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Smarter ecosystems for smarter cities? A review of trends, technologies, and turning points for smart urban forestry

Sophie A. Nitoslawski[a,*], Nadine J. Galle[b], Cecil Konijnendijk Van Den Bosch[a], James W.N. Steenberg[c,d]

[a] Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, Forest Sciences Centre, 2424 Main Mall, Vancouver, BC, V6T 1Z4, Canada
[b] College of Engineering and Architecture, UCD Engineering and Materials Science Centre, University College Dublin, Belfield, Dublin 4, Ireland
[c] School for Resource and Environmental Studies, Dalhousie University, Kenneth C. Rowe Management Building, 6100 University Ave, Halifax, Nova Scotia, B3H 4R2, Canada
[d] Nova Scotia Department of Lands and Forestry, 1701 Hollis St, Halifax, NS B3J 3M8, Canada

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ABSTRACT

Smart cities are increasingly part of urban sustainability discourses. There is a growing interest in understanding how citizen engagement, connected technology, and data analytics can support sustainable development. Evidence has also repeatedly shown that green infrastructure such as urban forests address diverse urban challenges and are critical components of urban sustainability and resilience. Nevertheless, it is unclear whether green space and urban forest management are gaining significant traction in smart city planning. It is thus timely to consider whether and to what extent urban forests and other green spaces can be effectively integrated into smart city planning, to maximize green benefits for all city dwellers.

We address this gap by exploring current and emerging smart city trends and technologies, and highlight practical applications for urban forest and green space management. Current "smart urban forest" projects reveal a focus on novel monitoring techniques using sensors and Internet of Things (IoT) technologies, as well as open data and citizen engagement, particularly through the use of mobile devices, applications ("apps"), and open-source mapping platforms. We propose a definition and promising approach to "smart urban forest management", emphasizing both the potential of digital infrastructure to enhance forest benefits and the facilitation of citizen stewardship and empowerment in green space planning. Cities are getting faster and smarter – can (and should) the trees, and their managers, do the same?

1. Introduction

The cities of the future should, by necessity, strive to be greener. Green infrastructure creation and management are vital to urban resilience and livability (Duinker et al., 2015). Although varying definitions for the term exist, examples of green infrastructure include managed parks and open green spaces, naturalized woodlands, green roofs and walls, and stormwater management systems such as rain gardens (Allen, 2012). Urban forests, comprising of all trees and associated vegetation within a city, are a particular type of green infrastructure that provide innumerable benefits to city dwellers (Konijnendijk, Ricard, Kenney, & Randrup, 2006). These benefits, also known as ecosystem services, include, but are not limited to, heat mitigation (Norton et al., 2015), energy savings (Armson et al., 2012), protection from air pollution (Abhijith et al., 2017), biodiversity and natural richness (Ilkin, Knight, Lindenmayer, Fischer, & Manning, 2013), carbon sequestration and storage (Nowak & Crane, 2002), stormwater and flood water management (Denman, May, & Moore, 2016), public and social support spaces (Peters, Elands, & Buijs, 2010; Tzoulas et al., 2007), and a sense of place and belonging (Pearce, Davison, & Kirkpatrick, 2015). These benefits are vital for health promotion and the general wellbeing of urban residents throughout their lifetime (Lee & Maheswaran, 2011).

Over half of the world's population now live in urban areas, and by 2030, one person out of every three will live in a city with over a million inhabitants (United Nations, 2016). Building resilience against urban stresses has become a top priority for local governments and citizens alike (International Organization for Migration, 2015; Meerow,

* Corresponding author.
E-mail address: snito@mail.ubc.ca (S.A. Nitoslawski).

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Newell, & Stults, 2016). Municipalities play significant roles in infrastructure and asset management and renewal, local economic development, affordable housing and transit, and, importantly, environmental action and sustainable development (Dale, Burch, Robinson, & Strashok, 2018). "Greener" strategies require local-level planning, governance, and implementation to answer context-specific needs (Bulkeley & Kern, 2006; Fünfgeld, 2015; Rauken, Mydske, & Winsvold, 2014). However, the management of our green spaces and urban trees is often plagued by challenges particular to these local-level contexts: lack of resources, insufficient or unworkable information on existing green and grey infrastructure, infrastructure deterioration and replacement, housing affordability and high demand for physical space, densification, election cycles and political change, perceived undesirability and inconveniences of trees, disciplinary silos in municipal government, unequal access to public green space, and altered and frequently degraded urban environments (Dickie et al., 2014; Duinker et al., 2015; Haaland & Konijnendijk, 2015; Heynen, 2006; Morgenroth, Santos, & Cadwallader, 2015; Nitoslawski, Steenberg, Duinker, & Bush, 2017; Steenberg, Robinson, & Duinker, 2018; Steenberg, Robinson, & Millward, 2018; Wolch, Byrne, & Newell, 2014). These factors highlight the importance of ensuring that municipalities have adequate financial, technological, and governance tools at their disposal in their transition towards a more sustainable future.

"Smart cities" is a ubiquitous term that has gained traction across sectors and has pervaded the fields of sustainability, urban planning, engineering, and computer science – thus, many definitions exist (Albino, Berardi, & Dangelico, 2015). Earlier iterations such as "wired cities", "digital cities", and "intelligent cities" generally referred to cities considered "pioneers in embedding digital infrastructure and systems into their urban fabric" (Kitchin, 2014, p. 1). Although there are many iterations of the term "smart city", scholars have found it useful to establish two broad but related meanings of the term. The first refers to the widespread integration into the urban environment of Information and Communication Technologies (ICTs) and Internet of Things (IoT) tools to monitor, assess, and manage municipal assets and services more strategically and efficiently (Bibri & Krogstie, 2017b). The abundant data collected through these means arguably provide more insight into the city as an ecosystem, and can be used in analysis, modeling, and prediction (Kitchin, 2014). The second meaning of "smartness" focuses on people, with ICTs acting as tools to drive citizen engagement and mobilization, along with participatory governance schemes (Møller et al., 2018). It has been suggested that a city is not truly smart without effectively harnessing the power of social capital, entrepreneurship, and innovation, otherwise understood as encompassing the knowledge economy (Kourtit, Nijkamp, & Arribas, 2012).

