FUTURE CITIES CANADA

MANAGING URBAN GREEN INFRASTRUCTURE FOR CLIMATE CHANGE THROUGH AN OPEN SMART CITY LENS

COMMUNITY SOLUTIONS NETWORK
RESEARCH BRIEF

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Executive Summary

Green infrastructure and natural assets in and around urban areas include trees, parks, bioswales, green roofs, rain gardens, woodlands, and wetlands. They fulfill ecosystem functions, provide a suite of services and benefits related to climate change mitigation and adaptation, contribute to health and well-being as well as to urban resilience. Researchers have found that ***municipal investments in green infrastructure are economically advantageous and, in the longer term, often present lower-cost solutions to climate-related issues***. Recent green infrastructure funding streams and capacity-building initiatives available to Canadian municipalities highlight the importance placed upon these systems to achieve urban resilience and sustainability objectives.

Meanwhile, cities both in Canada and abroad are showing interest in integrating smart-city concepts and technologies in urban planning and management processes. Smart-city ideas will likely play a role in driving future technological applications and data-driven solutions in urban infrastructure planning, including green infrastructure and natural asset management. This research brief addresses knowledge gaps emerging from the intersection of natural asset management and smart cities, by discussing key considerations for integrating smart-city concepts and technologies in urban natural asset planning and proposing subsequent opportunities, challenges, and risks for Canadian municipalities.

Identifying, measuring, monitoring, and valuing natural assets not only facilitates communication between the community and managing bodies, but also saves capital and overall operating costs in the face of uncertainty. To move towards climate resilience, cities should consider integrating multiple sources of information and datasets about urban natural assets and their usage. This can help municipalities sustain service delivery in perpetuity, and also help them understand the full range and value of services provided to people by natural assets, which include ecological, economic, health, and cultural benefits.

A smart-city lens can help cities envision more data-driven approaches to the natural asset planning cycle. Data-driven tools and technologies for natural asset planning and management generally fall into one of two broad categories:

1. Identifying, valuing, and enhancing natural assets along with their benefits; and
2. Connecting natural assets and planning/management processes to relevant stakeholders, including citizens.

The management of natural assets is not without its challenges. These can include oppressive regulatory environments, lack of standardized design parameters, financing, and difficulties putting a monetary value on ecosystem functions, services, and benefits. Adopting smart-city practices such as openness (e.g. making data openly and widely available), integration (e.g. breaking down disciplinary and departmental silos) and transferability (e.g. using standard and common platforms) may enable cooperation and collaboration both within managing bodies and between natural asset practitioners and stakeholders. There is still significant uncertainty about the widespread implementation of hardware/software solutions for inventorying, valuing, and monitoring natural assets. Nevertheless, given the field's nascency, there are also major opportunities for exploring ethical, data-driven natural asset planning approaches that help restore and protect green infrastructure—and engage with the urban citizens who benefit.

"This research brief addresses knowledge gaps emerging from the intersection of natural asset management and smart cities, by discussing key considerations for integrating smart-city concepts and technologies in urban natural asset planning and proposing subsequent opportunities, challenges, and risks for Canadian municipalities."

Foreword

by Open North

First defined in 2018 by Lauriault, Bloom and Landry, an Open Smart City is one where all actors, including residents, collaborate in mobilizing data and technologies to develop their community through fair, ethical, and transparent governance that balances economic development, social progress, and environmental responsibility.

As Canadian communities across the country explore smart city initiatives, there is a pressing need to better understand the opportunities and risks presented by data and emerging technologies and put open smart city principles into practice.

Open North has commissioned a series of research briefs for policymakers and practitioners to provide insight into how data and technology intersect with challenges local communities are grappling with, such as food security and shared transportation. The research briefs identify complex policy issues from an open smart city lens, describe their importance and provide key considerations for policymakers.

This research brief provides a smart city lens to natural asset planning and encourages municipalities to consider how data and technology can be leveraged to improve efficiencies and achieve sustainability objectives. Using four key concepts of the smart city (openness, integration, transferability, and collaboration), the author explores how these concepts can be used in practice in natural asset planning with examples from communities across the country. This research brief also provides a range of tools, technologies, and data sources that can be used for urban natural asset planning and their associated opportunities, risks and challenges.

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The research builds on the Open Smart Cities Guide, which provided the first ever definition of an Open Smart City. It was published in 2018 as a part of a year long collaborative research project led by Open North and funded by Natural Resources Canada's GeoConnections program in 2018. The authors are Dr. Tracey P. Lauriault (Carleton University), Rachel Bloom (Open North) and Jean-Noé Landry (Open North).

These research briefs are produced for the Community Solutions Network, a community-centric platform for communities to connect and build a national centre of excellence in open smart cities. As the project lead, Evergreen is working with lead technical partner Open North and other partners to provide valuable information, learning opportunities, advisory and capacity building services to Canadian communities in key areas of data and technology, helping to improve the lives of residents.

We offer—at no cost to communities—a comprehensive Advisory Service for Canadian communities interested in developing and implementing open smart cities projects. To learn more about the Advisory Service, please visit communitysolutionsnetwork.ca.

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Introducing and Defining Urban Green Infrastructure and Natural Assets

There is now widespread recognition that urban green infrastructure and natural assets will play a key role in supporting climate change mitigation and adaptation in cities (Federation of Canadian Municipalities 2021; Stanley et al. 2019). Although "green infrastructure" can take on a variety of meanings, it broadly refers to natural elements, such as vegetation, soil, and water bodies that provide a wide spectrum of benefits for healthy urban living (Metro Vancouver 2015). Green infrastructure and natural assets may also include designed and engineered elements, such as rain gardens, green roofs, and bioswales, that have been created to mimic natural functions (Municipal Natural Asset Initiative, 2018).

Urban trees, forests, parks, green spaces, wetlands, and other natural assets in and around urban areas provide a suite of benefits and services related to climate change mitigation and adaptation, contributions to health and well-being, and urban resilience (Lilauwala & Gubert 2019). More specifically, green infrastructure elements provide varied climate-related benefits such as cooling, shade, energy savings, stormwater management and flood mitigation, and, in some cases, carbon sequestration benefits (Duinker et al. 2015; Terton 2017). In addition to addressing climate concerns, urban natural assets also provide co-benefits to urban dwellers related to recreational, spiritual, and cultural ecosystem services. Over 80% of Canadians reside in urban areas and our largest, Toronto, is among the fastest growing cities in North America. For this majority of Canadians, daily contact with natural assets occurs in backyards, in urban parks, and in other urban green spaces (Millward & Sabir 2011; Sinclair et al. 2014). It is therefore important to recognize that urban green infrastructure and natural assets are highly tied to both social and ecological processes. Green infrastructure is often understood to be multifunctional (e.g. provide a diverse range of benefits and services), as well as manifest at varying scales - from a single tree, to an urban park, to a green belt (Allen et al. 2012; Hansen & Pauleit 2014) (Figure 1).

