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Cities and the Environment (CATE)

Volume 12 | Issue 1 Article 1

3-15-2019

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Recommended Citation
Ordóñez, C., Grant, A., Millward, A., Steenberg, J.,Sabetski, V. (2019) Developing Performance Indicators for Nature-Based Solution Projects in Urban Areas: The Case of Trees in Revitalized Commercial Spaces. Cities And The Environment (CATE)

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Developing Performance Indicators for Nature-Based Solution Projects in Urban Areas: The Case of Trees in Revitalized Commercial Spaces

It is becoming increasingly important to audit nature-based solutions (NBS) projects to understand their utility in addressing urban sustainability goals. However, the ecological and social complexity of such projects makes it difficult to develop performance indicators. Focusing on specific case studies and specific natural elements could advance this area of research. Urban trees are a vital component of many NBS initiatives. Cities with ambitious tree-planting goals rely on urban revitalization to provide the conditions necessary to grow trees in highly urbanized areas, and in this way deploy NBS projects. We present a conceptual and methodological framework of case-specific performance indicators in the context of NBS projects. This framework addresses the type of parameters, measures, and data that could be considered when assessing small-scale, NBS-inspired, revitalization projects, taking the natural elements of these projects, in this case the trees, as the unit of assessment. Our framework integrates ecological, environmental, and social indicators of tree performance and was developed with the experience gained from on-going, multi-year research projects at two revitalization sites in Toronto, Canada, where street trees grew in engineered sub-surface habitats. The framework includes indicators related to: urban tree ecology; tree characteristics; soils; climate and atmosphere; built environment; tree planting, care, and maintenance; social characteristics of the urban space; and human decisions and governance. This study frames the need for interdisciplinarity and case specificity in the development of performance indicators for NBS projects.

Keywords
street trees, urban forest management, green infrastructure systems, urban sustainability

Acknowledgements
This research was made possible by funding from the Ontario Centres of Excellence (OCE), the Tree Research & Education Endowment Fund, the Natural Sciences and Engineering Research Council of Canada (NSERC), and DTAH. Funding for research assistants affiliated with Ryerson University's Urban Forest Research & Ecological Disturbance (UFRED) Group was provided by the Dean's Office, Faculty of Arts, Ryerson University. The authors thank James Urban (FASLA), Michael James (DeepRoot Canada), Tanya Brown and Brian Brownlie (DTAH), Peter Simon (City of Toronto), as well as research assistants with the UFRED Group.

This article is available in Cities and the Environment (CATE): https://digitalcommons.lmu.edu/cate/vol12/iss1/1

INTRODUCTION

Nature-based solutions (NBS) are a key aspect of urban sustainability (Frantzeskaki et al. 2016). NBS are systemic solutions to problems related to the environmental quality of cities (Raymond et al. 2017). This approach can manifest in small-scale activities that focus on protecting or increasing natural elements in cities, such as restoring an urban wetland for enhancing water purification, or planting street trees for reducing urban heat and improving human health (Kabisch et al. 2016). NBS projects are designed to: 1) provide multi-functionality, which means delivering multiple environmental, social, ecological, and economic benefits, such as a combination of improved water filtration, improved street aesthetics, and improved human-nature connection, among others (Bush & Hes 2018); 2) include or protect existing natural elements that can provide these benefits, including water bodies, soils or vegetation, as these elements are managed through their lifecycle (Kabisch et al. 2016); and 3) harmonize natural and engineered elements as part of one system for the purpose of improving the functionality of natural elements, such as installing sub-surface engineering technologies to improve irrigation and soil quantity for growing trees in urban streets (Page et al. 2015).

Urban trees are intrinsically attached with NBS initiatives in cities. Trees can improve the urban environment (Willis & Petrokofsky 2017) by increasing air quality and reducing urban heat (Greene & Millward 2017). Since growing trees in highly urbanized spaces is challenging due to limited soil volume and irrigation (Nowak et al. 2004) and considering that tree-species selection or tree maintenance alone cannot ameliorate these stressors, cities with ambitious tree agendas rely on revitalization projects. Revitalization is a process characterized by changes to pedestrian walkways, public space improvements, streetscaping, and the integration of natural features, such as trees. Revitalization is one of the only ways to re-introduce natural elements, such as trees, into highly urbanized spaces, such as commercial streets. Revitalization provides an opportunity for a complete redesign and restructuring of the urban space in a way that is more conducive to growing trees (McPhearson et al. 2011). This sometimes means attaching trees to sub-surface, engineered, green infrastructure systems, such as structural cells (Bartens et al. 2010). Revitalization projects based on these systems can be conceived as manifestation of NBS projects. As such NBS projects become more ubiquitous, it is important to develop performance indicators to audit them. By studying the performance of the natural elements in these projects, we can assess NBS project success, as the natural elements are usually the ones that provide the benefits to people and the environment.

Developing case-specific performance indicators for natural elements in revitalization projects can help us understand how NBS projects operate in an empirical way, a way more grounded in the reality of how natural elements are introduced and managed in the urban landscape. The complex, engineered environments created by revitalization projects generate new environmental conditions that, in turn, influence the performance of its natural elements. However, developing performance indicators in these contexts is difficult because the natural elements, such as trees, are usually not the focus of assessment (Steenberg et al. 2017). Beyond mentioning that trees planted in highly urbanized areas suffer disproportionally from high stress (Nowak 2004), the urban-tree literature does not have much to say about indicators of performance in the context of revitalization projects based on green infrastructure systems. Most urban-tree performance research is focused at a broad spatial scale, with studies focusing on tree survivorship or mortality rates across a whole city (e.g., Vogt et al. 2015).

