks in a preceding year. Starting from 2022, this should be repeated for all the years in the analysis until the carbon storage number is updated for the future year of interest.

The economic benefits of carbon storage and sequestration services should be estimated by multiplying the CO_2 equivalents of storage and sequestration numbers by the adjusted social cost of carbon in the future. Since the recommended social cost of carbon for each year is reported in 2021 dollars (Government of Canada, 2023), these values need to be adjusted for inflation to present an appropriate equivalent rate for the year of analysis. Adjustments to the monetized value of carbon storage and sequestration in a future year can be made based on the inflation rate between that year and 2021. For instance, the social cost of carbon utilized in this study was adjusted for inflation from the recommended social cost of carbon of $256/ t CO_2 for 2022 (in $2021) to an inflated value of $275/ t CO_2 (in $2022) using the inflation calculator of Bank of Canada (Bank of Canada, 2022).

If future costs or benefits need to be reported in present-day terms, then a discount rate should be applied to the monetized values as well. Since future costs/benefits are usually considered less significant than present-day values, a discounting factor is applied every time future values need to be converted to present-day terms. A high discount rate means that future impacts are considered much less significant than present effects, whereas a low discount rate means that future impacts are closely to equally significant. As of 2022, the discount rate associated with the recommended social cost of Greenhouse Gasses (GHGs) in Canada is 2% (Government of Canada, 2023).

Using Earl Bales Park as an example, a step-by-step guide is provided below on how the total economic values associated with carbon storage and sequestration in 2023, 2024, and 2025 can be converted to 2022 dollars. In 2022, the park's carbon storage and sequestration (ANPP) numbers are 8200 t C and 97.6 t C/year, respectively.

- Step 1- Assuming a constant sequestration rate, the carbon stocks in the park need to be updated for each year by adding its annual sequestration to its carbon storage in the preceding year. The park's carbon stocks for the 2022-2025 period are listed in Table 4A.
- Step 2- The carbon storage and sequestration numbers in the park must be converted to their CO_2 equivalents for each year, using the 3.67 conversion multiplier. The CO_2 equivalents of storage and sequestration are listed in Table 4A.
- Step 3- Since the reported values for each year are in $2021, the social cost of carbon for each year must be converted to their 2022 equivalents. The adjusted social costs of carbon for the 2022 -2025 period are listed in Table 4A.
- Step 4- The CO_2 equivalents of carbon storage and sequestration numbers for each year need to be multiplied by the social cost of carbon in that year. The results are listed in Table 5A.

- Step 5- The discount rate should be applied to the monetized values calculated in Step 4 to get the discounted values for each year. Since the base year is 2022, a 2% discount rate means that the monetized values for 2023, 2024, and 2025 need to be multiplied by 0.98, 0.96, and 0.94 discount factors, respectively. The discount factor for 2022 is 1, as it is the base year in the analysis. The discounted values for the 2022-2025 period are listed in Table 5A.

- Step 6- The results from all years need to be added to get the total discounted benefits in $2022.

The total discounted benefits of storage and sequestration for the 2022-2025 period in the park are $33,646,927 and $393,465, respectively. These numbers illustrate the total economic costs of emissions (in $2022) due to anthropogenic or natural disturbances in four consecutive years or the benefits of preventing that from happening by protecting the natural assets in the park.

This cost-benefit analysis can be replicated for different sites and years in the study area.

Table 4A. Carbon storage and sequestration, their CO_2 equivalents, and the updated social cost of carbon from 2022 to 2025

Year	Carbon storage (tonne)	Carbon sequestration (ANPP in tonne /year)	CO_2 equivalent of storage (tonne)	CO2 equivalent of sequestration (tonne/year)	Social cost of carbon/tonne of CO_2 ($2021)	Social cost of carbon/tonne of CO_2 ($2022)
2022	8,200	97.6	30,094	358.192	$256	$275
2023	8,297.6	97.6	30,452.192	358.192	$261	$281
2024	8,395.2	97.6	30,810.384	358.192	$266	$286
2025	8,492.8	97.6	31,168.576	358.192	$271	$291

Table 5A. The discounted economic value of storage and sequestration from 2022 to 2025 using the adjusted social cost of carbon (in $2022)

Year	Economic value of storage ($2022)	Economic value of sequestration ($2022)	Discounting factor	Discounted economic value of storage ($2022)	Discounted economic value of Sequestration ($2022)
2022	$8,275,850	$98,503	1	$8,275,850	$98,503
2023	$8,557,066	$100,652	0.98	$8,385,925	$98,637
2024	$8,811,770	$102,443	0.96	$8,459,299	$98,345
2025	$9,070,056	$104,234	0.94	$8,525,853	$97,980
				Total: $33,646,927	Total: $393,465