Smart *sustainable* cities have also emerged from the smart cities discourse, as co-benefits in sustainable and smart practices are recognized and as researchers and practitioners seek to concurrently "incorporate sustainability in smart city approaches and to smarten up sustainable city models" (Bibri & Krogstie, 2017b, p. 186). Some scholars posit that the concept of a smart sustainable city is needed due to strong emphasis on technological, economic, and social indicators in smart city frameworks, at the potential expense of environmental sustainability (Ahvenniemi, Huovila, Pinto-Seppä, & Airaksinen, 2017). Given its inherent complexity, smart sustainable city development will require "transdisciplinary" strategies and efforts to ensure collaboration between various disciplines involved, such as urban planning, local economic development, civil engineering, and data, computer, and complexity science (Bibri, 2018).

Smart (and sustainable) city planning has been put forth as a promising model for enhancing municipal services and assets and for improving the lives of urban citizens. Furthermore, given the immediacy of modern technology, citizens' expectations and means of interacting with their local governments are changing. Citizens are seeking more accessible, transparent, and effective delivery of municipal services, ranging from waste collection to infrastructure renewal to tree maintenance (Dudley et al., 2015). Meanwhile, some municipalities are turning to the private sector, academia, and non-governmental organisations to provide the means for innovation in public spaces, without the associated bureaucratic and financial constraints that could inhibit a culture of experimentation and lower tolerance for risk-taking (The Globe & Mail, 2018; Tomalty, 2017). In short, novel financing mechanisms, technological innovation, and unconventional governance schemes are disrupting business as usual, and the long-term repercussions for public green space management remain to be seen.

In this paper, we address a major gap in the current literature by focusing on the intersection between urban forest management and smart city planning. Through a state-of-the-art review (Grant & Booth, 2009), we outline how smart-city trends and related technologies have been and can be applied to urban forestry and green-space planning. Based on cases to date, we propose an approach for conceptualizing *smart urban forests* and *smart urban forest management*. We also discuss further avenues of research that are needed to understand implications for researchers and practitioners, as well as for the citizens who greatly benefit from greener spaces. We intend for our paper to serve as a first attempt at a comprehensive review of knowledge to date on smart urban forest management, and as a springboard for establishing a dialogue between those involved in smart city planning, as well as forest and green space decision-makers. There is no doubt that people in cities connect with trees (Peckham, Duinker, & Ordóñez, 2013), and it is timely to consider how trees might connect – quite literally – to people.

2. Smart cities, urban green spaces, and urban forestry

Smart technologies are already being applied in environmental and resource management, made all the more accessible with increasing technological capabilities, and with recent calls to action for technology investments in the environment (Arts, van der Wal, & Adams, 2015; Bakker & Ritts, 2019; Joppa, 2017). Artificial intelligence, the simulation of human intelligence processes (such as learning and reasoning) by computer systems, has been employed to predict and model forest fires (Lagerquist, Flannigan, Wang, & Marshall, 2017; Sakr, Elhajj, Mitri, & Wejinya, 2010). Google Earth Engine, a cloud-based geospatial processing platform, has been used to monitor, map, and analyse international forest change (Palomino, Muellerklein, & Kelly, 2017). Unmanned aerial vehicles (UAVs), or drones, assist in forest regeneration through surveying, fertilizer spraying, and precision aerial seeding (Elliott, 2016). Remote sensing technology (e.g., LiDAR, hyperspectral imagery), aided by machine learning, has mapped and assessed the species and structure of individual trees (Alonzo, Bookhagen, & Roberts, 2014). Cryptogovernance and blockchain technologies been piloted in the sustainability sphere as novel ways to build trust and avoid corruption by tracing resources such as fish and timber along the supply chain (Chapron, 2017). Wireless sensor networks have been deployed in greenhouse settings to measure and regulate environmental parameters (Mesas-Carrascosa, Verdú Santano, Meroño, Sánchez de la Orden, & García-Ferrer, 2015; Srbinovska, Gavrovski, Dimcev, Krkoleva, & Borozan, 2015). Radio-frequency identification (RFID) microchips have been proposed as a means to collect and store information about plant pathology, and to share information via web-based platforms (Luvisi, Panattoni, & Triolo, 2012). Similar chips could be used to tag trees for identification and biomonitoring purposes, as well as for "virtualiz[ing] green areas" (Luvisi & Lorenzini, 2014).

Despite the fact that smart city planning is currently one of the fastest growing discourses in urban sustainability (Joss, Cook, & Dayot, 2017), it is unclear whether urban green space and forest management are gaining significant traction in smart city planning. Indeed, there is little mention of green infrastructure and natural asset management in funding mechanisms and policy initiatives for smart cities. In Europe, most of the funding from the EU and associated partners for smart-city projects has been limited to energy, transit and mobility, and ICTs (Climate & Energy Fund, 2018). India's "Smart City Mission" aims to

build 100 smart cities through "smart solutions", which fall within the realms of e-governance, management of waste, water and energy, and urban mobility (Government of India, 2015). However, these solutions fail to mention urban green space and forest management (Dwevedi, Krishna, & Kumar, 2018). A report detailing opportunities for smart cities in Southeast Asia highlight smart applications for social infrastructure, utilities, mobility, security, local economy and community, and the built environment – but with no reference to green infrastructure (McKinsey & Company, 2018). In Canada, the Smart Cities Challenge was launched in 2017 to encourage municipalities to address local issues and improve the lives of their residents through the "use of data and connected technology" (Infrastructure Canada, 2017). The Smart Cities Challenge received 130 applications from across the country, and the finalists' visions and challenge statements focus on energy systems, transportation, and health (Infrastructure Canada, 2019). In the scholarly literature, recent and comprehensive reviews on smart cities, smart sustainable cities, and smart governance in environmental management (Albino et al., 2015; Bakker & Ritts, 2019; Bibri & Krogstie, 2017a; Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014; Silva, Khan, & Han, 2018) fail to elaborate on intersections between smart city trends, technologies, and urban green space management.