Healthy urban ecosystems can be considered economic assets that enhance urban resilience (Terton 2017). Investments in green infrastructure have been found to be economically advantageous and, in the longer term, municipalities often benefit from lower-cost, "nature-based" solutions to a wide range of challenges (Elmqvist et al. 2015). In contrast to built or engineered assets (e.g. roads, buildings), natural assets can provide services in perpetuity and increase in value over time. For example, a recent pilot project with 6 municipalities across Canada found that integrating natural assets into planning for flood management, water quality, and drinking water supply provided a total value of more than $400 million based on engineered replacement costs alone (Municipal Natural Asset Initiative, 2020). In the case of urban forests, research has suggested that protecting large trees in particular delivers significant savings related to energy conservation, health benefits, shade, and stormwater control (USDA n.d.). Natural asset management refers to the process of inventorying existing natural assets, assessing their current state, and developing a plan to restore and/or maintain these assets into the future (Municipal Natural Asset Initiative, 2017).

"Although "green infrastructure" can take on a variety of meanings, it broadly refers to natural elements, such as vegetation, soil, and water bodies that provide a wide spectrum of benefits for healthy urban living. Green infrastructure and natural assets may also include designed and engineered elements, such as rain gardens, green roofs, and bioswales, that have been created to mimic natural functions."

Meanwhile, cities both in Canada and abroad are showing interest in integrating smart-city concepts and technologies in urban planning and management processes (Albino et al. 2015; Kitchin 2014). The growing smart cities discourse refers to the use of data and connected technology to support urban planning and enhance the quality of life for urban dwellers (Impact Canada Initiative 2021). This concept will likely play a role in driving future technological applications and data-driven solutions in urban infrastructure planning more broadly and, related, green infrastructure and natural asset management (Nitoslawski et al. 2019). As digital systems continue to be integrated into the urban fabric, vast amounts of data are being created. The question remains how this wealth of information can inform urban natural asset planning and management. As cities play increasingly important roles in climate change adaptation and mitigation (Mi et al. 2019), as well as sustainable development more broadly, urban natural asset managers and practitioners will be called upon to more effectively manage these resources to support broader sustainability and resilience objectives (Endreny et al. 2017). In short, natural assets are critical components of urban ecosystems, and cities are increasingly interested in implementing smart-city concepts and technologies. Yet, the following questions remain:

1. How can municipalities implement natural asset management practices, with an eye towards smart-city and climate change planning?
2. What digital technologies can play a role in natural asset planning and management, and what are subsequent opportunities, challenges, and risks for Canadian municipalities?

Figure 1: A snapshot highlighting the diverse range of green infrastructure and natural assets that can be found in Canadian urban areas, including urban trees and vegetation, woodlands and urban wildlife, parks and green spaces, water bodies, and other blue-green infrastructure.

Why Smart-City Concepts Matter for Green Infrastructure and Natural Assets

Natural asset and green infrastructure management, along with other climate resilient infrastructure, have been identified as key investment areas by federal, provincial, and municipal governments (Stanley et al. 2019). Recent federal budgets have committed to a funding stream for green infrastructure projects (Infrastructure Canada 2020a), and the Disaster Mitigation and Adaptation Fund (DMAF) provides the opportunity for municipalities to design and develop infrastructure (including natural assets) to manage risks associated with natural hazards (Infrastructure Canada 2020b).

There is also heightened risk that climate-related threats and events, such as flooding, urban-wildland fires, invasive species, urban heat islands, and extreme weather will cause significant damage to human, engineered, and natural assets in urban areas (Climate Atlas of Canada 2019; Ordonez & Duinker 2014). Many engineered public assets across Canada are already considered "at risk" (Canadian Infrastructure Report Card 2019), highlighting the importance of fully valuing, accounting for, and utilizing services provided by green infrastructure and natural assets. In order to effectively plan for, monitor, and manage urban natural assets, managers will require a thorough understanding of risks and management strategies at multiple temporal and spatial scales. To move towards more climate resilience, cities might consider integrating multiple sources of information and datasets about urban natural assets and their usage, to not only sustain service delivery in perpetuity, but also to understand the full range and value of services that they provide to people. A smart-city lens enables cities to envision more data-driven approaches to the natural asset planning cycle (Figure 2).

Events like COVID-19 have also highlighted the importance of urban green infrastructure and natural assets. They are increasingly called upon to safely provide green benefits to urban dwellers (Ugolini et al. 2020). The Canada Healthy Communities Initiative, a $31 million funding stream administered by the Government of Canada, aims to address these more recent needs by supporting the creation and management of safer and more vibrant public spaces (Community Foundations of Canada 2021). Eligible projects include green infrastructure initiatives as well as digital solutions for community engagement, knowledge dissemination, and capacity building. These opportunities further illustrate the potential synergies that may exist between green infrastructure mandates and investments and smart-city concepts and digital tools.

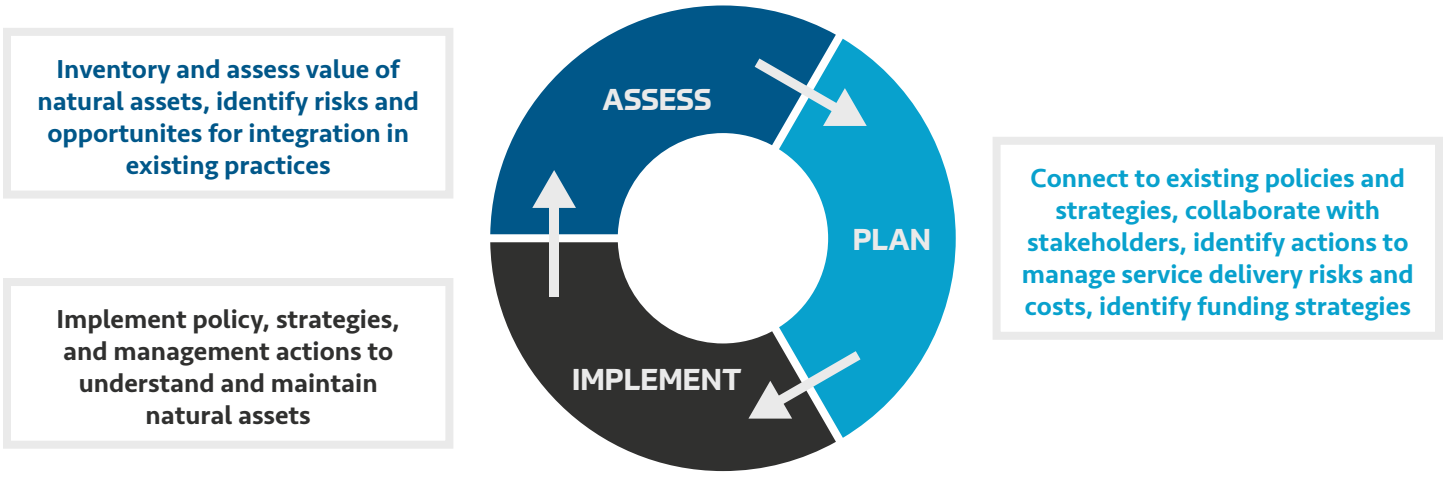

Figure 2: Illustration of the basic components of the natural asset planning cycle. Smart-city concepts have the potential to be applied at every stage with support, in some cases, from digital tools and technologies. Adapted from: Asset Management BC (2019) *Integrating Natural Assets into Asset Management - A Sustainable Service Delivery Primer*

As part of the 2017 Smart Cities Challenge, Infrastructure Canada outlined four key concepts of the smart city (Impact Canada Initiative 2021). These are discussed below, with examples of how these concepts can be used in practice in natural asset planning (with particular emphasis on urban forest management).