Similarly, the NBS and green-infrastructure-system literature provides little information on how to develop performance indicators for case-specific and small-scale NBS projects. A problem is the complexity and multi-dimensionality of NBS projects, which means considering a wide range of ecological, environmental, social, and economic parameters. Current efforts limit performance indicators to only a narrow set of environmental measures (Green et al. 2016). For instance, most of the research on green infrastructure systems, such as sub-surface soil technologies, focus on improving water quality (Scholz & Grabowiecki 2007) and water runoff (Schubert et al. 2017). Some studies focus on the environmental impact of these systems, such as carbon neutrality (Flynn & Traver 2013). Few, if any, studies focus on the actual performance of the natural elements in NBS projects. This performance is vital to understand whether these projects are being successful at supplying the environmental, social, and economic benefits they are designed to deliver. To develop such performance frameworks, interdisciplinary conceptual and methodological advancements must be made.

This paper responds to these needs by presenting an approach for developing a performance assessment framework in NBS-inspired revitalization projects. We conceive NBS projects in the urban context to mean activities that include or protect natural elements in cities, such as planting trees on a street. We take the natural element as the unit of assessment. Our approach is case-specific and is grounded in the reality of how natural elements are managed in urban areas, so they can provide the environmental, ecological, social, and economic benefits they are meant to provide. We bring together several bodies of literature, including: urban tree performance (e.g., Lu et al. 2010); green-infrastructure systems (e.g., Schubert et al. 2017); urban ecology (e.g., Cadenasso & Pickett, 2008); and NBS research (e.g., Kabisch et al. 2016; Raymond et al. 2017) to develop a methodological approach to monitor and assess the performance of NBS projects. We base this framework on a three-year experience of studying two revitalization projects in Toronto, Canada, where: 1) the interaction of ecological, social, economic benefits where considered in their design; 2) trees were planted and grew in an improved engineered environment, in this case, sub-surface soil structures; and, 3) there was a high expectation for good tree performance and a low tolerance for tree decline and mortality. We describe these projects and review the literature to unpack the parameters, indicators, measures, and type of data that was considered to assess project performance. We later discuss the limitations of our work and future research. While preliminary, this work can inform monitoring and auditing processes of NBS projects and contribute to a better integration of green and grey infrastructure in initiatives where the biological and social realities rarely align.

AN NBS PROJECT PERFORMANCE FRAMEWORK

Case Studies

Two revitalization projects were studied in Toronto, Canada to develop our performance framework presented here: the Bloor Street and Queens Quay Boulevard projects.

Bloor Street is a major east-west commercial-retail thoroughfare in Toronto, the largest city in Canada by both population and geographic extent (Statistics Canada 2011). It is also a major downtown shopping district in the city. A portion of the street was the focus of a multi-million-dollar revitalization project that was finalized in 2011, which included changes to the pedestrian walkway, streetscaping, and tree planting. Similarly, Queens Quay Boulevard is an important commercial and tourism area along the Toronto waterfront, and was the focus of another multi-million-dollar revitalization project where structural soil cells were used below the Martin Goodman Trail, a multi-purpose waterfront recreation trail (Figure 1).

Both projects included the installation of structural soil cells, which constitute a sub-surface, weight-supporting lattice, containing prescribed soil (quantity and quality) for supporting tree establishment and growth (Page et al. 2015). These cells are frequently included in streetscape revitalizations to collect surface water runoff, thereby serving as a stormwater management technique, as well as providing passive irrigation to trees planted in them (Urban 2008, DeepRoot 2017).

Hundreds of trees were planted at each of these two sites with their root environment contained in these cells, where tree roots shared soil across trenches of interconnecting cells, extending continuously for an entire sidewalk block. After approximately five years growing along Bloor Street, many of the original 133 trees planted there either showed severe signs of decline or had died. In May/June of 2015, all the trees were removed and replanted with new tree species. In contrast, as of the end of 2017, many of the Queens Quay trees remain alive and present fair to good canopy condition (Figure 2; Table 1).

Despite forethought, planning, and investment in a highly engineered sub-surface streetscape, reasons for the poor performance of trees originally planted along Bloor Street were puzzling. The Bloor Street experience fueled discussions about the effectiveness of NBS and what the role of trees should be in streetscape design. There was negative media attention (e.g., Katsarov 2017 in The Globe and Mail), and stakeholders wanted to know exactly what happened to the trees and feared that, unless they could correct these problems, the same poor tree outcomes may occur in other revitalized spaces, such as Queens Quay Boulevard.

While an auditing system for assessing these projects would have been useful and would have helped to understand how to assess tree performance, no such information was readily available. Also, the information from urban-tree performance research could not be simply extrapolated, since this is usually based on more conventional tree-planting sites. With no previous examples to draw from, we developed our own case-specific assessment framework. For developing such a framework, we reviewed the type of measures that could be collected from trees and from their growing environment, as shown in the next section. We then synthesized this information into a performance framework, which was refined through a participatory approach with the project stakeholders and is described in the subsequent section.