This is not to say that smart city planning and urban forest management are completely disconnected. There is exploration of communication tools ("e-tools") and volunteered geographic information (VGI) to enhance public participation and leverage citizen knowledge in green-space planning (Foster, Dunham, & Kaylor, 2017; Møller et al., 2018). Open-source mapping platforms are becoming increasingly popular for tree inventories and other urban forest amenities (e.g. OpenTreeMap). Deep learning techniques, processes by which algorithms are used to simulate how the human brain adaptively learns, have been applied across broad areas to estimate tree canopy cover in major cities (Cai et al., 2018). Artificial neural networks have been used to model and predict urban tree mortality (Jutras, Prasher, & Mehuys, 2009; Steenberg, Robinson, Millward et al., 2018; Steenberg, Robinson, Nitoslawski et al., 2018). Social media platforms have been created or utilized for citizens to report tree maintenance needs, and in some cases have inadvertently highlighted the various ways in which citizens value trees (BBC News, 2015). Nevertheless, evidence from smart-city funding initiatives and current scholarly literature suggests that what is still lacking is a comprehensive understanding of "smart urban forest" applications, along with a dialogue about the implications of the growing smart-city movement for urban foresters, researchers, and other practitioners, as well as for the ecosystems they manage.

3. Trends and technologies

This review unearthed two interacting themes for smart applications in urban forestry (Table 1, Fig. 1). The first refers to the idea that data and digital technologies can be used as tools to improve the delivery of benefits (or ecosystem services) provided by urban green infrastructure. The use of wireless networks, high-powered sensors, and data loggers can provide information in real time about environmental parameters such as stormwater absorption and air quality at specific green sites. Along with information gathered from sensing networks, open and big data can shed light on relationships yet to be explored and sufficiently quantified between forest variables (e.g. biodiversity) and outcomes (e.g. public health). The combination of sensors, ICTs, and cloud-based storage will also allow for unprecedented environmental monitoring and visualisation in real time (Bakker & Ritts, 2019). Large volumes of data and access to government data that was previously restricted can provide insights into urban forest dynamics, which might have been impossible with traditional methods of data collection; one such example is predicting tree mortality from development using building permit data (Steenberg, Robinson, Millward et al., 2018; Steenberg, Robinson, Nitoslawski et al., 2018). However, scholars have also noted that the sheer abundance of data gathered using smart technologies may pose a new challenge for environmental managers (Bakker & Ritts, 2019).

The second theme centers on the potential for data and smart technologies to enable stakeholder participation and engagement, to connect people to nature and facilitate citizen empowerment in urban forest management. This is exemplified by the use of open mapping platforms and VGI initiatives, providing citizens with the opportunity to directly contribute knowledge directly to management processes (Goodchild, 2007). These platforms, used in conjunction with social media and mobile applications, could also pave the way for immediate and integrative public consultation processes about green space values, design, and decision-making. 5 G ("5th Generation"), the next generation of mobile communication networks expected to be faster and more flexible than its predecessor, could further enable these processes by reducing network latency and increasing the amount of data that can be transferred and manipulated (Andrews et al., 2014). Online and integrative platforms may result in more inclusive public consultation and engagement, particularly when targeting specific demographics or groups that tend to be underrepresented at public engagement events. Cloud-based and online platforms may also allow for more effective collaboration across government and sectors, and promote government transparency (Bertot, Jaeger, & Grimes, 2012).

3.1. Augmented and virtual reality

Immersive virtual environments (IVE), created through combination of hardware and software systems, refer to a distinct type of virtual reality where individuals are "surrounded" by "synthetic" information meant to generate the illusion of real environments (Smith, 2015). Virtual reality experiences often involve headsets or projections on large screens. Augmented reality (AR) is where the real environment is enhanced with computer-generated, virtual objects, often for visualisation purposes (Mirauda, Erra, Agatiello, & Cerverizzo, 2017). To date, applications for urban forest and green space management have generally informed landscape design through public values elicitation. For example, researchers at North Carolina State University (USA) have used a robot to capture 360-degree, high-resolution images of a downtown Raleigh plaza and a city park. By manipulating vegetation to create several immersive virtual reality (IVR) scenarios, values about urban park designs and tree arrangements were elicited from virtual "visitors" (Tabrizian, Baran, Smith, & Meentemeyer, 2018). This method, although still in an early stage, could constitute part of an integrative public consultation process for new green infrastructure projects. In Raleigh, it has already encouraged decision-makers to critically assess tree density across multiple urban settings. Further applications of VR and AR could test physiological responses to varying urban green space designs. Researchers in Sweden have used VR to test stress responses and recovery (e.g. cortisol, heart rate) in virtual natural environments in order to elicit the impacts of nature sounds (Annerstedt et al., 2013), paving the way for management decisions informed by relationships between green spaces and human health.