Openness

Open data (government data made usable and barrier-free), promotes more transparent decision-making and empowers citizens while strengthening the relationship between residents and public organizations. An application of the concept of openness in green infrastructure management could entail a municipality making all public tree inventory data available and in a downloadable, usable format with information about when, how, and why the data was collected, and by whom. Researchers, interested citizens, and other stakeholders could interact with the data, report potential problems, and, depending on municipal needs, contribute to the inventory itself, enabling the assessment stage.

Openness in practice: Many Canadian municipal governments, representing over 60% of the Canadian population, have already established open data initiatives and policies (Public Sector Digest 2016). Examples of open data on natural assets at the municipal level are numerous. For example, the City of Ottawa provides an updated dataset with information on tree location and attributes (e.g. size, species) within the city, as well as parks (City of Ottawa 2021). Other municipalities with similarly available datasets include Vancouver, Victoria, Edmonton, Toronto, Mississauga, Montréal, Guelph, Waterloo, and Winnipeg, among others. The City of Toronto Open Data Portal also includes information about ravines and protected natural areas (City of Toronto 2018) and building permits granted for green roofs (City of Toronto 2021). More broadly, the federal open government portal administered by the Government of Canada houses national-level data on forests and natural assets, with data also available through the National Forest Information System.

Integration

Data and connected technology can help break down the silos that exist within local governments and public organizations. For example, a mobile app and web dashboard could create and process green infrastructure-related 311 calls to a municipality, that can be used by citizens and city workers who are working in different municipal departments. Information gleaned from citizen requests could also provide guidance on policy content development. These may also help align policies and strategies at the municipal level (e.g. climate adaptation policies, biodiversity policies, sustainable development policies). This alignment could support collaboration opportunities as part of the planning stage.

Integration in practice: The City of Calgary recognized that ensuring the survival of newly-planted urban trees constitutes a major challenge. Therefore, the municipality developed a system to measure and monitor watering needs using water flow sensors connected to watering vehicles and a geographic information systems (GIS) platform, which mapped watering needs and progress. This solution requires collaboration between multiple departments, but was able to successfully track tree watering progress in real time, optimize water consumption, and share watering data with the public (City of Calgary 2021).

Transferability

When tools and technological approaches are open-source, transparent and standardized, they can be used by various people, groups, and communities, no matter their size or capacity. For instance, using an open-sourced natural asset inventory map with available metadata supports the implementation stage. Other communities could access and adopt this data depending on needs, and data inputs can be used to directly inform management actions.

Transferability in practice: As discussed above, many municipalities house urban tree and natural asset inventories in open data portals, which provides the opportunity for data

sharing, visualization, and analysis across multiple cities and contexts. In some cases, municipalities make use of existing platforms provided by geospatial companies such as ESRI and Azavea. OpenTrees.org is an independent resource and currently the world's largest open database of municipal park and street trees, with available code to replicate the database as well as visualize tree data around the world. Providing access to data on urban natural assets worldwide could enable further collaborative research opportunities as well as shed light on more practical management needs at various spatial scales.

Collaboration

Ideally, collaboration to some degree should occur at every stage of the natural asset planning cycle. Connected technology can enable communities to bring traditional and non-traditional partners together, to work on joint visions and projects. Multiple municipal departments and funding bodies (e.g. federal government, private sector and industry) should work in tandem when developing planning tools and ensuring alignment between policies. If data is collected, open and usable citizens and interest-based community groups could contribute to natural asset inventorying and value assessment allowing for all identified stakeholders to contribute, to varying degrees, to natural asset monitoring during implementation.

Collaboration in practice: In 2019, the City of Halifax, with the help of volunteers, non-profit and academic partners, launched an initiative called "Text-a-Tree", as a dual citizen engagement and research strategy. The goal of this project was to find out what makes trees important to people; citizens were provided the opportunity to voice their opinions, values, and perceptions about the trees around them via a text-messaging system, while also contributing more broadly to urban forestry research (Halifax Tree Project 2020). This project, based on a similar initiative from the City of Melbourne (Lafrance 2015), highlights the potential for public involvement and engagement in urban natural asset management via digital technology. Similar use cases could also support the identification of specific green spaces, trees, and other natural assets that hold high cultural value for urban dwellers (Baumeister et al. 2020).

Case Study: Toronto and Region Conservation Authority

The Toronto and Region Conservation Authority (TRCA) exemplifies some smart-city concepts in their sustainability initiatives. Given that the jurisdiction of the TRCA is watershed-based, there are many opportunities to protect, restore, and design green infrastructure for the ecological, economic, social, and cultural benefits associated with sustainable water resource and natural asset management.

The TRCA uses various datasets to inform planning strategies and management actions. The conservation authority manages monitoring stations that provide real-time information on water levels in rivers and streams, as well as precipitation and weather data. Other publicly available and open data include water quality measurements, groundwater monitoring, natural feature areas, and natural cover enhancement areas (TRCA 2018). Trail counters, small devices that register park and trail users, also provide information on green space usership and help inform planning and maintenance priorities. The TRCA is currently developing a web application (ArcGIS StoryMaps) for users to interactively explore data and reporting information, including infographics, about various watershed features, climate risk, and subsequent management strategies (Figures 3 & 4 on p.10).

The TRCA also actively collaborates with other stakeholders, including six participating municipalities that fall within the conservation authority's jurisdiction, to enhance the delivery of services and benefits from natural assets. These include academic institutions, professional associations, landowners, industry and private businesses, and community groups and members. In one such instance, TRCA partnered with the Greenbelt Foundation and Ryerson University to research how trees contribute to climate change resilience, particularly with regards to urban heat mitigation. In their 2020 Annual Report, a key innovation objective is to work with municipalities, academia, and industry to "monitor, evaluate, and pilot new innovative technologies in TRCA's work" (TRCA 2020, p.23), which will include investments in digital technologies to support TRCA's value proposition.