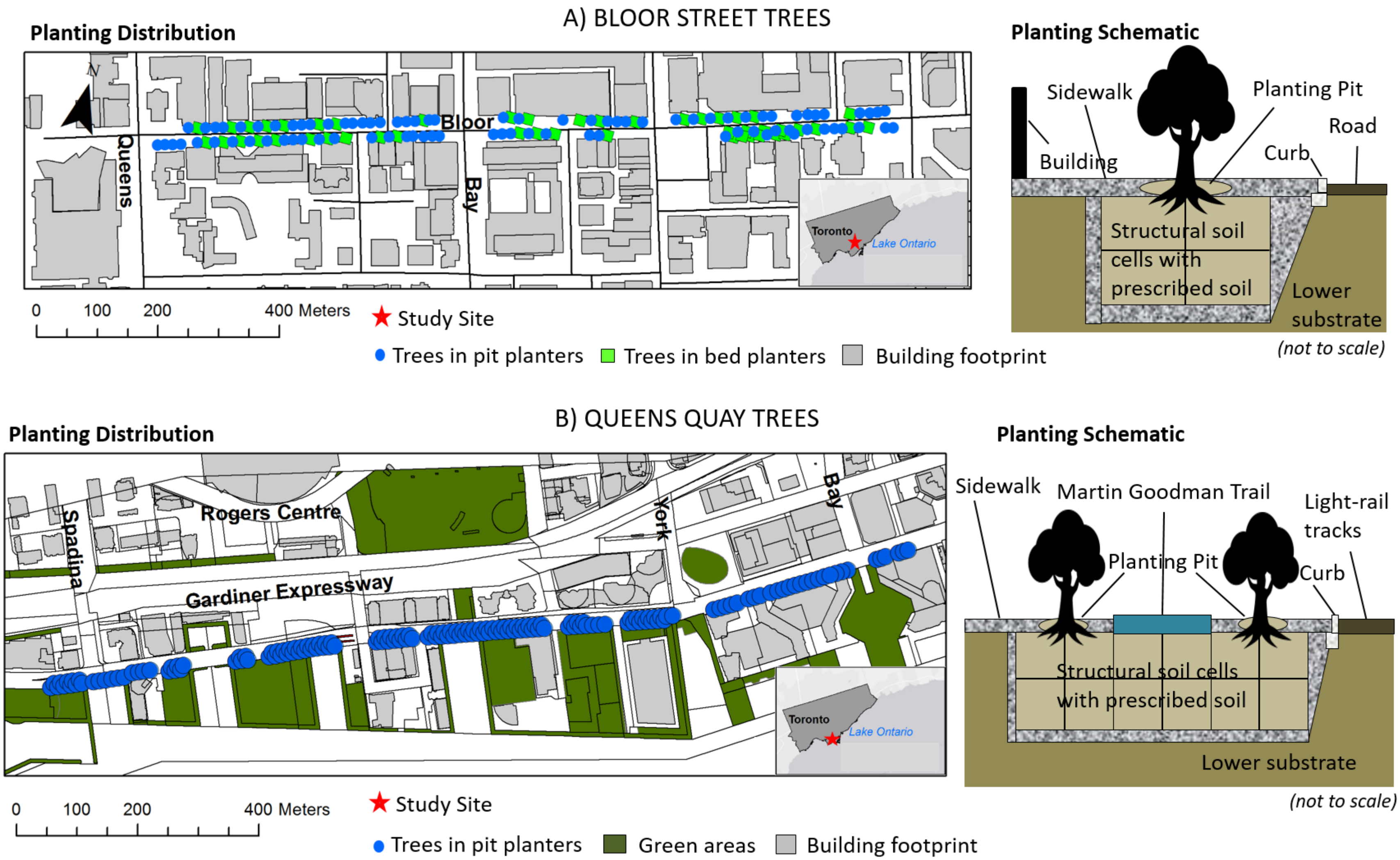

Figure 1. Planting location and distribution, and planting schematic, of the a) Bloor Street and b) Queens Quay trees.

Figure 2. Clockwise: a) New tree plantings along Bloor Street, September 2016 (photo credit: Steenberg, 2016); b) Tree plantings along Queens Quay Boulevard, Toronto Waterfront, September 2016 (photo credit: Ordóñez, 2016); c) Removal of Bloor Street trees by City of Toronto crews, May/June 2015 (photo credit: Grant, 2015); and d) Tree trunk samples collected from removed trees at Bloor Street for dendrochronological analysis (photo credit: Sabetski, 2016).

Table 1. Characteristics of the urban space and tree-growing habitat along Bloor Street and Queens Quay Boulevard.

Characteristic	*Bloor Street*	*Queens Quay Boulevard*
Project Completion (tree-planting)	2010	2015
Number of trees planted	133	154
Trees Growing on Site (end of 2017)	129	151
Tree Removal and Re-Planting	All original trees removed in 2015; new trees planted in 2015	Removal of dead trees only
Tree Species	Original: *Platanus x acerifolia*, removed in 2015. Current: *Ulmus americana* and *davidiana*, and *Gymnocladus dioicus*	Current: *Platanus occidentalis* and *Platanus x acerifolia*
Type of Planter	Raised flower-bed planters and street-level pit planters with protective grates; bare soil under grates	Street-level, pit planters with no protective grates; 1-2 cm granite stone soil cover
Engineering system	Underground structural soil cells	Underground structural soil cells
Type of urban space	High-density commercial-retail; urban canyon (tall buildings on both sides of street)	Mixed-use: retail, residential, and recreational; low to mid-rise buildings
Ownership	Private businesses and condominiums	Mixed private-public: businesses, residential, parks and recreational space, theatres and arts, marina
Type of traffic	Pedestrian and high-intensity vehicle traffic	Pedestrian, recreational, moderate- intensity vehicle traffic, light-rail transit

A Review of Urban Tree Performance

The goal of this review was to develop a multidisciplinary assessment framework for NBS projects using trees as the unit of assessment. While the review is not exhaustive or systematic, it is informative, with the goal of reviewing the many factors that influence tree-performance at both the scale of individual trees, and at the streetscape scale of a project. We include factors that could be used both as proxies to understand, and as variables to explain tree performance (Figure 3; Table 2). Each of the sub-sections below represent a component of the final assessment framework.

Urban Tree Ecology

Urban tree ecology, generally grounded in forest ecology, determines where trees can grow and in which cities (Miller et al. 2015). There are some important differences between the ecology of urban forests and the ecology of hinterland forests. For instance, while the realized climatic niche of many tree species can predict the realized climatic niche of urban tree populations, the niche of urban trees is generally wider (Kendal et al. 2018). In addition, urban forests are frequently highly heterogeneous in terms of tree arrangement, composition, and human-tree interactions (Rowntree 1984). This means that tree species distribution does not usually reflect natural patterns, since some trees species are either preferred more than others, or are able to perform better under urban conditions, such as drought (Gillner et al. 2016), high soil salinity (Cekstere & Osvalde 2013), and restricted soil volumes (Sjöman et al. 2012), among many others. Tree species that are tolerant of drought, high salinity, and air pollution, as well as aesthetically-pleasing trees, are generally over-represented in urbanized spaces (Jenerette et al. 2016).

