NRC Research Press

REVIEW

A conceptual framework of urban forest ecosystem vulnerability

James W.N. Steenberg, Andrew A. Millward, David J. Nowak, and Pamela J. Robinson

Abstract: The urban environment is becoming the most common setting in which people worldwide will spend their lives. Urban forests, and the ecosystem services they provide, are becoming a priority for municipalities. Quantifying and communicating the vulnerability of this resource are essential for maintaining a consistent and equitable supply of these ecosystem services. We propose a theory-based conceptual framework for the assessment of urban forest vulnerability that integrates the biophysical, built, and human components of urban forest ecosystems. A review and description of potential vulnerability indicators are provided. Urban forest vulnerability can be defined as the likelihood of decline in ecosystem service supply and its associated benefits for human populations, urban infrastructure, and biodiversity. It is comprised of (*i*) exposure, which refers to the stressors and disturbances associated with the urban environment that negatively affect ecosystem function, (*ii*) sensitivity, which is determined by urban forest structure and dictates the system response to forcing from exposures and the magnitude of potential impacts, and (*iii*) adaptive capacity, which is the social and environmental capacity of a system to shift or alter its conditions to reduce its vulnerability or to improve its ability to function while stressed. Potential impacts, or losses in ecosystem service supply, are temporal in nature and require backward-looking monitoring and (or) forward-looking modelling to be measured and assessed. Vulnerability can be communicated through the use of indicators, aggregated indices, and mapping. A vulnerability approach can communicate complex issues to decision-makers and advance the theoretical understanding of urban forest ecosystems.

Key words: urban forest, vulnerability, social–ecological system, ecosystem services, indicator.

Résumé : L'environnement urbain devient le milieu le plus commun dans lequel les gens passeront leurs vies. Les forêts urbaines, et les services écosystémiques qu'elles procurent, deviennent une priorité pour les municipalités. Quantifier et communiquer la vulnérabilité de cette ressource sont des initiatives essentielles afin de maintenir un approvisionnement constant et équitable de ces services écosystémiques. Nous proposons un cadre conceptuel théorique pour l'évaluation de la vulnérabilité des forêts urbaines qui incorpore les composantes biophysiques, bâties et humaines des écosystèmes forestiers urbains. On fournit une revue et une description des indicateurs de la vulnérabilité potentielle. La vulnérabilité des forêts urbaines peut être définie comme la probabilité d'une baisse de l'approvisionnement des services écosystémiques et des avantages associés pour les populations humaines, l'infrastructure urbaine et la biodiversité. Elle comprend *i*) l'exposition, ce qui désigne les stresseurs et les perturbations associés à l'environnement urbain qui influent négativement sur la fonction écosystémique, *ii*) la sensibilité, qui est déterminée par la structure de la forêt urbaine et qui prescrit la réponse du système à la contrainte d'expositions et l'ampleur des impacts probables et *iii*) la capacité d'adaptation, qui est la capacité sociale et biotique d'un système à changer ou à modifier ses conditions afin de réduire sa vulnérabilité et d'améliorer sa capacité à fonctionner sous le stress. Les impacts probables, ou les pertes d'approvisionnement de services écosystémiques, sont de nature temporelle et requièrent une surveillance rétrospective et/ou une modélisation prévisionnelle à être mesurés et évalués. La vulnérabilité peut être communiquée au moyen de l'utilisation d'indicateurs, d'un ensemble d'indices et de la cartographie. Une approche de vulnérabilité peut communiquer des questions complexes aux décideurs et faire avancer la compréhension théorique en matière des écosystèmes forestiers urbains. [Traduit par la Rédaction]

Mots-clés : forêt urbaine, vulnérabilité, système social et écologique, services écosystémiques, indicateur.