3.2. Open data, big data, and analytics

Effective urban forest and green space management requires adequate data (Steenberg, Duinker, & Nitoslawski, 2019). Tree inventories are understood to be crucial for establishing a strong basis for strategic planning, given the information they provide about the quantity and quality of the canopy. Urban forest structure, green cover, species composition and diversity, available planting spaces, and tree condition are a few attributes that managers and practitioners rely on to make short- and long-term decisions about the urban forest resource (Kenney et al., 2011). Open government initiatives, where urban forest data becomes publicly available, has provided non-municipal actors with the opportunity to access and manipulate tree data, and uncover complex

Table 1
Summary of trends, technologies and applications for urban forest management. "Trending" refers to concepts that have already been implemented and are becoming more mainstream in the urban forestry discourse. "Imagining" refers to cases that have not yet been tested or have only been piloted on a small scale, illustrating future research needs.

Trends and concepts	Technologies and tools	Application for UF management	Barriers to implementation	Relevant case studies	Status (Trending/ Emerging/ Imagining)	References
Augmented reality (AR) and virtual reality (IVR)	• Mobile applications ("apps") • Artificial intelligence, machine learning, and deep learning • Geographic information systems (GIS)	• Citizen science • Tree assessment and mensuration • Green space user-ship, design, and optimization	• Cost (e.g. software development) • Digital divide associated with age, income, or other socioeconomic conditions	• MetaTree for visualizing urban forest data (New York City, USA) • Immersive virtual reality (IVR) for designing urban green spaces (North Carolina State University, USA) • VR for testing stress responses and recovery in virtual forests (Sweden) • AR for re-imagining urban landscapes at the Urban Ecosystem design Lab (Adelaide, Australia)	Trending/ Emerging:	Cirulis & Brigmanis, 2013; Jepson & Ladle, 2015; West, Margolis, O'Neil-Dunne, & Mendelowitz, 2012
Open data, big data, and analytics	• Cloud storage and computing (Google Earth Engine, GBDX) • Artificial intelligence, machine learning, and deep learning • Data mining • Wireless sensor networks (WSNs)	• Forest indicator monitoring • Forest outcome modeling and assessment, including relationships between indicators and outcomes • Geospatial analyses on larger scales and in real-time	• Citizen and municipal data privacy concerns • Data collection and storage capacity • Risk of apophenia, or the propensity of the human brain to see patterns in random data • Cost (e.g. software development) • Capacity for maintenance	• TreeMania sensors collect data on soil moisture in real-time and automatically send email/SMS updates to managers (Oostrum, The Netherlands) • Green City Watch, high-resolution satellite imagery (± 30 cm) and geospatial artificial intelligence (geoAI) to monitor urban green space (Amsterdam, The Netherlands) • Smart Green Infrastructure Monitoring for assessing performance of green infrastructure (University of Illinois, USA; Georgia Tech University, USA) • Sensor-outfitted green infrastructure with watering updates sent to neighbouring residents (Geijsteren, The Netherlands) • Treepedia, quantifying street tree canopy from Google Street View (Senseable City Lab, MIT, USA) • Smart Forest Network with digital sensors and telecommunications capacity for integrated monitoring (USDA Forest Service, USA) • Senscity, IoT sensors to monitor urban climate change impacts (Melbourne, Australia) • Tree water sensors (Swinburne Water Resources, ICT International & RMIT University, Australia) • Treemetrics offers cloud-based, precision forest management (Cork, Ireland) • National Parks Board use GPS and LiDAR (Light Detection and Ranging) sensors to remotely track grass-cutting operations (Singapore) • PhotosynQ Platform with MultispeQ, a hand-held sensor combining a handheld fluorometer, a chlorophyll meter, and a bench-top spectrometer to bring laboratory quality measurements to field applications (Michigan State University, USA)	Trending	Campbell et al., 2013; Hu & Wang, 2015; Kitchin, 2014; Laney et al., 2015; Luvisi & Lorenzini 2014; Mead et al., 2013

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Table 1 (*continued*)

Trends and concepts	Technologies and tools	Application for UF management	Barriers to implementation	Relevant case studies	Status (Trending/ Emerging/ Imagining)	References
Robotics, automation, and cybernetics	• Artificial intelligence, machine learning, and deep learning • Cloud storage and computing • Cybernetics	• Tree and stand interventions (e.g. pruning, removal) • Species identification • Risk assessment and disease diagnostics • Plant growth and functioning optimization ("E-plants", "Cyborg botany")	• Cost (e.g. hardware/ software development) • Capacity for (human) verification and maintenance • Ethical concerns • Technological capability	• TreeBot, tree-climbing robot (Guangdong, China) • E-plants, vegetation with integrated electronics (Linköping University, Sweden) • Designers Walk building, where trees could "plug into" building maintenance system (Toronto, Canada) • Elowan, the plant-robot hybrid, using a plant as a sensing device (Massachusetts Institute of Technology, USA) • Robotic lawn mowers trialed by the National Parks Board (Singapore Botanic Gardens, Singapore)	Emerging/ Imagining	Cantrell, Martin, & Ellis, 2017; Gui et al., 2017; Gulsrud et al., 2018; Lam & Xu, 2011; Manzella et al., 2013; Robinson et al., 2017; Stavrinidou et al., 2015; Stavrinidou et al., 2017; Wetser, Dieleman, Buisman, & Strik, 2017
Alternative ("smart") green infrastructure	• Artificial intelligence, machine learning, and deep learning • Data loggers and sensors	• Delivery of green benefits and ecosystem services such as particulate absorption and carbon sequestration	• Cost (e.g. hardware/ software development)	• CityTree, a bio-tech filter with IoT imbedded technology to measure environmental performance (Berlin, Germany, and other cities in Europe)	Emerging	W. Detiger, personal communication, January 24, 2019
Mobile and citizen science	• Mobile applications ("apps") • Crowdsourcing and volunteered geographic information platforms • Wearable technologies • Blockchain for data security, information sharing and storage	• Data collection and analysis • Providing a platform for citizens to connect with nature and green spaces	• Data quality and capacity for verification • Citizen and municipal data privacy concerns • Digital divide	• OpenTreeMap for urban tree inventories (USA and Canada) • NYC Street Tree Map (New York City, USA) • Urban Forest Map (San Francisco, USA) • CityTrees (Ryerson University, Canada) • Urban Forest Visual Map (Melbourne, Australia) • TreeChain network, a blockchain and IoT peer platform for tree planting and ecological restoration (Sydney, Australia) • Curio Canopy (Dublin, Ireland) • Plant and tree identification apps (e.g. Plantsss, PlantSnap, Vancouver Trees, iNaturalist)	Trending	Baynham-Herd, 2017; Castell et al., 2015; Confalonieri et al., 2013; Foster & Dunham, 2015; Foster et al., 2017; Gabrys, 2014; Jepson & Ladle, 2015; Møller et al., 2018; Roman, Campbell, & Jordan, 2018
Integrative public consultation and participatory governance	• Social media platforms • Mobile applications ("apps") • Cloud storage and computing • Artificial intelligence, machine learning, and deep learning • Geographic information systems (GIS) • Wearable technologies • Augmented reality • Blockchain for data security, information sharing and storage	• Value elicitation from citizens about forests and green spaces • Data collection on citizen outcomes (e.g. health) from forest and green space design	• Citizen data privacy concerns • Digital divide, and subsequent environmental justice and accessibility issues	• Citizen-volunteered Fitbit data showing where specific green spaces keep residents active (Duluth, USA) • Maptionnaire for public information and engagement (Helsinki, Finland) • MijnPark ("My Park") for collecting information about how people use and perceive parks (Amsterdam, The Netherlands) • Cryptocurrency for tree planting, such as TreeCoin and CarbonCoin	Emerging	Gulsrud et al., 2018; Steenberg et al., 2019