Tree Characteristics

Tree performance at the individual level is mostly indicated by tree growth, canopy condition, and damage. Lower tree growth rates usually mean a higher probability of tree mortality (Gillner et al. 2013). An ideal tree performance examination will capture tree-growth data continuously using metrics related to the physical characteristics of trees, such as diameter at breast height (DBH), tree height, canopy density, or tree-ring growth (Jutras et al. 2009). However, in some cases, only cross-sectional, historical data on tree condition may be available. These data are usually captured qualitatively using ratings of tree-foliar condition, such as classifying trees according to ratings of "good", "fair", "poor", or "dead", or quantitatively using estimated percent crown dieback as an indicator (Nowak et al. 2008) or indices based on forest assessments (Johnstone et al. 2013). These measures are ubiquitous in municipal urban-forest inventories and, in many cases, are the only available metrics to describe historical tree performance (IUFRO et al. 2010). Like condition, metrics of tree damage, such as trunk wounds, broken branches, and leaf chlorosis, are usually qualitatively assessed (e.g., presence/absence, or rank order), but can be vital in giving an indication of how trees perform (Lu et al. 2010, Kenney & Puric-Mladenovic 2014). Other important tree characteristics, such as species and age, can also dictate some of the variation in tree performance patterns. The abundance of metrics that can be used to describe tree characteristics indicates the complexity of evaluating tree performance in urban places (Table 2).

Tree Pests & Diseases

The presence of and level of infestation by a pest or a disease in urban trees is an important consideration when assessing tree performance. Many pests and diseases are species- or genus-specific, such as emerald ash borer affecting ash trees in North America (Poland & McCullough 2006); therefore, a single pest or disease may be considered in specific situations where vulnerable tree species are growing. Climate change may exacerbate the presence, abundance, or level of affectation caused by weather-dependent pests and diseases (Tubby & Webber 2010).

Soils

Soil provides the rooting medium and essential nutrients to above-ground growth of trees, and it can be used as an indicator of tree suitability and performance (Steenberg et al. 2017). The physical characteristics of urban soils often include high levels of compaction (Millward et al. 2011), which can hinder root development and water availability (Day et al. 2010). Soil texture can enhance or reduce the effects of compaction (Day et al. 2010). Soil availability can also influence tree performance, since reduced soil volumes can result in poor water drainage and holding capacity, limited nutrient availability, and inadequate mechanical support (Sanders & Grabosky 2014).

The chemical characteristics of urban soils are also important. Macronutrients, such as nitrogen and potassium, organic matter, and micronutrients, such as magnesium and calcium, are often in lower concentrations in urban soils, where these limited concentrations can slow tree growth (Cekstere & Osvalde 2013). Urban soils also commonly exhibit elevated levels of salinity and alkalinity (Hazelton & Murphy 2011). In northern climates, road salts used for de-icing can accumulate in urban soils (Cunningham et al. 2008), causing chlorosis and necrosis to leaves and buds, and increase osmotic stress for tree roots (Czerniawska-Kusza et al. 2004). High salinity and alkalinity can displace soil nutrients (Kargar et al. 2015), further deteriorating plant-suitable soil chemistry. Finally, trace metal contamination, a common feature of urban soils due to industrial activity, can affect tree performance negatively by influencing seedling development (Renninger et al. 2013), although several metals (e.g., zinc) are essential to plants in trace amounts (Nagajyoti et al. 2010).

Climate and Atmosphere

The microclimatic and atmospheric conditions of urban areas can influence tree mortality and decline. The temperatures in urban areas are usually higher than the surrounding rural areas (i.e., urban heat island (Arnfield 2003), and urban areas tend to suffer more from heat stress (Kershaw & Millward 2012). Such conditions make the urban environment less hospitable for cold-adapted tree species (Yang 2009) and can cause phenological responses in urban trees, such as early flowering (Roetzer et al. 2000). The elevated temperatures of urban areas can influence water availability and cause drought conditions for trees (Nitschke et al. 2017). Finally, air pollution such as particulate matter and ozone, can cause damage to tree leaves and reduce biomass production, though these effects are species-specific (Xu et al. 2015).

Built Environment

The built environment of the urban landscape can influence the environmental conditions in which urban trees grow. The geometry and density of buildings affects both the irradiation essential for photosynthesis and plant growth, and the microclimate of urban areas (Oke 1987). Although many tree species can adapt to this low light environment (Harris & Bassuk 1993), a reduction of direct sunlight hours can affect urban tree growth (Jutras et al. 2010). Moreover, the built environment can exacerbate the effects of a hot and dry urban microclimate on trees, as reviewed above. Trees that are surrounded by pavement and buildings are usually affected by heat stress and reduced water availability (Fahey et al. 2013). Finally, the built environment can also reduce habitat quality or promote negative human-tree interactions. Proximity of a tree to the street curb, the level of exposure to high-traffic settings, the presence of tree guards, the type of planting pit, vandalism, among many other factors, can be useful for measuring the influence of the built environment on tree performance (Jutras et al. 2010, Lu et al. 2010, Roman et al. 2014, Mullaney et al. 2015).