1. Introduction

The urban environment is quickly becoming the most common setting in which people worldwide will spend their lives (United Nations 2014). Urban areas are also growing in extent, as urbanization and urban expansion are occurring at a rate that exceeds human population growth (Alig et al. 2004). Municipalities and city residents are consequently directing their focus on maintaining and enhancing urban forest ecosystems and the array of beneficial ecosystem services they provide (Clark et al. 1997; Kenney and Idziak 2000). Urban trees and forests are consequently being recognized as a vital component in the overall sustainability of cities (Grove 2009; Duinker et al. 2015). Documented ecosystem services generated by the urban forest provide a diverse and substantial set of environmental, social, and economic benefits (Nowak and Dwyer 2007). These ecosystem services range from air pollution removal and urban heat moderation to increased real estate values and human health benefits (Ulrich et al. 1991; Nowak and Dwyer 2007; Donovan and Butry 2010). With this growing importance of urban forests to the majority of the global popula-

Received 29 February 2016. Accepted 23 August 2016.

J.W.N. Steenberg. Environmental Applied Science and Management, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada; Urban Forest Research and Ecological Disturbance Group, Department of Geography and Environmental Studies, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada.
A.A. Millward. Urban Forest Research and Ecological Disturbance Group, Department of Geography and Environmental Studies, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada.
D.J. Nowak. Northern Research Station, USDA Forest Service, 5 Moon Library, SUNY-ESF, Syracuse, NY 13210, USA.
P.J. Robinson. School of Urban and Regional Planning, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada.
Corresponding author: James W.N. Steenberg (email: james.steenberg@ryerson.ca).

 Published at www.nrcresearchpress.com/er on 24 October 2016.

tion, both researchers and communities are increasingly focusing on the qualification, quantification, and management of these ecosystem services.

However, the urban forest is a vulnerable resource. The dense human populations and the alteration and degradation of natural environments that characterize cities lead to harsh growing conditions, which make tree growth and forest establishment difficult (Nowak et al. 2004; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005). Moreover, there is diversity and conflict in how urban forests, and more broadly urban ecosystems, are defined, modelled, and managed (Konijnendijk et al. 2006). This is largely due to disciplinary divides (e.g., arboriculture, forestry, ecology, geography, urban planning) and the interdisciplinary nature of urban forests in general (Steenberg et al. 2015). Vulnerability science can provide a framework for integrating key intellectual contributions from these various disciplines while investigating the sustainability of ecosystem service supply from urban forests. For this paper, we define urban forests as the individual trees, forest stands, and associated biotic and abiotic components in a given urban landscape (Miller 1997; Kenney et al. 2011). Our definition also includes the influences of human populations and the built environment on urban forest structure and function (Konijnendijk et al. 2006), which aligns more with the modern ecosystem concept (Pickett and Grove 2009).

Forests in general are vulnerable to environmental change and altered disturbance regimes because the longevity and stationary nature of trees restrict or inhibit necessary adaptations to rapid change (Nitschke and Innes 2008; Lindner et al. 2010). Urban forests suffer additional vulnerability due to their setting in constantly changing, heterogeneous, and stressed urban environments that are frequently different from the environments in which most tree species have evolved (Alberti et al. 2003; Cadenasso et al. 2013). Much of the discourse on urban forests and trees in the city is centered on the effects of various stressors and disturbances on individual trees, with a prominent focus on street trees (e.g., Jutras et al. 2010; Roman and Scatena 2011; Koeser et al. 2013). There is a considerable knowledge gap around the combined effects of these stressors and their interaction with urban forest ecosystem structure, inclusive of the built environment and human population. There is a need to synthesize this existing body of research on urban forest stressors and disturbances in the broader context of ecosystem structure and function and ecosystem service supply.

The purpose of this paper is to adopt a vulnerability science approach to review and synthesize key contributions from disciplines that directly and indirectly address threats to urban forest ecosystems. We propose a theory-based conceptual framework for the assessment of urban forest vulnerability that integrates the biophysical, built, and human components of urban forest ecosystems. We also provide a review of relevant bodies of literature and subsequently identify potential vulnerability indicators that have been applied in past research. Lastly, we review various methods of assessing and analyzing vulnerability, with an emphasis on quantitative, indicator-based approaches. The applicability of vulnerability science for complex social–ecological systems and its capacity to shift research away from an impacts-only perspective make it a suitable approach for investigating the urban forest resource. With the complex nature of urban forest ecosystems, integrative approaches and tools for identifying potential losses in function or undesirable changes in structure can be highly valuable for guiding urban forest planning and management.