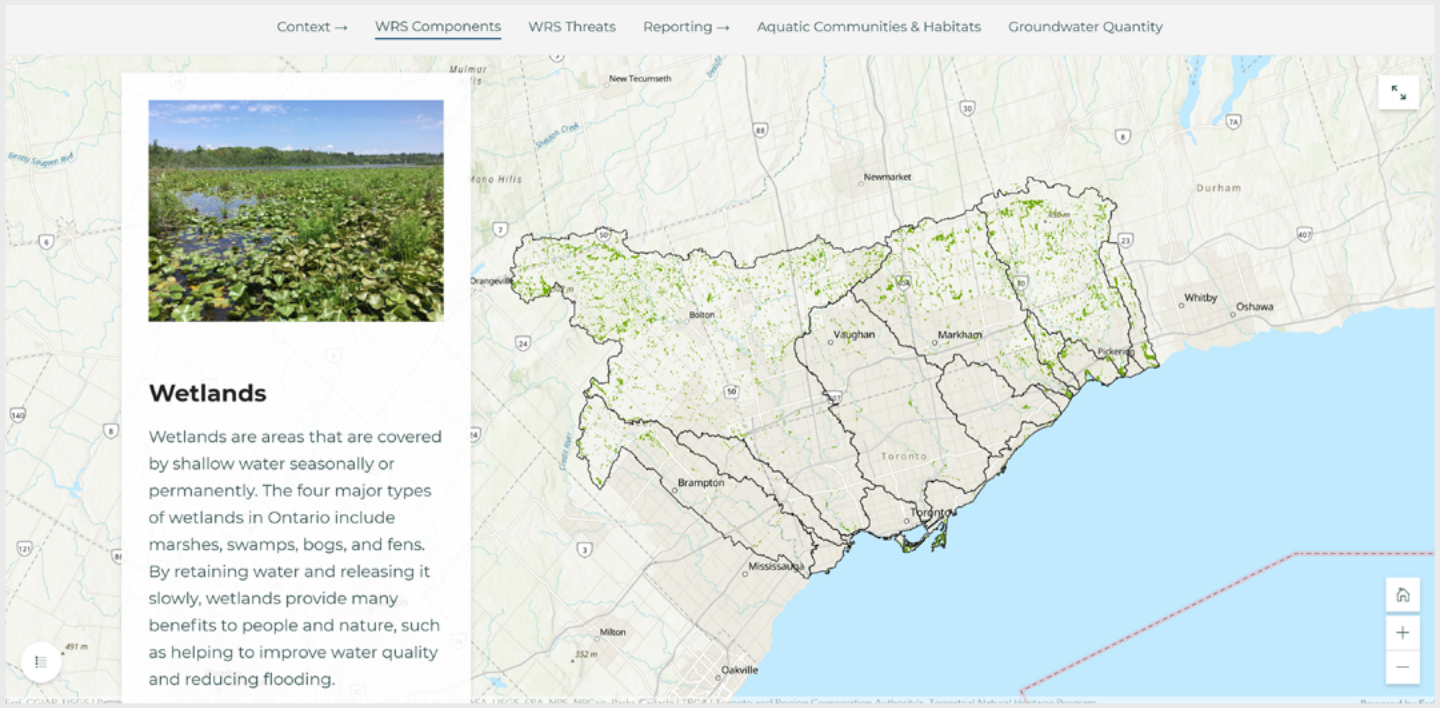

Figure 3: Map of wetland areas available via the Watershed and Ecosystems Reporting Hub. Source: https://storymaps.arcgis.com/collections/8c517b063c81449d8fba71ca02d4278f

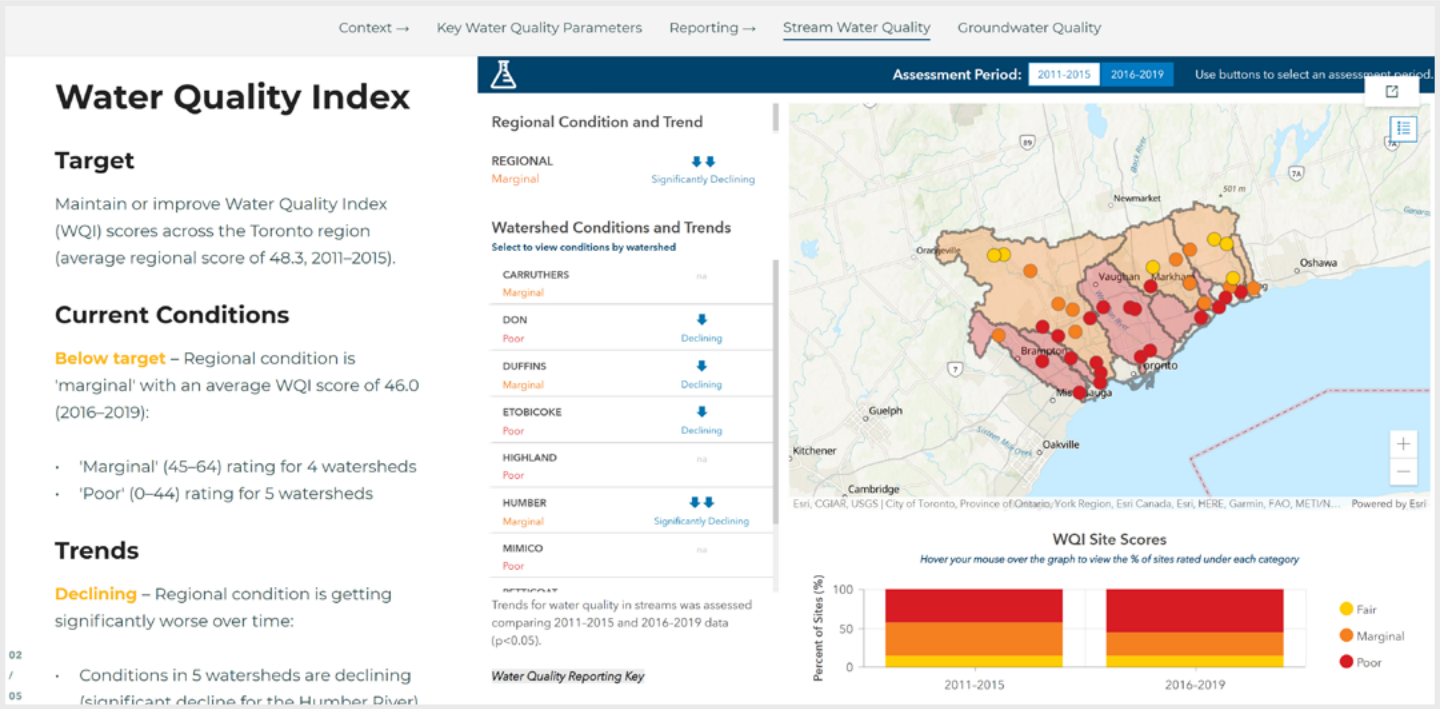

Figure 4: Interactive dashboard displaying water quality data available via the Watershed and Ecosystems Reporting Hub. Source: https://storymaps.arcgis.com/collections/8c517b063c81449d8fba71ca02d4278f

Digital Tools and Technologies for Urban Natural Asset Management: Challenges, Risks, and Opportunities

Identifying, measuring, monitoring, and valuing natural assets not only facilitates communication between the community and managing bodies, but also saves capital and overall operating costs in the face of uncertainty. This information allows governments and decision-makers to ensure that natural assets are providing optimal levels of benefits to society, while making room for more infrastructure projects within tight budgets.