Appendix D - Supplementary information on heat mitigation

The statistical approach used for the analysis is developed by integrating historical population health data of mortality counts and emergency department visits with the changes in ambient conditions. The statistical model deploys Poisson regressions over a historical dataset (from 2003 to 2019) using records of daily all-cause mortality counts, daily emergency department visits, and meteorological parameters including daily weather measurements. This study focuses only on warm and hot seasons, which extend from May to September each year. The weather data were obtained from the Toronto City weather station (43.67N 79.40W, climate ID: 6158355). The health records were retrieved from Statistics Canada, Research Data Centers (RDCs) utilizing the Canadian Vital Statistics - Death Database (CVSD) for mortality counts. The dataset was built on a daily scale for humidex, all-cause mortality (MOR_all), and daily total emergency visits (EMR_all) focusing on the impact of heat events on health responses. The elderly mortalities and emergency visits were defined when the cases are classified as elderly (age > 65) and were tracked by a percentage of the all-cause mortalities and total emergency visits, respectively. Heat-related ambulance calls were traced within the city. The relationship between ambulance calls and municipal tree canopy in the City of Toronto was adopted from a local study (Graham et al., 2016). The correlation was used in this analysis to predict the variations of ambulance calls based on the changes in greenery cover.

The relationship between heat stress and health records was monitored by regression analyses. The predictive regression showed that mortality records positively correlate with humidex following non-linear behavior. Also, it depends on the month during the hot season. The statistical regressions result in evidence-based equations to predict all-cause mortality and vulnerable mortality based on the historical datasets of the city. As an example, the generated equation for all-cause mortality is graphically presented in Figure 2A. Also, the ambulance calls are predicted based on previous correlations and adapted to the population of the city. All the statistical equations are integrated into the microclimate modeling to predict the changes in health records based on altering the greenery cover of the city.

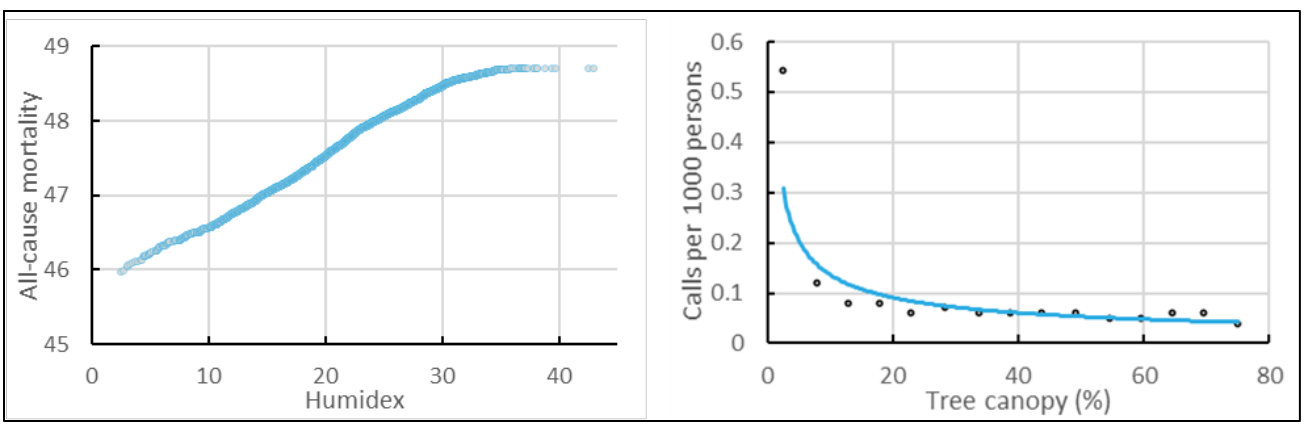

Figure 2A. Representation of statistical models used in the integrated heat-health framework

Appendix E - Supplementary information on the fuzzy membership function and overlay method used in the analysis

The Fuzzy overlay analysis was carried out in two steps. In the first step, the maps of all ecosystem services were transformed into a gradient of values between 0 and 1 using the fuzzy (increasing) linear function:

$$\mu(x) = \begin{cases} 0 & x \leq a \\ \dfrac{x-a}{b-a} & a < x < b \\ 1 & x \geq b \end{cases}$$

In this formula, a and b are user-defined minimum and maximum values. For each mapped ecosystem service layer, a and b were set respectively equal to the minimum and maximum quantified ecosystem service values. The transformed layers were then overlaid using the fuzzy "compensatory and" operator, which is known as the fuzzy "Gamma operator" in the ArcGIS environment:

$$\mu(x) = (1 - \prod_{i=1}^{n} \big(1 - \mu_i(x)\big))^{\gamma} * (\prod_{i=1}^{n} \mu_i(x))^{\ (1-\gamma)}$$

In this formula, $\mu(x)$ is the membership value of each pixel in the final fuzzy set. More specifically, it is the Ecosystem Service Provision Index for each pixel in the final map of service provision. Gamma is the overlay parameter which determines degrees of compensation between the input criteria into the overlay analysis. It was set to a default value of 0.9.