2. Vulnerability in social–ecological systems

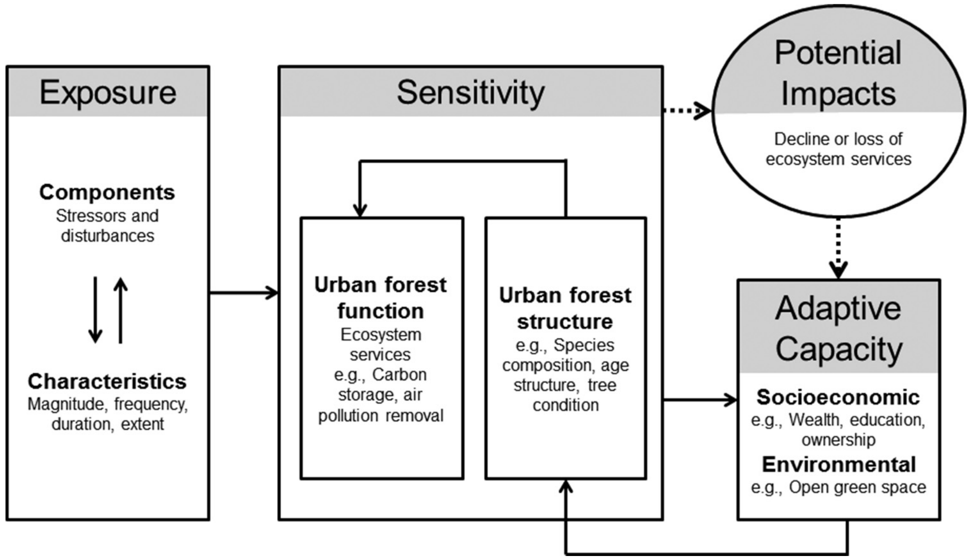
Social–ecological systems are multiscaled, dynamic systems whose structure and function are shaped by both biophysical processes and human institutions and activities (Berkes and Folke 1998). Most of Earth's ecosystems are influenced by human populations and social processes to some degree. The concept of social–ecological systems is as much a framing mechanism for interdisciplinary research and environmental problem solving (Grove 2009; Binder et al. 2013). Correspondingly, the study of social–ecological systems often entails direct focus on linkages between social and ecological processes, the supply of natural resources and ecosystem services, and complex environmental problems (Binder et al. 2013). The latter focus on environmental problems (e.g., climate change) has created a logical intersection with vulnerability science (Turner et al. 2003*a*).

Vulnerability science is an increasingly used concept and method for approaching issues of sustainability and ecosystem service supply in social–ecological systems (Turner et al. 2003*a*; Schröter et al. 2005; Adger 2006; Eakin and Luers 2006; Lindner et al. 2010). Vulnerability can be defined in simple terms as "…the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or a stress/stressor" (Turner et al. 2003*a*, p. 8074). The concept of vulnerability has a long history within a diversity of disciplines, and there remains variability in terminology, concepts, and methodological approaches arising from the different lineages (Turner et al. 2003*a*; Eakin and Luers 2006; Cumming 2014). However, these divergences tend to be dependent on the research objectives of a given study (Eakin and Luers 2006). The important similarity is that vulnerability science shifts research away from just stressors and impacts towards a holistic view of the entire system (Luers et al. 2003; Adger et al. 2004).