Tree Planting, Care, and Maintenance

Technical maintenance factors, such as time of planting (Sherman et al. 2016), inadequate pruning (Miller et al. 2015), and soil fertilization practices (Harris et al. 2008), can influence tree performance at the scale of a tree-planting project (Figure 3). In addition, nursery stocking and practices can restrict the availability of certain tree species (Polakowski et al. 2011), and the way trees are grown in a nursery can influence post-transplant survivorship and performance (Allen et al. 2017). While urban-tree maintenance, such as adequate pruning, is an important determinant in how trees perform overtime (Miller et al. 2015), this is not only an activity carried out by professional practitioners. Citizen-led maintenance can also influence tree survival. For instance, community-based watering regimes can improve the survivorship of young trees (Mincey & Vogt 2014).

Social Characteristics of the Urban Space

Despite the long list of ecological, environmental, and technical factors that determine urban-tree performance, humans, acting individually or socially, can influence this performance immensely. The social characteristics of an urban space, such as ownership and income level, may determine street maintenance and, in turn, influence tree mortality and decline (Vogt et al. 2015). These issues may determine the level of buy-in of a community towards tree planting (Rae et al. 2010). This can, in turn, influence community-based stewardship, defined here as the action taken by people in the wider community to assume responsibility for their urban forest. This stewardship can expand resources for tree care (Vogt & Fischer 2014) and help plant or maintain trees in overlapping ownership regimes (Roman et al. 2015). Stewardship is achieved either through formal co-management agreements for tree care and maintenance (see above), or through increased volunteerism, which is when urban citizens offer their time and skills to tend to or monitor their city trees (Moskell et al. 2010, Boyce 2010) (Table 2; Figure 3).

Human Decisions and Project Governance

Human decisions are the most important when it comes to directing the management of urban forests and trees (Nowak 1993). The concept of governance can help us understand how decision-making by different stakeholders can shape the reality of tree-related projects (Green et al. 2016). In urban forests, governance operates through public, civil, and private organizations, which come together to direct human action toward common goals using hybrid, adaptive, network, and co-managing modes of decision-making (Lawrence et al. 2013).

Human decisions and project governance are relevant to tree performance because they define: 1) the policy environment; 2) the mechanisms of engagement, leadership, and knowledge transfer between stakeholders; and 3) the level of public participation. Policy influences management frameworks, and ideally, stronger street-tree policies mean better urban forest outcomes (Galenieks 2017). For instance, the City of Toronto's Green Standard now requires minimum soil volumes for landscape plans (City of Toronto 2017). Yet, the mere existence of standards or tree-protection bylaws may not necessarily translate into losing fewer trees to urban development (Conway & Urbani 2007). Institutional leadership (Mincey et al. 2013), adaptive management (Green et al. 2016), active communication among stakeholders and knowledge sharing (Janse & Konijnendijk 2007) can often result in better-managed greening projects. The influence of technical stakeholders, such as municipal urban forestry departments, can influence tree performance by prompting critical technical choices, such as species selection (Conway & Vander Vecht 2015). While community preferences for tree species can influence urban forest structure in individual or grouped yet confined private areas (Avolio et al. 2015), tree-species selection and urban forest structure in public spaces reflects deeper ecosystem values operating at a broader social scale (Ordóñez et al. 2017). Finally, public participation can legitimize decisions, increase information flow between the experts and the non-experts, reduce delays in decision-making, and guide management towards social justice and equity (Danford et al. 2014). The participation of marginalized groups (e.g., racialized, low-income) is also vital, since these are usually the groups that live in areas with fewer urban trees (Pham et al. 2012).

Refining the Framework

The complex and polycentric governance of urban nature necessitates the engagement of multiple stakeholders in the development of meaningful planning processes and projects (Pahl-Wostl, 2002; Lawrence et al. 2013). The same is arguably true for tool development, such as the framework presented in this paper, if they are to be actually adopted by these same stakeholders. Stakeholder engagement contributed to the research project design in the case studies and the development of our final framework. The process took the form of continued dialogue and correspondence throughout project planning and design, implementation, and monitoring in the form of in-person meetings, phone conversations, and email. Starting in the Spring of 2015, we held at least one-to-one and face-to-face meeting with each stakeholder and continued to communicate with them thereafter via meeting, phone, or email. At each of these meetings we shared the performance framework with the stakeholder and received some feedback from them on measures and parameters to consider. We held two formal workshops during 2017 to present the preliminary and final results of our work and invited all stakeholders to take part of these events. Stakeholders engaged included municipal government (i.e., urban forestry department and street works in the City of Toronto), landscape architects (i.e., firms involved in the design of the Bloor Street and Queens Quay revitalizations), architects, engineers (i.e., subcontractors in charge of hydrological design and monitoring), arborists (i.e., subcontractors in charge of tree maintenance), property managers in the project areas, and a structural soil cell design firm.

The framework, based on the literature review (see literature review section above) and early dialogue with project stakeholders, was designed around likely causes of the Bloor Street tree failures. The final framework includes both indicators that were assessed in the two case studies (i.e., tree characteristics and soils) and those that were added afterwards based on research findings and identified gaps in the assessment and monitoring (e.g., socio-demographics). The stakeholder engagement process for this study was constrained by the tight timelines of two complex public works projects (i.e., Bloor Street tree replacements and Queens Quay revitalization). While our stakeholder engagement was less formal or structured than in an ideal scenario (e.g., formalized schedule of workshops, elicitation tools, and list of stakeholders), it was centered on early and honest solicitation of stakeholders with a clear communication of our objectives and how their feedback will be used (Glicken, 2000).