(*continued on next page*)

Table 1 (*continued*)

Trends and concepts	Technologies and tools	Application for UF management	Barriers to implementation	Relevant case studies	Status (Trending/ Emerging/ Imagining)	References
Public-private partnerships	• Civic and municipal innovation spaces	• Dedicated space for collaboration between multiple stakeholders	• Institutional inertia • Silos within municipal government and between stakeholder groups • Citizen data privacy concerns • Appropriation of public spaces by private sector	• Sidewalk Toronto, a "smart" neighbourhood (Toronto, Canada) • UI Labs, a civic innovation hub and business incubator (Chicago, USA) • Innovation Garden, a regional innovation ecosystem (Espoo, Finland) • "Forest City", a "smart", real-estate megaproject with a focus on vertical forests (Johor Bahru, Malaysia)	Trending/ Emerging	Arts et al., 2015; Dwevedi et al., 2018; Hillgren, 2013

urban forest dynamics (Steenberg, Robinson, Millward et al., 2018; Steenberg, Robinson, Nitoslawski et al., 2018). The cases outlined here describe more novel urban forest data collection and analysis techniques using smart concepts and technologies, and highlight a growing interest in wireless sensor networks (WSNs) and artificial intelligence for green space management at varying scales.

In the Netherlands, where a severe drought caused significant tree loss from June to September 2018, *TreeMania*'s sensors collect data on soil moisture content in real-time and send emails or SMS-updates to tree managers and workers (Van Velzen, Modderkolk, & Bouma, 2018). The sensors have been deployed across 5500 trees in the southern Netherlands, and when those updates are acted upon, have a 99% success rate in keeping newly planted trees alive (W. Detiger, personal communication, January 24, 2019). In the Dutch village of Geijsteren, the sensors were installed for trees located in the town square. Instead of tree managers, neighbouring residents receive the watering updates, promoting citizen engagement and participation in tree maintenance. In the future, machine learning-based moisture prediction algorithms, combining real-time moisture data with weather forecasts, location factors, and historical data, will be developed to add further nuance to tree watering strategies (W. Detiger, personal communication, January 24, 2019).

In Amsterdam (NL), a geospatial artificial intelligence (geoAI) platform called Green *City Watch* outputs semi-automated 'Urban Greenprints' to assess and monitor urban green infrastructure using AI algorithms and sub-meter resolution (± 30 cm) satellite imagery (Observa Natura, 2019). The underlying classification index is comprehensive enough to cover a significant portion of the key performance indicators (KPIs) on ecology, social impact, amenities, and economic value. The goal is to offer continuous monitoring in near real-time to ensure that municipal decision-makers can understand the suite of values associated with trees.

In Chicago (USA), the *Smart Green Infrastructure Monitoring* pilot measures the performance (e.g. temperature, wind speed, soil moisture, rainfall, and other weather-related parameters) of various stormwater management strategies such as permeable pavement, bioswale, infiltration planters, and tree pit filters. Using sensors and cloud-based analytics, the pilot project is the first to quantify the effectiveness of green infrastructure using these technologies, and is looking to compare the performance of various green site designs to better target future interventions. The openly available results of the pilot demonstrated that green infrastructure reduces surges of water on the drainage system, and pinpointed which strategies were most effective (UI Labs, 2018).