The early roots of vulnerability research characterized it either as a lack of entitlement or as vulnerability to natural hazards, as described in the review by Adger (2006). The entitlements approach focused on social aspects of vulnerability, looking at variability in population characteristics that lacked access (i.e., entitlement) to natural resources or ecosystem services due to drought, disease, war, or other disasters (Sen 1984). While concepts from this background merged with modern definitions of vulnerability, they also diverged into separate areas looking at poverty and often overlooked biophysical processes (Adger 2006). The hazard-based approaches were rooted more in the physical sciences and were focused on risk, and examined environmental hazards as well as society's potential for loss (Burton et al. 1993; Eakin and Luers 2006). However, political ecologists argued that the hazard paradigm disregarded social elements, and did not address why certain marginalized populations were more vulnerable (Cutter 1996). Certainly, these definitions were not independent of each other (Adger 2006), and issues around natural hazards and underlying social vulnerabilities were bridged early on (Blaikie et al. 1994). More recently, there has been a growing consensus on conceptual approaches to vulnerability research that have converged within the arena of global environmental change and sustainability science (Luers et al. 2003; Turner et al. 2003*a*; Metzger et al. 2006, 2008; Lindner et al. 2010). Vulnerability assessment has since become a core component of several international, collaborative environmental change investigations, including the Intergovernmental Panel on Climate Change (IPCC) assessment reports and the Millennium Ecosystem Assessments.

Modern definitions of vulnerability identify it as an element of social–ecological systems that is an outcome of multiple and interacting social and biophysical properties across spatial and temporal scales (Metzger et al. 2006). Turner et al. (2003*a*) proposed one of the more widely accepted conceptual frameworks for understanding the vulnerability of social–ecological systems. They argue that the vulnerability of a system is comprised of exposure, sensitivity, and resilience/adaptive capacity. Exposure refers to the magnitude, frequency, duration, and spatial extent of stressors and disturbances that affect a system (Burton et al. 1993). Sensitivity is the relative level of response by a system to stressors or disturbances, and is determined by intrinsic characteristics of the system itself (Turner et al. 2003*a*). Adaptive capacity is the

Fig. 1. Conceptual framework of urban forest ecosystem vulnerability, adapted from Turner et al. (2003*a*).



capacity for a system to shift or alter its conditions to reduce its vulnerability or to improve its ability to function while stressed (Adger 2006).

Some studies investigating system vulnerability to environmental change make distinctions between adaptive capacity and resilience (Adger et al. 2004; Adger 2006), while others appear to simply substitute resilience with adaptive capacity (Luers et al. 2003). Adger (2006) and Miller et al. (2010) speak to the compatibility and indeed commonality between resilience and adaptation, though others caution against the unclear and incompatible use of vulnerability, adaptive capacity, and resilience terminology (Gallopin 2006). Gallopin (2006) suggests that resilience and adaptive capacity are indeed subsets of the overall coping capacity of a system under stress. Resilience is also gaining popularity as an approach to understanding urban social–ecological systems (Miller et al. 2010), which will be discussed further in Section 5. However, most recent studies investigating vulnerability to environmental change, including ecosystem service vulnerability, adopt the adaptive capacity terminology (Schröter et al. 2005; Metzger et al. 2006, 2008; Lindner et al. 2010; Ordóñez and Duinker 2014). The Turner et al. (2003*a*) framework of vulnerability, and similar derivatives, has been successfully applied to a variety of social–ecological systems in the context of environmental change, including agricultural systems (Luers et al. 2003), Arctic populations and resource extraction (Turner et al. 2003*b*), and forests and ecosystem service supply (Metzger, et al. 2006, 2008; Lindner et al. 2010). In this paper, we adapt and expand this framework for application in urban forest ecosystems.

3. Urban forest vulnerability framework

Developing a conceptual framework of vulnerability is an important first step prior to the identification of specific metrics or indicators (Adger et al. 2004). The framework of urban forest vulnerability developed for this study (Fig. 1) builds on the widely used approach introduced by Turner et al. (2003*a*). In their conceptualization of vulnerability in coupled human–environment systems (i.e., social–ecological systems), they propose a local-level framework comprised of exposure, sensitivity, and resilience with external and multiscale (e.g., local–global) linkages. Our framework also incorporates concepts from the Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM) research (e.g., Schröter et al. 2005). The ATEAM project was an international, interdisciplinary research collaboration funded by the European Commission with the purpose of identifying and assessing global change impacts on ecosystem service supply (Schröter et al. 2005; Metzger et al. 2006). Their quantitative, spatially-explicit vulnerability framework was applied by Metzger et al. (2006, 2008) and Lindner et al. (2010) to investigate the vulnerability of ecosystem services in Europe. Lastly, our framework incorporates novel elements of vulnerability unique to urban forest ecosystems that are described throughout the remainder of this section.