Table 1 summarizes a range of tools, technologies, and data sources that can be harnessed to support different stages of the natural asset planning process. In the longer term, digital practices can support a range of climate change mitigation and adaptation use cases. The recording and discovery of long-term vegetation patterns can enable early detection of abiotic (e.g. drought, changing precipitation patterns) and biotic (e.g. invasive pests, disease) stress. Integrated Geographic Information Systems (GIS) facilitate the creation of natural asset datasets, databases, and maps that include both static and dynamic characteristics and trends. These systems may also be applied to monitor and manage large/significant trees for climate stress, to allow for proactive management before trees display visible stress and must be removed. The long-term monitoring of activities in green urban areas can identify shortcomings and specific needs, like equitable access to parks in a city or efficient distribution of green space, particularly when "green refuges" become critical during extreme heat events. In peri-urban areas, monitoring dynamics in rural and isolated regions is useful for the characterization of wildlife, or for safety and conservation practices, such as detecting crowded areas and identifying opportunities for tree, soil, and root protection in parks.

Defining the Role of Data and Connected Technology for Green Infrastructure and Urban Natural Assets

The majority of tools and technologies outlined below fall into one of two broad categories:

1- Identifying, assessing, and enhancing natural assets and their functions/benefits. These can include stormwater regulation, pollution mitigation, shade and cooling, health and recreational benefits. This is often accomplished via Geographic Information Systems (GIS) and both ground-based and aerial remote sensing tools (Li et al. 2019). They can be used in addition to and/or complement field-based methods.

2- Connecting natural assets and planning/management processes to relevant stakeholders, including citizens. This may include eliciting values about green spaces and incorporating citizen science-based contributions to natural asset inventorying. Consultation, engagement, and stewardship opportunities may be mediated through social media platforms, public participation in GIS (Foster et al. 2017; Palomino et al. 2017), and even augmented/virtual environments (Dorward et al. 2017; Tabrizian et al. 2018).

Table 1: Summary of key tools and technologies (current and emerging) with potential natural asset planning and management application(s), as well as subsequent opportunities, risks, and challenges

Data, Tools & Technologies	Natural Asset Management Application(s)	Opportunities	Risks & Challenges
Satellite imagery	• Natural asset inventory • Monitor natural asset conditions and response to environmental change (lower resolution)	• Open-source dashboards and cloud-based computing platforms (e.g. Google Earth Engine) enable computationally heavy spatial and temporal analyses using existing imagery • Some data readily available (e.g. Landsat)	• Can be costly for high-resolution imagery • Requires expertise for data analysis
Street-view imagery	• Natural asset inventory • Urban "greenness" quality and quantity assessment	• Easily accessible and user-friendly for rapid and coarse inventories where resources may be lacking (e.g. street-tree inventory from Google Street View)	• Data is not always high-quality, nor available in raw form for formal analysis • Not available in all urban and peri-urban areas
Multispectral sensing, infrared, laser scanning (LiDAR)	• Natural asset inventory • Natural asset condition assessment (e.g. structure of urban vegetation, plant health)	• LiDAR can help assess structural attributes of various assets • Multispectral and infrared sensing can remotely enable natural asset health assessment	• Costly • May require higher levels of computing storage and power • Requires expertise for data processing and analysis
Unmanned aerial vehicles and/or systems (UAV, UAS)	• Natural asset inventory • Monitor natural asset conditions and response to environmental change (higher resolution) • Assessing risk	• Affordable alternative to other remote-sensing tools • Risk mitigation (e.g. safer tree inspections)	• Concerns about data security and privacy • Regulatory requirements • Limitations associated with payload and flight time
Mobile GPS data	• Understanding relationships between people and natural assets • Assessing population health risks	• Can provide finer scale information about human movement and use of natural assets • Collection of big data can provide new capabilities for data-driven decision making	• Concerns about data security and privacy • Difficulties collecting data through mobile carriers • Requires expertise for data analysis

Table 1 (cont.): Summary of key tools and technologies (current and emerging) with potential natural asset planning and management application(s), as well as subsequent opportunities, risks, and challenges

Data, Tools & Technologies	Natural Asset Management Application(s)	Opportunities	Risks & Challenges
Virtual and augmented environments	• Understand relationships between people and natural assets • Elicit values about green space design • Assess response to nature exposure	• Can provide finer resolution information about human movement, behaviour, and use of natural assets	• Concerns about reducing contact with "real" nature • Equity and inclusion concerns in terms of who has access to digital platforms (e.g. digital divide), and who has the resources to participate
Geographic Information Systems (GIS)	• Natural asset inventory • Data collection and management platform to support natural asset monitoring	• Can provide a standard platform for storing and managing data on natural assets (e.g. ArcGIS) • Allows municipalities to share data readily via open government initiatives • Can directly connect to citizen request platforms (e.g. 311)	• Can be costly, depending on provider • System and data management architecture can be complicated and require some expertise
Public participation geographic information systems (PPGIS)	• Natural asset inventory • Support citizen science and stewardship activities • Cultural ecosystem services mapping	• Crowd-sourced data collection and management platforms (e.g. web dashboards, mobile apps) could lessen the resource load for municipalities	• Data quality • Equity and inclsion concerns in terms of who has access to digital platforms (e.g. digital divide), and who has the resources to participate
Mobile applications and social media	• Support citizen science and stewardship activities • Understand relationships between people and natural assets	• Crowd-sourced data collection and management platforms could lessen the resource load for municipalities • Could provide opportunities for more "bottom-up" monitoring initiatives	• Data quality • Equity and inclusion concerns in terms of who has access to digital platforms (e.g. digital divide), and who has the resources to participate
Ground-based sensors and data loggers	• Monitor natural asset and environmental conditions (e.g. air quality, soil moisture) • Quantify and value ecosystem services	• Can provide finer resolution information on environmental conditions that influence natural asset monitoring and management, as well as services provided by natural assets	• System and data management architecture can be complicated • Data storage requirements • Requires expertise for data analysis • Concerns about data privacy depending on location

Challenges and Risks for Canadian Municipalities

The management of natural assets is often fraught with challenges related to resource constraints, lack of expertise, grey infrastructure renewal needs, infrastructure conflicts, political willingness to prioritize natural assets, departmental silos, and lack of high-quality data on green infrastructure (Duinker et al. 2015; Morgenroth et al. 2015, Steenberg et al. 2018).

Differing Practices and Worldviews

A longstanding challenge facing natural asset managers and sustainability practitioners relates to different disciplinary practices and worldviews; for example, integrating green infrastructure elements into traditional asset management processes can be difficult. This is due to problems in regulatory environments such as lack of standardized design parameters and difficulties putting a monetary value on ecosystem services, and financing. These problems can act as barriers at various stages of the planning process (Matsler 2019; Zuniga-Teran et al. 2020). Equitable access to green has also been established as a major concern as green infrastructure and natural asset management processes continue to develop (Nesbitt et al. 2018).