3.3. Robotics, automation, and cybernetics

To date, there is relatively scarce research and pilot studies examining the potentially emerging role of robotics, broadly referring to the design, operation, and application of robots, for urban tree and green space management. Tree climbing robots, which could eventually facilitate pest diagnostics and pruning needs, have been developed and tested on a small scale (Gui, Tang, & Mukhopadhyay, 2017). Automated lawn mowers are commercially available (e.g. Automower® by Husqvarna) and have been trialed in Singapore, which could pave the way for the automation of other landscape management practices such as weeding and fertilizing. There is (early-stage) exploration of plant growth optimization through the use of integrated electronics, where plant "circuitry" is merged with electronic circuits (Stavrinidou et al., 2015, 2017). "E-plants" or "Cyborg plants" could eventually serve as sensing devices for "feedback regulated control of plant [or tree] physiology" (Stavrinidou et al., 2015). Architects are also theorizing ways in which green and grey infrastructure might combine and allow for simultaneous monitoring and maintenance. In Toronto, Canada, the proposed Designers Walk building would feature trees and vegetation that could "plug into" the building's maintenance system and allow for

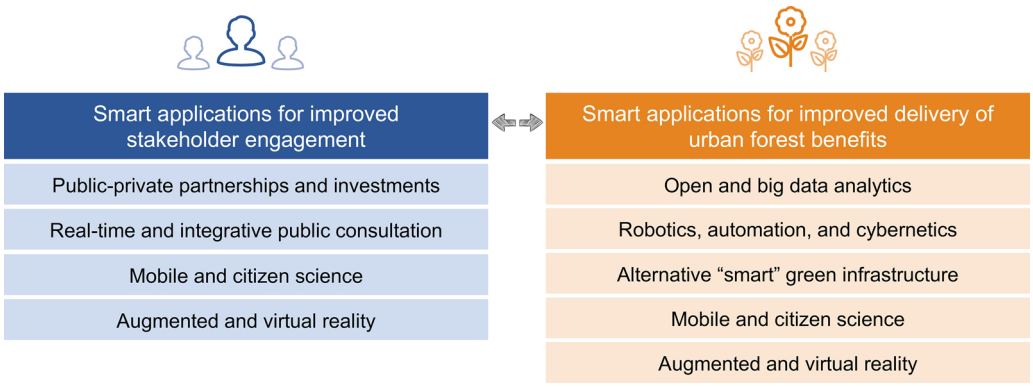


Fig. 1. Summary of trends in smart planning to date that are relevant to urban forest management, according to the two themes.

integrated irrigation and fertilizing systems (The Globe & Mail, 2018).

3.4. Alternative and "smart" green infrastructure

It is well known that urban landscapes are not always well suited for trees and associated vegetation; degraded soil quality and compaction, under- and aboveground infrastructure conflicts, the urban heat island effect, and pollution are just a few factors that may limit the longevity and vitality of urban green infrastructure (Nitoslawski, Duinker, & Bush, 2016). Alternative green infrastructure, designed and built to mimic the properties and benefits of more traditional green infrastructure, may be one solution to urban stresses. For example, CityTree by Green City Solutions is touted as a customisable urban climate solution that uses mosses and IoT technologies to filter air. A digital platform allows for performance indicator monitoring in real time, and optimizes functioning and plant care (EIT Climate-KIC, 2019). Although it is worth exploring alternatives to trees and other green infrastructure in highly built and dense urban environments, there is no doubt that trees provoke biophilic responses in urban dwellers, providing spiritual, intellectual, and aesthetic fulfillment – intangible and yet irreplaceable benefits (Peckham et al., 2013).

3.5. Mobile and citizen science

Citizen science generally refers to "partnerships between scientists and non-scientists in which authentic data are collected, shared, and analyzed", often with broader educational goals and impacts (Jordan, Ballard, & Phillips, 2012). More recently, citizen science has gained significant traction in ecological research, which could in part be attributed to the recognition of place-based and community-based stewardship as effective forms of environmental governance (Shandas & Messer, 2008). Furthermore, the ubiquity of social media, web-based tools and platforms, and mobile devices present new opportunities for user-generated content for research purposes (Foster et al., 2017). Although the quality of data collected by citizens has been called into question (Foster et al., 2017), well-executed and successful citizen science cases have led to important scientific achievements such as the discovery of new species (Schilthuizen, Seip, Otani, Suhaimi, & Njunjić, 2017) and have contributed to increased ecological literacy among non-scientists (Jordan et al., 2012). In urban forest management, citizen science projects often focus on data collection for tree inventories and monitoring, values elicitation, and engagement in strategic planning processes (Roman et al., 2018).

In one such example, from 2015 to 2016, over 2300 volunteers in New York City (USA) identified and measured every single street tree, as part of a program called *TreesCount!* initiated by the New York City Department of Parks and Recreation (US Forest Service, 2017). They also recorded the presence of trunk and bark damage, which occur frequently in urban settings where construction and landscaping are common-place, allowing specialists to monitor the more heavily damaged trees. The analysis also revealed the invasion of the Callery pear (*Pyrus calleryana*), a species responsible for not only a repulsive smell, but also being highly susceptible to bark inclusions and limb breakage during strong storms – a poor choice for a post-Hurricane Sandy NYC (Culley & Hardiman, 2007). Digital tools like the NYC Street Tree Map provide opportunities to observe and quantify forest composition, structure, and vitality, as well as mitigate any associated risks.

Similarly, the Urban Forest Visual Map was completed for Melbourne (AUS) in 2017. Unlike NYC's map, which estimated the ecological benefits (in dollars) of each individual tree, Melbourne's map visualizes tree life span, diversity, and canopy cover through images and graphs. Although the platform has increased awareness on tree stewardship amongst citizens, future research is needed to quantify its outreach and impact. Other open-source mapping platforms have been tested and implemented in cities across North America by municipalities and non-profit organisations (e.g. OpenTreeMap, https://opentreemap.github.io/).

3.6. Integrative public consultation

In 2018, researchers at the Vrije Universiteit (NL) experimented with a mobile app called MijnPark ("My Park") to collect the information about citizen perceptions of a local park due for renovation. Once the app was downloaded, the user was sent to three of thirty possible locations. At each location, they were asked about their experience at that location (e.g. safety, noise) and their perception of the vegetation, surrounding facilities, and overall sentiments about the park. A publicity campaign in and around the park, and on social media, resulted in 154 respondents. Initial results built a profile of the typical Rembrandtpark visitor and analyzed the differences between the app and survey data. The MijnPark app is unique in that it asks about the respondent's perceptions of a certain area on the spot, so that locations where more (or less) attention is needed can be identified and prioritized.