Appendix F - ESPI-W and ESPI-C Maps

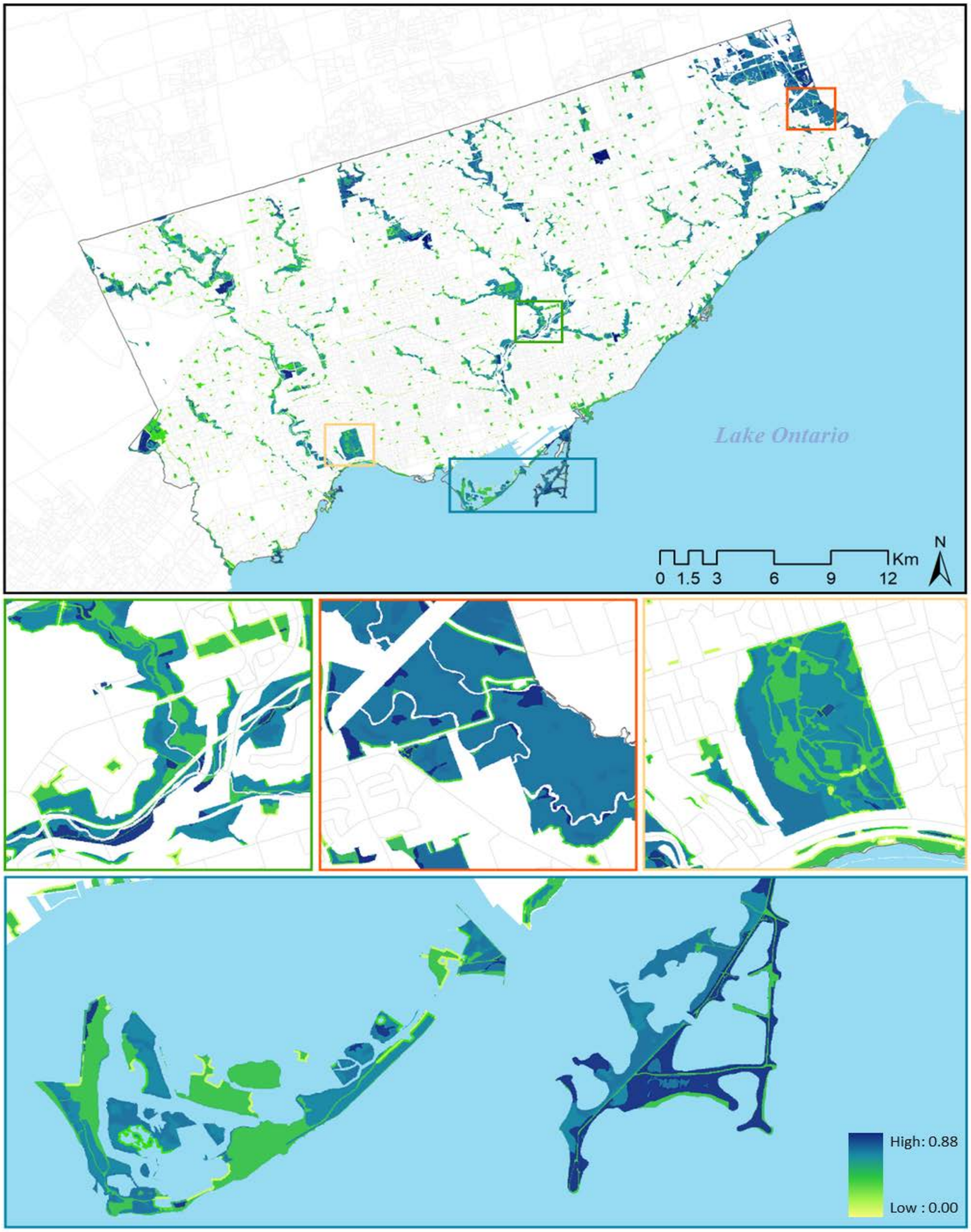

Figure 3A - The map of ESPI for water (ESPI-W). This map illustrates the magnitude and geographic distribution hydrologic services in response to annual precipitation (parts of the Rouge National Urban Park, Don Valley, High Park, and Toronto Island Park and Tommy Thompson Park are magnified to show the geographic distribution of ESPI-W)