We define urban forest vulnerability as the likelihood of decline in ecosystem service supply and its associated benefits for human populations, urban infrastructure, and biodiversity. Building on the aforementioned existing frameworks, urban forest vulnerability is similarly comprised of exposure, sensitivity, and adaptive capacity. Potential impacts are an outcome of system exposure and sensitivity and are described as losses or undesirable changes in ecosystem service supply. For example, a city street lined entirely with ash species (*Fraxinus* spp.) will be more sensitive to an exposure to the emerald ash borer (*Agrilus planipennis*) than a street with greater species diversity. The potential impacts of this exposure to stress are widespread dieback and mortality, corresponding to a loss of the ecosystem services provided by these trees.

Our definition and conceptual framework are derived from research investigating vulnerability to global environmental change in social–ecological systems (e.g., Turner et al. 2003*a*; Schröter et al. 2005). Where this study differs is that the stressors and disturbances of interest are not climatic variables, but rather those associated with densely settled urban environments. These might include typical forest disturbances (e.g., wind damage), but also urban development, alterations to the built environment, and social processes of cities (e.g., policy development and management intervention). However, the underlying concern is the decline or loss of system function in response to persistent and (or) sudden change (Schröter et al. 2005; Metzger, et al. 2006, 2008; Lindner et al. 2010). The following sections describe the conceptual framework of urban forest vulnerability. We also review and summarize several key determinants of urban forest structure and function from the literature that may represent suitable indicators of vulnerability (Tables 1, 2, and 3).

3.1. Exposure

Exposure refers to the types, magnitude, frequency, duration, and extent of stressors and disturbances that negatively affect system functioning (Burton et al. 1993; Turner et al. 2003*a*). Urban forest exposure therefore refers to the stressors and disturbances associated with the urban environment that negatively affect tree

Table 1. Potential indicators of urban forest exposure.