3.7. Public-private partnerships

Cross-sector and stakeholder collaboration is understood to be key to innovation in municipal spaces (Hillgren, 2013; Tomalty, 2017). In some instances, the public sector (e.g. municipalities) has turned to the private sector (e.g. business) in order to overcome potential inefficiencies and constraints that often plague local governments (Koppenjan & Enserink, 2009). One such partnership is Sidewalk Toronto, a collaborative project between Waterfront Toronto (itself a tri-government organisation funded by the City of Toronto, the Government of Ontario, and the Government of Canada) and Sidewalk Labs, a subsidiary of Alphabet Inc. (and sister company to Google) to redevelop an underutilized area into a "smart" neighbourhood. Although still in

its planning stages, Sidewalk's proposal includes a "digital maintenance system" for plants and trees with moisture sensors that would communicate with green space managers in real time about infrastructure needs (Sidewalk Labs, 2019, p. 152).

4. Turning points for smart urban forestry

The field of smart urban forestry—and, more broadly, smart ecosystem management or "technoecology" (Allan et al., 2018)—is emergent. We envision the following key turning points or paradigm shifts for smart applications in urban forestry, and aid in the conceptualization of key definitions below (Section 5). These are inferred from what is known to date, and proposed in anticipation of how the field is expected to progress given current trends, technologies, and current cases and examples described above.

The first turning point is the ubiquitous use of Wireless Sensor Networks (WSNs) and associated technologies (e.g. cloud-based platforms, 5 G) to monitor urban forests and green infrastructure, with the eventual goal of monitoring and decision-making in real time. As exemplified by our outlined examples, there is increasing recognition that data, and particularly big and open data, can shed light on previously understudied ecosystem processes and dynamics and allow for more refined modeling and predictive capabilities. Combined with cloud computing and faster network capabilities, complex urban forest and green space dynamics can be more readily understood and quantified.

The second turning point is the recognition that urban forests are social-ecological systems, where all urban dwellers can play a significant role in maintaining urban forest health and functioning, and vice versa. For example, the use of wearable technologies for monitoring physiological responses to green exposure can subsequently inform green space design. In relevant instances, citizen science would encompass all aspects of urban tree stewardship such as design, monitoring, and maintenance of urban trees. This could be achieved through virtual and/or augmented reality, interactive mobile apps that connect the user to the municipal tree inventory platform, and integrative public consultation where public values are elicited from a green space user on the spot.

The third turning point, as we currently envision it, is the self-regulation and the self-organisation of urban forest ecosystems enabled by smart technologies. Plants and trees as sensing devices ("E-plants"), as well as automatic and self-watering systems in times of drought, would be early examples of this concept. Here, there is potential for limited human intervention; ecosystem needs are self-diagnosed and addressed through external and/or integrated sensor networks, as well as algorithms that constantly readjust and adapt to ecosystem baselines. Urban forests (and the cities in which they are found) become social-ecological-*technological* systems (SETS) (Chester et al., 2015; McPhearson et al., 2016). SETS, as a framework for conceptualizing urban systems, emphasizes the important role that technology plays in urban built infrastructure – we extend this concept to encompass trees and vegetation as green infrastructure.

5. Key definitions

Given this review, we offer the following definitions for smart urban forest and smart urban forest management:

Smart urban forest: The collection of trees and associated vegetation within a city that are designed, monitored, and managed using digital technologies, through which forest benefits are enhanced and self-organisation, self-regulation, and automation can be achieved. These technologies include, but are not limited to, open and big data, sensor networks, artificial intelligence, robotics, augmented and virtual reality, and social media.

Smart urban forest management: The design, establishment, monitoring, and management of urban trees and vegetation through the use of digital technologies, for the joint purpose of improving the urban environment and engaging all relevant stakeholders in its governance.

More recent urban ecological theory recognizes that urban ecosystems are not solely comprised of biophysical components; social processes also influence ecosystem structure and function (Grimm et al., 2008; Steenberg et al., 2019). We emphasize the dual importance of smart city trends and technologies for both enhancing the delivery of urban forest benefits and engaging the various actors who have a stake in effective urban forest management, including governmental authorities, non-governmental organisations, businesses, citizens, and other local groups (Lawrence, De Vreese, Johnston, Konijnendijk van den Bosch, & Giovanni Sanesi, 2013). Interagency cooperation, cross-sector partnerships, and civic engagement have already been identified as crucial factors for effective management of urban forest ecosystems (Steenberg et al., 2019), and we posit that these are just as vital for developing, testing, and implementing smart applications in urban forest management.

6. Future research

There is a dearth of research on smart applications in urban forest management, therefore the discussion around smart city concepts and related technologies in this paper are limited to what has been developed or piloted thus far. Further research is needed on the impact of other technologies and their emerging uses in green space management, such as ambient intelligence and sentient computing, where embedded systems are responsive and adaptive, particularly to human presence (Bibri & Krogstie, 2017a; Cook, Augusto, & Jakkula, 2009). As sensor networks for determining environmental quality and performance become more ubiquitous (Cook et al., 2009; Laney, Pennington, & Tweedie, 2015; Mead et al., 2013), and as "strong AI" (where the reasoning and decision-making capabilities of a computer system are equal to that of humans) progresses, it is worth considering what dynamic, adaptive, and responsive human-forest systems might resemble.