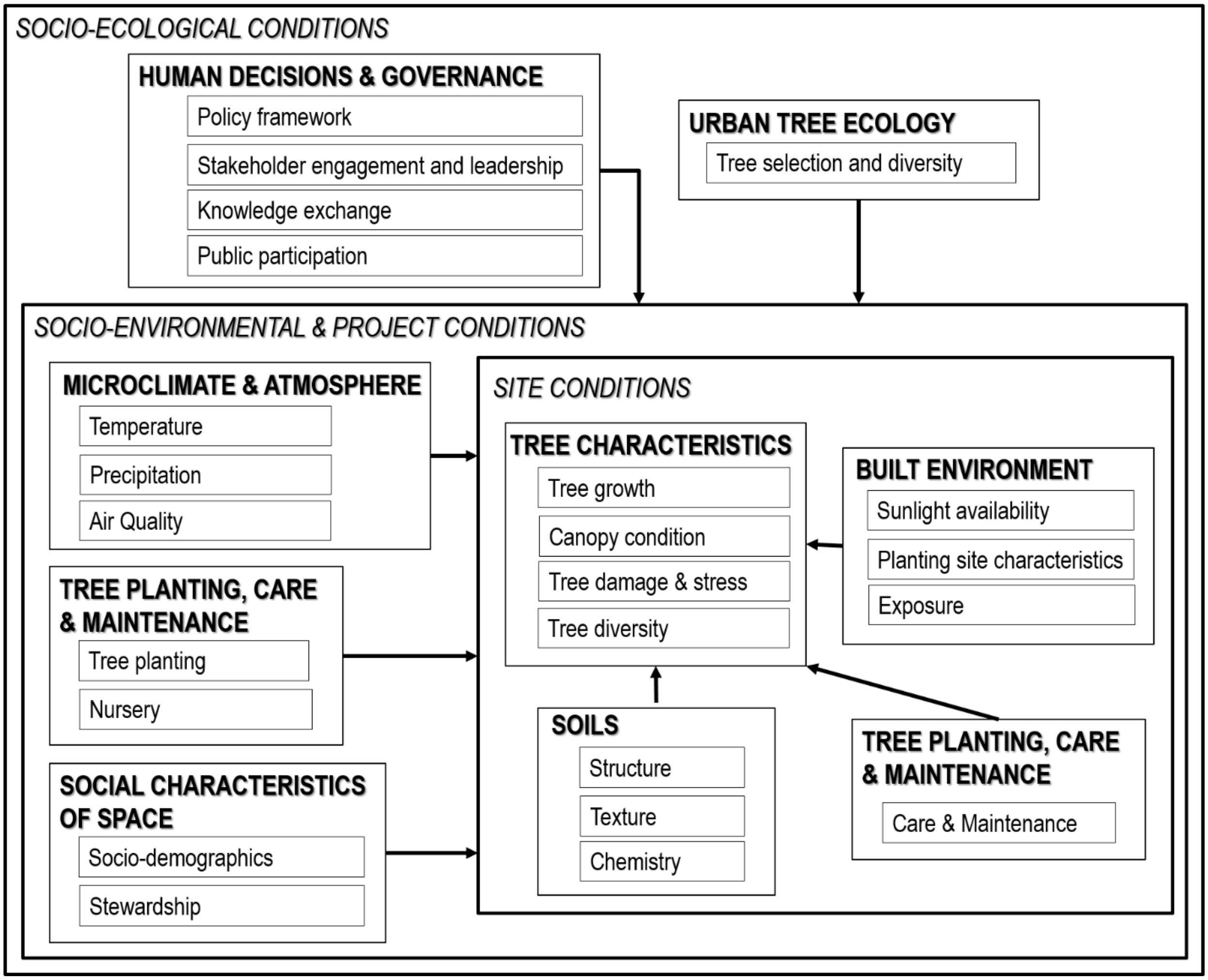

Figure 3. Model of the interaction of performance indicators for trees in the context of revitalization projects as developed for the Bloor Street and Queens Quay case studies, indicating examples of parameters and associated indicators (see also Table 2).

Table 2. Performance indicators for trees in the context of revitalization projects as developed for the Bloor Street and Queens Quay case studies, indicating examples of parameters, associated indicators, and examples of measures and types of data (n.a. refers to not assessed in the Bloor Street and Queens Quay contexts).

Parameter	*Indicator*	*Example of Measures and Types of Data*	*Examples of how these were used at Bloor Street & Queens Quay*	
			Type of Measure	*Types of Data*
Built Environment	Sunlight availability	Sunlight exposure or potential maximum sunlight availability in hours/day or across the growing season	Hours of sunlight for March 20 (spring equinox)	Numeric (hr)
			Hours of sunlight for June 20 (summer solstice)	Numeric (hr)
			Range hours of sunlight	Numeric (hr, maximum value minus minimum value)
			Average hours of sunlight	Numeric (hr)
	Micro-climate	Average °C/day, month, or year; evapotranspiration; evaporation; proximity to buildings (distance and orientation)	n.a.	n.a.
	Planting site characteristics	Type of planter; presence of metal grates or tree guards; land use; building density; conflict with overhead wires, power lines, other trees, or traffic; ground surface cover (e.g., soil, grass, asphalt, concrete)	Type of Planter	Categorical, binomial (Bed/pit)
	Exposure	Distance to the curb (m); distance to green space; distance to road intersection and type of intersection; type of traffic (e.g., car/pedestrian)	Side of the street	Categorical, binomial (South/North)
			Nearest type of road intersection	Categorical, binomial (minor/major)
			Distance to nearest road intersection	Numeric (m)
			Distance to nearest light-rail transit stop	Numeric (m)
Climate and Atmosphere	Temperature	Average °C/day, month, or year; extreme heat (e.g., Extreme Heat Factor); growing season length (e.g., Growing Degree Days)	Extreme Heat Factor (EHF) *	Numeric, index (product of the difference between 3-day average temperatures and the highest 3-day average based on data from the nearest weather station)
			Growing Degree Days (GDD)	Numeric, index (residuals when the daily average temperatures exceed 10°C based on data from the nearest weather station)