Biases and Incomplete Data

There are potential risks associated with the use of digital tools and technologies for green infrastructure and natural asset management. One key concern, which is widely discussed in smart-city discourses, is the potential for assumptions and biases (particularly when applied to more sophisticated data processing and analysis techniques) to inaccurately represent complex environments. Depending on where and how data on natural assets and people are collected and used (e.g. geographic coverage, populations represented), biases and incomplete information may inherently exist in datasets, affecting outputs and information derived from the data (Heikinheimo et al. 2020). Some researchers argue that the integration of digital tools into natural environments, where technology plays an important role in mediating human-nature relationships, may serve to dissociate people further from nature (Kahn et al. 2010). Public-private partnerships, such as the now defunct Sidewalk Toronto project, may also engender concerns about the privatization of public goods and assets, including natural assets.

Impacts on the Labour Market

Future research should explore risks associated with employment in the urban green infrastructure sector. Automation and the growing reliance on digital-based work will likely result in shifts away from more traditional resource management methods, and it remains to be seen how these trends will change the nature of work for practitioners in arboriculture, urban forestry, community forestry, and water resource management, among others.

Challenges with Adoption and Implementation

Despite its importance to climate adaptation, sustainability, and human wellbeing, natural asset management is in its relative infancy, and there is evidence to suggest that the uptake of natural asset projects is slow among Canadian municipalities (ICF 2018). There is also considerable uncertainty about more widespread implementation of hardware/software solutions for inventorying, valuing, and monitoring natural assets. A multitude of factors related to local needs (e.g. anticipated climate change impacts, local sustainability and development objectives) and capacity (e.g. resources available, political willingness, technological expertise, community buy-in) will likely dictate whether and to what extent smart-city concepts and technologies are needed or warranted. The adoption of digital-based tools and smart-city concepts in natural asset management will also generate new questions about infrastructure monitoring and renewal (Grabowski et al. 2017). It will be important to examine more closely the acceptability of technological innovation among practitioners, and how we can anticipate and adapt to environmental uncertainty and change using digital technology.

Key Opportunities for Canadian Municipalities

Private Sector Investment

The issues faced by natural asset managers may also present opportunities for innovative thinking and collaborative decision making. The growing availability of open data at the municipal level provides fodder for the private sector to identify problems and develop data-driven solutions more effectively (Public Sector Digest 2016). There is now broader recognition that the private sector needs to play a large role in creating and maintaining low-carbon and nature-based solutions, requiring approximately $5.7 trillion invested annually in green infrastructure as of 2020 (World Resources Institute, n.d.). Technology companies have also expressed considerable interest in developing data-based solutions to green infrastructure challenges (e.g. Microsoft AI for Earth). Public and private financing mechanisms (public-private partnerships, bonds, carbon finance, development charges, stormwater fees) for urban green infrastructure have been discussed at length by Merk et al. (2012) and Scott et al. (2018). These trends may present opportunities for municipalities to engage with private sector entities and forge long-lasting collaborative financing mechanisms. For Canadian municipalities that do not yet have an asset management plan—up to 70% in the case of small communities—there is an opportunity to begin integrating green infrastructure concepts and natural asset management processes from the start (Canadian Infrastructure Report Card 2019).

Diversity, Equity and Inclusion

As municipalities consider incorporating smart-city practices and digital technologies into management processes, it will be just as important to elicit local and historical narratives. It will also be critical to develop and implement equity, diversity, and inclusion policies, and consult with a range of community perspectives on urban values and sense of place, to inform future planning and development (Young & Lieberknecht 2019). There is a growing push towards applying an equity lens to urban forest policy making and planning. For example, American Forests, a nonprofit conservation organization, has pledged to target urban tree plantings in areas disproportionately affected by the effects of climate change as part of the Trillion Trees Initiative. Some communities, such as the Region of Peel, have developed tools to determine priority tree planting areas to support health benefits and enhance social equity (Morrison 2017). Canadian municipalities should aim to support historically underserved areas and communities, and identify potential barriers to accessing assets and amenities such as public green spaces.

Recognizing that municipalities across Canada have diverse needs and capacities, the following opportunities are intended to provide municipalities a "jumping-off" point in adopting a framework for managing urban natural assets using digital tools and smart-city concepts:

1. ***Consider managing urban forests and other urban green infrastructure elements as asset classes.*** For example, including trees in infrastructure reports (York Region 2018) constitutes an important step in formalizing natural

assets as infrastructure that provide measurable benefits and require sustained funding and management planning. Subsequent steps in this process might include one of the following: identifying and inventorying key urban natural assets, assessing the value of the natural asset and associated services provided to the municipality (including cultural, recreational, and spiritual values), and developing an ongoing maintenance plan. The World Bank (2019) provides a summary of valuation tools and techniques available to green infrastructure and natural asset managers.

2. ***Identify and nurture alignment within and between municipal departments.*** For example, creating and managing a public tree inventory might require collaboration between parks and recreation, urban planning and urban forestry, public works departments and IT/digital offices.
3. ***Where possible, make data openly available and usable, and be transparent about data collection and management protocols.*** Datasets on natural assets may include public tree (e.g. street and park tree) inventories, a map of public green spaces, parks, and natural areas, and tree canopy distribution, among other features. Cities should provide metadata and update data portals regularly to ensure that the public has access to the most recent data.
4. ***Identify potential partners and collaborators equipped to provide ecological and/or technological expertise.*** These may include non-profit organizations, UAV (i.e. drone) operators, geospatial specialists, technology and data visualization solutions companies, as well as academic institutions. Public-private partnerships, for example, can help bridge technological and financial gaps and help pilot customer-oriented initiatives.
5. ***Explore digital-based strategies for engaging with citizens, community groups, and other stakeholders***. Initiatives that provide an avenue for citizens to engage with green infrastructure (e.g. text-a-tree, email-a-tree) or with management processes (e.g. 311 service request platform and database) elicit important opinions and values associated with municipal natural assets. These can inform management decisions and funding priorities, and support the case for fully considering urban nature as critical infrastructure.

References

Albino, V., Berardi, U., & Dangelico, R. M. (2015). Smart Cities: Definitions, Dimensions, Performance, and Initiatives. *Journal of Urban Technology, 22*(1), 3–21. https://doi.org/10.1080/10630732.2014.942092

Allen, W. L. (2012). Environmental Reviews and Case Studies: Advancing Green Infrastructure at All Scales: From Landscape to Site. *Environmental Practice, 14*(1), 17–25. https://doi.org/10.1017/S1466046611000469

Asset Management BC. (2019). *Integrating Natural Assets into Asset Management - A Sustainable Service Delivery Primer.* https://www.assetmanagementbc.ca/wp-content/uploads/Integrating-Natural-Assets-into-Asset-Management.pdf

Baumeister, C. F., Gerstenberg, T., Plieninger, T., & Schraml, U. (2020). Exploring cultural ecosystem service hotspots: Linking multiple urban forest features with public participation mapping data. *Urban Forestry & Urban Greening, 48,* 126561. https://doi.org/10.1016/j.ufug.2019.126561