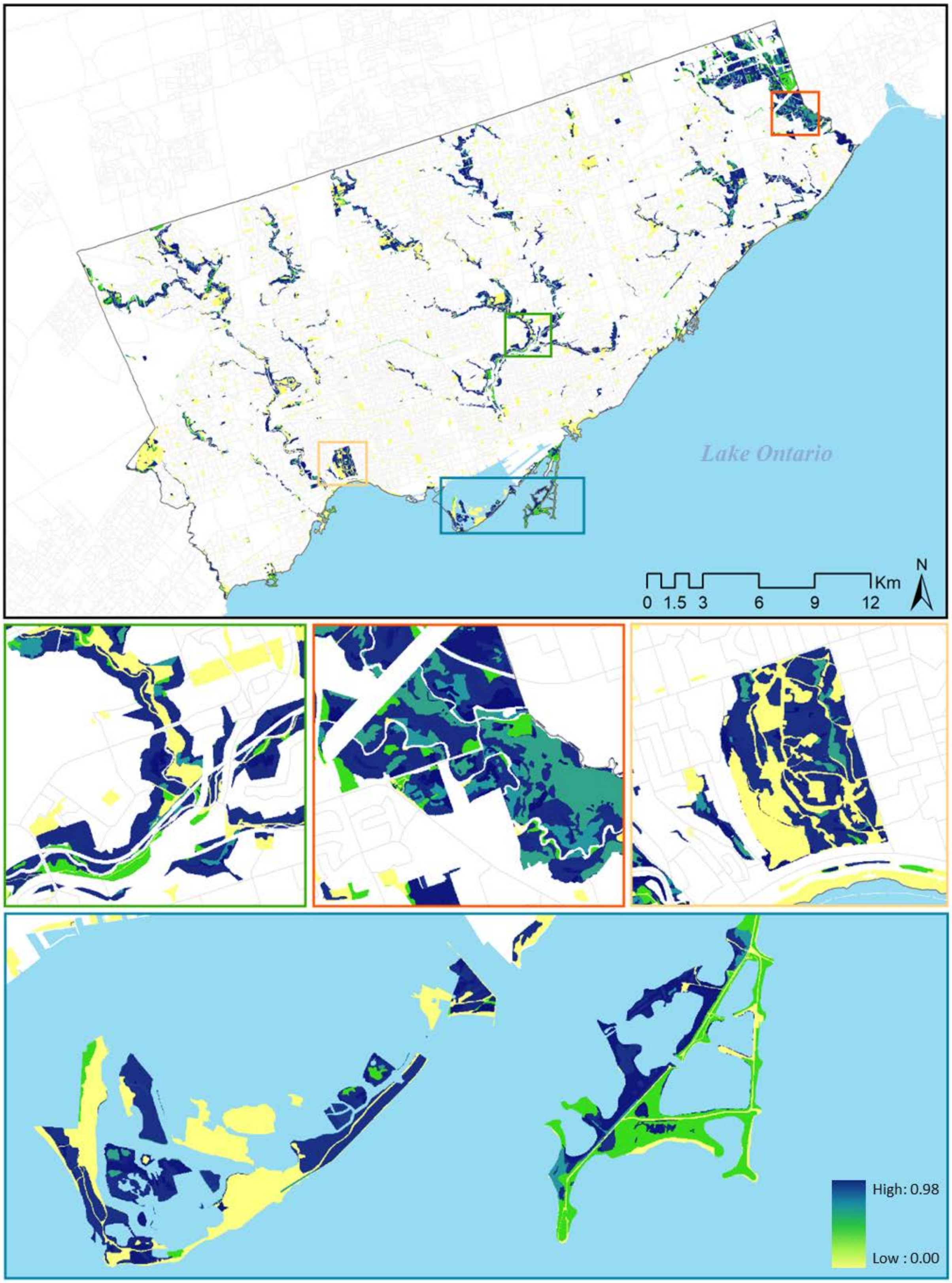

Figure 4A - The map of ESPI for carbon (ESPI-C). This map illustrates the magnitude and geographic distribution of carbon storage and sequestration services across the study area (parts of the Rouge National Urban Park, Don Valley, High Park, and Toronto Island Park and Tommy Thompson Park are magnified to show the geographic distribution of ESPI-C)

Toronto and Region Conservation Authority