* See Nairn and Fawcett, 2015

Table 2. *Continued*

Parameter	*Indicator*	*Example of Measures and Types of Data*	*Examples of how these were used at Bloor Street & Queens Quay*	
			Type of Measure	*Types of Data*
Climate and Atmosphere	Precipitation	Rainfall in mm/day, month, or year; precipitation index (e.g., Standardized Precipitation Index)	Standardized Precipitation Index (SPI)	Numeric, index (likelihood that a given month received the recorded amount of precipitation based on historical averages from nearest weather station)
	Air quality	Amount of pollutants/day, month, or year (e.g., PM5, PM10, NOx, SOx, or O3, in mg or ppm)	n.a	n.a
Human Decisions & Governance	Policy framework	Existence of tree-protection bylaws; management plan; tree-species prioritization; planting environment specifications; adaptive management	n.a.	n.a.
	Stakeholder engagement and leadership	Degree of participation of urban foresters, engineers, architects and urban planners, volunteers, and non-professional citizen groups	n.a.	n.a.
	Knowledge exchange	Mechanisms of knowledge dissemination (e.g., open-houses, reporting, meetings, etc.); communication channels (i.e., direct, indirect, etc.)	n.a.	n.a.
	Public participation	Participation of residents or citizens (not as stakeholders); participation of marginalized groups (e.g., racialized, immigrants, LGBTQ)	n.a.	n.a.
Social Characteristics of the Urban Space	Socio-demographics	Ownership regime (e.g., public, private); income-level of the space of residents; education level of residents; tenancy or ownership	n.a.	n.a.
	Community-based stewardship	Care and maintenance agreements with community; characteristics of volunteers (e.g., experience, number of participants)	n.a.	n.a.

Table 2. *Continued*

Parameter	*Indicator*		*Example of Measures and Types of Data*	*Examples of how these were used at Bloor Street & Queens Quay* *Type of Measure*	*Types of Data*
Soils	Structure		Compressibility of soil (in MPa); Volume of planting pit (in m^3)	Penetrability of the soil at different depths (0 to 450 mm)	Numeric (MPa)
	Texture		% by mass of sand, silt, and clay particles	Composition of sand, silt, and clay soil particles	Numeric (% by weight)
	Chemistry	Nutrient content	Potassium, nitrogen, phosphorus, calcium, magnesium content (in ppm), and organic matter content (% by mass)	Organic matter, Calcium, Magnesium, Phosphorus, Potassium, and Nitrogen content	Numeric (% by mass, or ppm; from samples collected at selected time of year)
		Salinity	Sodium, calcium, magnesium content (in ppm), and electro-conductivity (EC; in dS/m)	Sodium and electro-conductivity	Numeric (ppm and dS/m; from samples collected at selected time of year)
		Alkalinity	Calcium content (in ppm) and pH	Calcium content and pH	Numeric (ppm and pH; from samples collected at selected time of year)
Tree Characteristics	Tree growth		DBH (cm), crown width (m), tree height (m), basal area derived from dendrochronological data (cm^2)	Diameter of tree trunk (DBH)	Numeric (cm; at selected time of year)
				Tree height	Numeric (m; at selected time of year)
				Tree crown width	Numeric (m; at selected time of year)
				Basal Area Increment (BAI)	Numeric (cm^2; estimated from tree rings measured from high-resolution images of sanded trunk cross-sections)
	Canopy condition		Dead or alive; qualitative assessment of foliar condition (e.g., categorical variables for dead, poor, fair, and good condition); quantitative assessment of foliar condition (% of canopy)	Tree-foliar condition	Ordinal, 0 – 3 scale, selected time of year (where 0 = dead, 1 = poor, 2 = fair, and 3 = good foliar condition)
				Chlorophyll content of leaves	Numeric (SPAD units, using SPAD502Plus Chlorophyll Meter, Konica Minolta Inc., 2016)
	Damage and stress		Presence/absence, or rank order of trunk wound or trunk cracks, bark peel, broken branches, leaf chlorosis, sucker growth, dieback, rot, cavity, and/or unnatural lean	Mortality	Categorical, binomial (alive/dead)
				Tree damage	Categorical, binomial (yes/no presence of torn limbs, scars, dieback, pruning scars, appreciable cracks, and appreciable bark peel)

Table 2. *Continued*

Parameter	*Indicator*	*Example of Measures and Types of Data*	*Examples of how these were used at Bloor Street & Queens Quay* *Type of Measure*	*Types of Data*
Tree Planting, Care, and Maintenance	Tree planting	Size and age at planting (e.g., calliper, whip); planting technique (e.g., ball and burlap, container, bare root); soil fertilization/mulching	Estimated year of tree planting or death	Categorical (year; at selected time of year as based on contractual reports and Google Street View® images)
			Estimated number of tree plantings or deaths on planting site	Numeric (as based on contractual reports and Google Street View® images)
			Years growing on site	Numeric (as based on contractual reports and Google Street View® images)
	Nursery	Type and location of nursery; production system used	n.a.	n.a.
	Care and maintenance	Monitoring frequency; pruning frequency; presence of watering bags; maintenance practices of site (e.g., cleaning, de-icing salt application); frequency and intensity of human-tree interactions (e.g., dog visits, securing bikes)	Presence of watering bags	Categorical, binomial (yes/no; at selected time of year based on Google Street View® images)
			Average number of dog visits at site	Numeric (as based on observations made on selected days and timings)
			Average number of dog walkers in a $100m^2$ radius from site	Numeric (as based on observations made on selected days and timings)
Urban Tree Ecology	Tree selection and diversity	Species and age (in years) of trees; tree preferences and/or desired benefits	Species name	Categorical (Taxonomy: *gen. sp.*)

DISCUSSION & FINAL REMARKS

NBS projects are being deployed faster than they are being studied, and researchers must work quickly to understand how these projects influence not only urban ecological dynamics, but transform the social benefits provided by nature in cities. Developing case-specific performance indicators for such projects from the perspective of urban nature is a useful way to advance this area of research. The Bloor Street and Queens Quay projects provided a unique learning opportunity for understanding how performance of an NBS project can be assessed through the lens of the natural element, and in a case-specific context. The performance framework emanating from the Bloor Street and Queens Quay case studies has been useful to assess the performance of the natural elements in these contexts. The interested reader can find complementary information in Ordóñez et al (2018).