In many countries, urban forestry and green space management fall under the jurisdiction of a municipality or other local-level body; trees are subject to municipal by-laws, and urban forest management plans (UFMPs) and strategies are, more often than not, developed and implemented by a municipal body (Nitoslawski et al., 2016). Some research has shown that limited resources, disciplinary silos, bureaucratic constraints, cultures of risk aversion, and lack of capacity and expertise continue to counter innovation and impede knowledge transfer in municipal spaces (Tomalty, 2017; Ugolini, Massetti, Sanesi, & Pearlmutter, 2015). Future lines of research in smart urban forest management could focus on the effectiveness of a particular smart application in improving and promoting innovation in urban forestry management processes at the municipal level. It would be worthwhile to identify success factors for technology adoption and uptake in varying urban forest and municipal contexts, and explore how successful cases could be replicated in varying locales.

Smart city planning will not solve the problems that are still prominent in municipal forest management, and may in fact engender further challenges. This review revealed the need to explore and quantify potentially unintended consequences of emerging smart technologies on human and ecosystem health. For example, scholars have expressed concern about 5 G technologies due to the impacts of exposure to high frequency millimeter waves (Di Ciaula, 2018; Russell, 2018). Studies have shown that radio frequency electromagnetic field exposure can damage trees (Waldmann-Selsam, Balmori-de la Puente, Breunig, & Balmori, 2016), and preliminary observations and evidence also suggest that shifts in higher frequencies may alter insect behaviour and physiology (Thielens et al., 2018). The widespread adoption of 5 G will likely require dense networks of wireless devices and antenna, highlighting the importance of determining subsequent ecological effects (Di Ciaula, 2018). Another consideration should be ubiquitous (and cheap) WSNs becoming litter in the environment. On a related, albeit larger-scale, "space junk" has already become a problem. The

largest ever space debris study highlighted the growing popularity of small satellites, and the deployment of low-Earth orbit mega-constellations will greatly increase space debris and the frequency of catastrophic collisions (Lewis et al., 2017). Making sensors smaller, modular, and recyclable, extending a sensor's lifespan, and deploying sufficient retrieval programs are effective strategies for decreasing the likelihood of sensors polluting the environment.

The smart-cities movement may compound environmental justice issues and the digital divide (Gulsrud et al., 2018). The cases and examples outlined in this paper originate mostly from the Global North, illustrating a potentially uneven diffusion of technological practices, innovation, and Internet penetration rates (Sui, Goodchild, & Elwood, 2013). Even in wealthier urbanized countries such as the United States, consistent and reliable access to digital technology remains elusive for lower income and disadvantaged communities (Gonzales, 2016). Cities with a significant digital divide are also less likely to receive investments for smart city initiatives, which could further disparities between cities that "have" and those that "have not" (Neirotti et al., 2014). The threat of job loss and/or change due to robotics and automation (e.g. technological unemployment) may further result in social and economic upheaval (Brynjolfsson & McAfee, 2014), as scholars suggest that lower pay and education correlate with higher probability of automation (Frey & Osborne, 2013). Although foresters and urban planners are considered "low risk" according to Frey & Osborne's list, further critical analysis is needed on how the smart movement will change the nature of work for urban forest and arboricultural professionals.

Ethical concerns surrounding citizen data usage and privacy have also surfaced and prompted questioning about how smart-city technologies and their deployment may promote further capital accumulation with little regard for the actual needs of citizens (Colding & Barthel, 2017). In a city where every citizen may potentially be "convert[ed] into an environmental sensing device" (Bakker & Ritts, 2019, p. 207), there is mounting pressure to ensure that citizen agency is not lost, and that social and structural inequalities are not exacerbated. In the case of "smart neighbourhoods" and "innovation spaces" with heavy involvement from private-sector companies and investors, it becomes increasingly apparent that cities need to be wary about ceding control over public goods (Financial Post, 2018; Viitanen & Kingston 2014).

7. Conclusions

Cities are arguably entering a new age of unprecedented data collection, processing, and utilization in urban decision-making, e.g. "urban computing" (Bibri & Krogstie, 2017a), as well as citizen involvement and empowerment in city building (Ratti & Claudel, 2016). It is crucial to identify and explore the uses of digital and computing technologies for green infrastructure and expand upon future applications as they develop, particularly at the cross-section of academia, industry, and government. It is just as vital to consider how these tools can be harnessed to engage and empower citizens and community stakeholders, to ensure that green benefits are accessible and shared by all.

We have outlined current applications of smart city trends and technologies in urban forest and green space management. Based on cases to date, we have also inferred further emerging uses, of which planners, practitioners, researchers, and managers should be aware. We emphasize that this list is flexible and likely subject to change as smart urban forest initiatives continue to be piloted, developed, and tested. The cases highlighted in this paper demonstrate a growing interest in understanding how smart tools and technologies create opportunities for more effective environmental planning, monitoring, and decision-making in urban contexts.

If harnessed appropriately, the smart movement provides untapped opportunity for urban forestry to be brought to the forefront of municipal sustainability discourses. Indeed, with greater technological sophistication, many ecosystem services provided by trees and green spaces can be more readily quantified and integrated into municipal asset management and financing processes. When it comes to the non-material benefits of trees and green infrastructure, there is huge potential for community contribution to green space evaluation and planning through smartphone apps and social media, as well as online and integrative platforms for engagement.

In an increasingly digital society, intersections between urban nature and technology will become more prominent. The urban challenges that we face, such as pollution, climate-related events, population growth and immigration, and economic and social inequalities, call for innovative approaches to valuing and managing green spaces. Smart technologies may invariably allow trees to "connect" with us – to communicate their condition, convey health and optimize functioning, and potentially enhance co-benefits. Smarter urban forest management should aim to connect people to urban nature and its many benefits, to assist urban foresters, to enable decision-makers, to empower all citizens, and to reveal that forests – especially in the city – are key to healthy and sustainable living.

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