Canadian Infrastructure Report Card. (2019). *Monitoring the State of Canada's Core Public Infrastructure: The Canadian Infrastructure Report Card 2019.* http://canadianinfrastructure.ca/downloads/canadian-infrastructure-report-card-2019.pdf

City of Calgary. (2021). *Smart City Story: Technology and Trees.* https://www.calgary.ca/general/smartcity/tree-watering.html

City of Ottawa. (2021). https://open.ottawa.ca/datasets/13092822f69143b695bdb916357d421b_0

City of Toronto. (2018). https://open.toronto.ca/dataset/ravine-natural-feature-protection-area/

City of Toronto. (2021). https://open.toronto.ca/dataset/building-permits-green-roofs/

Climate Atlas of Canada. (2019). *Canadian Cities and Climate Change.* Prairie Climate Center. https://climateatlas.ca/canadian-cities-and-climate-change

Community Foundations of Canada. (2021). *Canada Healthy Communities Initiative.* https://communityfoundations.ca/initiatives/chci/

Dorward, L.J., Mittermeier, J.C., Sandbrook, C., Spooner, F. (2017). Pokemon Go: benefits, costs, and lessons for the conservation movement. Conserv. Lett., 10 (1), 160-165. https://doi.org/10.1111/conl.12326

Duinker, P.N., Ordóñez, C., Steenberg, J.W.N., Miller, K.H., Toni, S.A., Nitoslawski, S.A. Trees in Canadian Cities: Indispensable Life Form for Urban Sustainability. (2015). *Sustainability, 7*(6), 7379-7396. https://doi.org/10.3390/su7067379

Elmqvist, T., Setälä, H., Handel, S., van der Ploeg, S., Aronson, J., Blignaut, J., Gómez-Baggethun, E., Nowak, D., Kronenberg, J., & de Groot, R. (2015). Benefits of restoring ecosystem services in urban areas. *Current Opinion in Environmental Sustainability, 14,* 101–108. https://doi.org/10.1016/j.cosust.2015.05.001

Endreny, T., Santagata, R., Perna, A., Stefano, C. D., Rallo, R. F., & Ulgiati, S. (2017). Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban wellbeing. *Ecological Modelling, 360,* 328–335. https://doi.org/10.1016/j.ecolmodel.2017.07.016

Federation of Canadian Municipalities. (2021). *Natural assets bolster climate resilience.* https://fcm.ca/en/resources/mcip/natural-assets-bolster-climate-resilience

Foster, A., Dunham, I.M., Kaylor, C. (2017). Citizen science for urban forest management? Predicting the data density and richness of urban forest volunteered geographic information. *Urban Science, 1,* 30. https://doi.org/10.3390/urbansci1030030

Grabowski, Z. J., Matsler, A. M., Thiel, C., McPhillips, L., Hum, R., Bradshaw, A., Miller, T., & Redman, C. (2017). Infrastructures as Socio-Eco-Technical Systems: Five Considerations for Interdisciplinary Dialogue. *Journal of Infrastructure Systems, 23*(4), 02517002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000383

Halifax Tree Project. (2020). *Text-a-Tree.* https://www.halifaxtreeproject.com/textatree

Hansen, R., & Pauleit, S. (2014). From Multifunctionality to Multiple Ecosystem Services? A Conceptual Framework for Multifunctionality in Green Infrastructure Planning for Urban Areas. *AMBIO, 43*(4), 516–529. https://doi.org/10.1007/s13280-014-0510-2

Heikinheimo, V., Tenkanen, H., Bergroth, C., Järv, O., Hiippala, T., & Toivonen, T. (2020). Understanding the use of urban green spaces from user-generated geographic information. *Landscape and Urban Planning, 201,* 103845. https://doi.org/10.1016/j.landurbplan.2020.103845

ICF. (2018). *Best practices and resources on climate resilient natural infrastructure.* Prepared for Canadian Council of Ministers of the Environment. https://www.ccme.ca/files/Resources/climate_change/Natural_Infrastructure_Report_EN.pdf

Impact Canada Initiative. (2021). *Smart Cities Challenge.* https://impact.canada.ca/en/challenges/smart-cities/challenge

Infrastructure Canada. (2020a). *Investing in Canada plan funding stream: Green infrastructure.* https://www.infrastructure.gc.ca/plan/gi-iv-eng.html

Infrastructure Canada. (2020b). *Disaster Mitigation and Adaptation Fund: Overview.* https://www.infrastructure.gc.ca/dmaf-faac/index-eng.html

IUCN. (2021). *Nature-Based Solutions.* Commission on Ecosystem Management. https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions

Kahn, P. H., Severson, R. L., & Ruckert, J. H. (2009). The Human Relation With Nature and Technological Nature. *Current Directions in Psychological Science, 18*(1), 37–42. https://doi.org/10.1111/j.1467-8721.2009.01602.x

Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal, 79*(1), 1–14. https://doi.org/10.1007/s10708-013-9516-8

Lafrance, A. (2015). *When you give a tree an e-mail address.* The Atlantic. https://www.theatlantic.com/technology/archive/2015/07/when-you-give-a-tree-an-email-address/398210/

Lauriault, T.P., Bloom, R., & Landry, J.N. (2018). *Open Smart Cities Guide v.1.0*. OpenNorth. https://opennorth.ca/publicationdetail?id=3Ptq7I6gVIfzBfl2ZAYoNs

Li, X., Chen, W. Y., Sanesi, G., & Lafortezza, R. (2019). Remote Sensing in Urban Forestry: Recent Applications and Future Directions. *Remote Sensing, 11*(10), 1144. https://doi.org/10.3390/rs11101144

Lilauwala, R., Gubert, C. (2019). *Green Infrastructure for Climate Adaptation: Visualization, Economic Analysis, and Recommendations for Six Ontario Communities.* Green Infrastructure Foundation. https://static1.squarespace.com/static/588221e420099e47b8fe06d8/t/5eceae-4495844040ae3d25bc/1590603358923/GI_for_Climate_Adaptation_WEB.pdf

Matsler, M.A. (2019). Making 'green' fit in a 'grey' accounting system: The institutional knowledge system challenges of valuing urban nature as infrastructural assets. *Environmental Science & Policy, 99,* 160–168. https://doi.org/10.1016/j.envsci.2019.05.023

Merk, O., Saussier, S., Staropoli, C., Slack, E., Kim, J-H. (2012). Financing Green Urban Infrastructure. *OECD Regional Development Working Papers 2012/10,* OECD Publishing. http://dc.doi.org/10.1787/5k92p0c6j6r0-en

Metro Vancouver. (2015). *Green Infrastructure in Metro Vancouver - Policy Backgrounder.* http://www.metrovancouver.org/services/regional-planning/PlanningPublications/PolicyBackgrounder-GreenInfrastructure.pdf

Mi, Z., Guan, D., Liu, Z., Liu, J., Viguié, V., Fromer, N., & Wang, Y. (2019). Cities: The core of climate change mitigation. *Journal of Cleaner Production, 207,* 582–589. https://doi.org/10.1016/j.jclepro.2018.10.034