Assessing the performance of natural elements in case-specific NBS projects is conceptually and methodologically nuanced. Green infrastructure systems, which are usually part of NBS projects, can bring about new concerns for nature performance, specifically about soil contamination, urban-heat stress, and nature maintenance. To address these concerns, any assessment framework must be based on a comprehensive and multi-dimensional suite of indicators that could explain how urban-nature performs in these new contexts. To respond to the ecological and social realities of urban ecosystems, realities that are better understood at finer spatial scales (Cadenasso & Pickett, 2008), such as at the scale of neighbourhoods (Steenberg et al. 2015), these indicators must operate at both the individual-organism level and the ecosystem level (Roman et al. 2014; Table 2). Also, NBS projects are inherently interdisciplinary (Kabisch et al. 2016), and assessment frameworks must reflect this. Finally, a single project may not provide enough variability to assess performance effectively, so only by comparing different NBS projects will we be able to understand the performance of natural elements in these contexts.

Our performance framework (Table 2) is innovative in several ways. First, it specifies not just the parameters but also the measures and data that could be used to assess tree performance in the context of NBS projects taking the natural element as a unit of analysis. Second, it goes beyond the standard measures of some of these parameters. For instance, besides standard measures of tree canopy condition and tree damage, which are typical in many tree-performance assessments, the framework includes the use of tree trunk samples for a deeper dendrochronological analysis of tree growth. It also includes ways to collect historical tree-condition data through a combination of techniques, including: 1) internal and contractual tree-assessment reports; 2) tree assessment reports done independently by the City of Toronto; and 3) interpretation of close-range digital images from Google StreetView® (Table 2; see Berland & Lange, 2017). Additionally, built-environment factors that are the most relevant to the location and spatial distribution of the trees were collected, such as modelling the shadow patterns of the street to estimate sunlight availability for each planting site (Figure 1; Table 2). An important issue at many tree-planting sites is the high-traffic of dog walkers. However, there are no standards to assess the influence of dogs on tree-performance. To compensate for this, and in our framework, we adapted methods used in bicycle traffic studies (see Schasberger et al. 2012) and visitor behavior in parks (see Zhai & Korça-Baran 2017) to capture dog-traffic data through systematic observation, considering variability of traffic across weekdays and times of day (Table 2).

While case-specific indicators are useful, some indicators may be more context-specific than others, thus reducing their utility. For instance, dendrochronological data are useful for describing tree growth, but these data may not always be available due to the impracticality of collecting tree trunks. In such cases, other continuous biometric measures of trees, such as DBH or tree-height, can also be used. However, these data must be collected continuously over a long time-period to be useful (Jutras et al. 2010), thus evidencing the need for constant monitoring of NBS projects. Moreover, researchers should be careful when developing measures for built-environment indicators, since these could comprise an endless list of features of the space with many of these measures potentially having no validity elsewhere (Lu et al. 2010). Added to this complexity is the fact that the technology associated with NBS projects is tailored to the specific characteristics of the space (Page et al. 2015). In short, there must be a balance between the specificity and generalizability of NBS project performance indicators.

Advancing performance frameworks for NBS projects will depend on how we deal with the less measurable social indicators, including human decisions (e.g., timing of tree plantings, watering, species selection, public participation), and the social characteristics of the space (e.g., citizen stewardship). In our framework (Table 2), factors related to the parameters, Social Characteristics of the Urban Space and Human Decisions and Project Governance, were difficult to quantify in the context of our projects. In this case, data were simply not available due to proprietary concerns, or the stakeholders involved were not be able to provide enough specificity about the indicators included in the framework, or we simply have not had enough time to assess the feasibility of these indicators. Nonetheless, while such indicators are not easily quantified, researchers can compensate for this by establishing positive and close relationships with the stakeholders of such projects to help them understand how these factors may play a role in urban-nature performance. Interested researchers can evaluate these factors through qualitative processes that can generate information about a wide range of issues, including institutional engagement, leadership, knowledge transfer, socialization of ideas, and coordination of conflicting priorities (Green et al. 2016). More formal and structured stakeholder processes can help make the best of this type of information (Glicken, 2000).

Finally, due to technological innovation (Green et al. 2016), changing environmental conditions, such as climate change (Lohr et al. 2014; Ordóñez et al. 2015; Brandt et al. 2016), and the increased attention being given to urban forests to address urban sustainability problems (Willis & Petrokofsky 2017), we must reduce the uncertainty associated with urban forest performance by developing robust assessment frameworks (Steenberg et al. 2017). Many NBS initiatives still operate in unknown ground, and many of them will not perform as expected. In this context, it is useful to conceive NBS projects as real-life experiments (Felson & Pickett 2005). In some ways, understanding what we do with natural elements in cities, whether these are trees, grasses, or other types of biodiversity, could be useful to understand broader ecological dynamics, such as climate change (Lahr et al. 2018). As such, attaching measurable and case-specific performance indicators to these projects is useful not only to assess their effectiveness, but also for generating much needed data to answer bigger questions about natural dynamics in urban ecosystems. The performance assessment frameworks presented here (Table 2) can help inform these research procedures with the goal of minimizing uncertainty in the novel area of NBS-inspired urban revitalization.

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Title:
Developing Performance Indicators for Nature-Based Solution Projects in Urban Areas: The Case of Trees in Revitalized Commercial Spaces

Date:
2019

Citation:
Ordonez Barona, C; Grant, A; Andrew, M; Steenberg, J; Sabetski, V, Developing Performance Indicators for Nature-Based Solution Projects in Urban Areas: The Case of Trees in Revitalized Commercial Spaces, Cities and the Environment, 2019, 12 (1)

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