Millward, A. A., & Sabir, S. (2011). Benefits of a forested urban park: What is the value of Allan Gardens to the city of Toronto, Canada? *Landscape and Urban Planning, 100*(3), 177–188. https://doi.org/10.1016/j.landurbplan.2010.11.013

Morgenroth, J., Santos, B., Cadwallader, B. (2015). Conflicts between landscape trees and lawn maintenance equipment—The first look at an urban epidemic. *Urban Forestry & Urban Greening, 14,* 1054-1058

Morrison, K. (2017). *Leveraging the Benefits of Greenspace for Environmental and Public Health Benefits: A Casebook of Ontario Initiatives.* https://static1.squarespace.com/static/5c3cebfd45776eee4408f72d/t/5ccd016d652deaddf2d9033a/1556939121047/Leveraging_the_Benefits_of_Greenspace_2-compressed.pdf

Municipal Natural Asset Initiative. (2017). *Defining and scoping municipal natural assets.* Discussion Paper. https://www.assetmanagementbc.ca/wp-content/uploads/definingscopingmunicipalnaturalcapital-final-15mar2017.pdf

Municipal Natural Asset Initiative. (2018). *Primer on Natural Asset Management.* Prepared for the 2018 FCM Sustainable Communities Conference. https://mnai.ca/media/2018/01/FCMPrimer_Jan1_2018.pdf

Municipal Natural Asset Initiative. (2020). *Cohort 2 National Project Overview.* https://mnai.ca/media/2020/04/MNAI-CohortSummary-iD2.pdf

Nesbitt, L., Meitner, M.J., Sheppard, S.R.J., Girling, C. (2018). The dimensions of urban green equity: A framework for analysis. *Urban Forestry & Urban Greening, 34,* 240-248. https://doi.org/10.1016/j.ufug.2018.07.009

Nitoslawski, S.A., Galle, N.J., Konijnendijk Van Den Bosch, C., Steenberg, J.W.N. (2019). Smarter ecosystems for smarter cities? A review of trends, technologies, and turning points for smart urban forestry. *Sustainable Cities and Society, 51,* 101770. https://doi.org/10.1016/j.scs.2019.101770.

Ordóñez, C., & Duinker, P. N. (2014). Assessing the vulnerability of urban forests to climate change. *Environmental Reviews, 22*(3), 311–321. https://doi.org/10.1139/er-2013-0078

Palomino, J., Muellerklein, O.C., Kelly, M. (2017). A review of the emergent ecosystem of collaborative geospatial tools for addressing environmental challenges. *Computers, Environment and Urban Systems, 65,* 79-92. https://doi.org/10.1016/j.compenvurbsys.2017.05.003

Public Sector Digest. (2016). *2016 Open Cities Index - Top 20 Results.* https://publicsectordigest.com/2016-open-cities-index-top-20-results

Scott, O., Fatoric, S., Merritt, R., Lee, V.F., Miley, D. (2018). *Engaging the Private Sector in Green Infrastructure Development and Financing: A Pathway Toward Building Urban Climate Resilience.* Report prepared for the United States Agency for International Development (USAID) and Adaptation Thought Leadership and Assessments (ATLAS). https://www.chemonics.com/wp-content/uploads/2019/06/Engaging-the-Private-Sector-in-Green-Infrastructure.pdf

Sinclair, A. J., Diduck, J., & Duinker, P. N. (2014). Elicitation of urban forest values from residents of Winnipeg, Canada. *Canadian Journal of Forest Research, 44*(8), 922–930. https://doi.org/10.1139/cjfr-2014-0016

Stahl, B. (2011). What Does the Future Hold? A Critical View of Emerging Information and Communication Technologies and Their Social Consequences. *Researching the Future in Information Systems.* https://doi.org/10.1007/978-3-642-21364-9_5

Stanley, M., Puzyreva, M., & Roy, D. (2019). *Advancing Natural Infrastructure in Canada: A forum report.* Winnipeg: International Institute for Sustainable Development.

Steenberg, J.W.N., Robinson, P.J., Millward, A.A. (2018). The influence of building renovation and rental housing on urban trees. *Journal of Environmental Planning and Management, 61,* 553-567.

Tabrizian, P., Baran, P.K., Smith, W.R., Meentemeyer, R.K. (2018). Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. *Journal of Environmental Psychology, 55,* 99-109. https://doi.org/10.1016/j.jenvp.2018.01.001

Terton, A. (2017). *Building a climate resilient city: urban ecosystems.* International Institute for Sustainable Development. http://prairieclimatecentre.ca/wp-content/uploads/2017/04/pcc-brief-climate-resilient-city-urban-ecosystems.pdf

Toronto Region and Conservation Authority (TRCA). (2020). *Conservation matters: 2020 Annual Report.* https://trcaca.s3.ca-central-1.amazonaws.com/app/uploads/2021/02/19104934/TRCA-AR-2020-FA-web.pdf

Toronto Region and Conservation Authority (TRCA). (2018). *Open data and information.* https://data.trca.ca/

USDA. (n.d.) *The Large Tree Argument.* https://www.fs.fed.us/psw/topics/urban_forestry/products/cufr_511_large_tree_argument.pdf

Ugolini, F., Massetti, L., Calaza-Martínez, P., Cariñanos, P., Dobbs, C., Ostoić, S., Marin, A.M. Pearlmutter, D., Saaroni, H., Šaulienė, I., Simoneti, M., Verlič, A., Vuletić, D., Sanesi, G. (2020). Effects of the COVID-19 pandemic on the use and perceptions of urban green space: An international exploratory study. *Urban Forestry & Urban Greening, 56,* 126888. https://doi.org/10.1016/j.ufug.2020.126888

The World Bank. (2019). *Natural Asset and Biodiversity Valuation in Cities.* Technical Paper. http://documents1.worldbank.org/curated/en/287521568801462241/pdf/Technical-Paper.pdf

World Economic Forum. (2013). *The Green Investment Report The ways and means to unlock private finance for green growth. A Report of the Green Growth Action Alliance.* http://www3.weforum.org/docs/WEF_GreenInvestment_Report_2013.pdf

Young, R. F., & Lieberknecht, K. (2019). From smart cities to wise cities: Ecological wisdom as a basis for sustainable urban development. *Journal of Environmental Planning and Management, 62*(10), 1675–1692. https://doi.org/10.1080/09640568.2018.1484343

York Region. (2018). *Corporate Asset Management Plan.* https://www.york.ca/wps/wcm/connect/york-public/2547467d-711b-482e-8602-0456b02bc96a/may+3+corporate+ex.pdf?MOD=AJPERES

Zuniga-Teran, A.A., Staddon, C., Vito, L., Gerlak, A.K., Ward, S., Schoeman, Y., Hart, A. Booth, G. (2020) Challenges of mainstreaming green infrastructure in built environment professions. *Journal of Environmental Planning and Management, 63*(4), 710-732. https://doi.org/10.1080/09640568.2019.1605890