Category	Indicator	Description	Source
Built environment	Land use	Land uses have variable intensities of use, population densities, and building intensities, and are a broad-scale indicator of environmental quality and of potential social stressors Commercial, industrial, utility, and transportation land uses tend to have lower canopy cover and higher mortality Residential and institutional land uses tend to have higher canopy cover and lower mortality rates Parks, cemeteries, and other green spaces typically represent the most forested areas within cities	Nowak et al. 2004; Jutras et al. 2010; Lu et al. 2010; Lawrence et al. 2012; Nowak et al. 2013*b*; Steenberg 2015
	Population density	The density of people in a geographic unit is a broad-scale indicator of environmental quality and the potential for social stressors on trees as densities increase	Tratalos et al. 2007; Troy et al. 2007; Landry and Chakraborty 2009; Pham et al. 2013; Grove et al. 2014; Steenberg 2015
	Light availability	Low light availability limits photosynthetic activity and plant growth	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Jutras et al. 2010; Lawrence et al. 2012
	Building intensity	Building intensity refers to the density and relative size of buildings in an area and is a broad-scale indicator of growing space, light availability, and microclimate	Forsyth 2003; Konijnendijk et al. 2005; Tratalos et al. 2007; Troy et al. 2007; Pham et al. 2013; Grove et al. 2014; Steenberg 2015
	Building height	The height of surrounding buildings influences light availability and microclimate	Konijnendijk et al. 2005; Landry and Chakraborty 2009; Pham et al. 2013; Steenberg 2015
	Building type	Building type is a finer-scale metric than land use and indicates available growing space, land use intensity, and overall environmental quality	Konijnendijk et al. 2005; Tratalos et al. 2007; Landry and Chakraborty 2009; Lu et al. 2010; Pham et al. 2013; Steenberg 2015
	Conflict with infrastructure	Conflicts with infrastructure, especially overhead utility wires, frequently lead to excessive pruning and premature tree removals	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Jutras et al. 2010; Steenberg 2015
	Distance from nearest building	Trees with shorter distances from buildings tend to have less growing space and more conflicts with infrastructure	Konijnendijk et al. 2005; Jutras et al. 2010; Steenberg 2015
	Distance from street	Trees with shorter distances from streets tend to have a higher exposure to pedestrian and vehicular traffic and pollution associated with roadways (e.g., de-icing salts)	Konijnendijk et al. 2005; Jutras et al. 2010; Roman and Scatena 2011; Steenberg 2015
	Imperviousness	Impervious surfaces limit the availability of space for tree establishment and growth, restrict water infiltration into soils, and increase urban temperatures	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Tratalos et al. 2007; Lu et al. 2010; Steenberg 2015
	Site size	Site size can restrict both above- and below-ground tree growth and is often an indicator of future conflicts with infrastructure	Trowbridge and Bassuk 2004; Lu et al. 2010; Koeser et al. 2013; Steenberg 2015
	Site type	The type of site where trees are established is influential on its overall level of exposure to social and physical stressors (e.g., higher exposure in sidewalk tree pits versus wide grass medians)	Trowbridge and Bassuk 2004; Jutras et al. 2010; Lu et al. 2010; Roman and Scatena 2011; Steenberg 2015
	Street width	Wider streets are indicative of higher stress from the built environment, especially vehicular traffic and associated pollutants	Jutras et al. 2010; Roman and Scatena 2011; Steenberg 2015
Biological stressors	Signs of infestation	Trees often have signs (e.g., leaf wilting, exit holes in bark) when infested with insects and pathogens, which can frequently be identified and differentiated in the field	McBride and Jacobs 1979; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Laćan and McBride 2008; Dukes et al. 2009; Herms and McCullough 2014
	Known existing infestations	Insects and pathogens that are identified can be used to estimate future risk for trees and adjacent areas, based on known forest composition and structure	McBride and Jacobs 1979; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Laćan and McBride 2008; Dukes et al. 2009; Herms and McCullough 2014

Table 1 (*concluded*).

Category	Indicator	Description	Source
Social stressors	Construction	Construction activities frequently damage trees and soils, especially root systems during excavations	Hauer et al. 1994; Trowbridge and Bassuk 2004; Koeser et al. 2013; Tardieu et al. 2015
	Pollution	Pollution is a common occurrence in urban environments, including emission-related air pollution, acid rain, and soil and surface water contamination, and is a source of stress for trees	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Zimmerman et al. 2005; Sitch et al. 2007
	Poor management	Poor management can physically damage trees (e.g., improper pruning) and affect their future growth and longevity (e.g., species selection and planting location)	Gilbertson and Bradshaw 1985; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Lu et al. 2010
	Vandalism	Vandalism (e.g., torn limbs) includes physical damage to trees, which is especially common among young street trees	Gilbertson and Bradshaw 1985; Lu et al. 2010; Steenberg 2015
	Vehicular/pedestrian traffic	High levels of traffic are associated with greater stress on urban trees, such as soil compaction and vandalism associated pedestrian traffic and air pollutants and de-icing salts associated with vehicular traffic	Trowbridge and Bassuk 2004; Jutras et al. 2010; Lu et al. 2010
Soils	Compaction	Loss of soil structure due to compaction and surface sealing can result in restricted root growth and degraded water infiltration	Craul 1992, 1999; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Jutras et al. 2010; Lu et al. 2010; Millward et al. 2011; Lawrence et al. 2012
	Contamination	Soil contamination from polluted runoff and de-icing salts alters soil pH and adversely affects plant growth	Craul 1992, 1999; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Zimmerman et al. 2005; Jutras et al. 2010; Millward et al. 2011; Lawrence et al. 2012
	Nutrients/organic matter	Low nutrient availability and organic matter content can result from leaf-litter removal and soil alterations, which adversely affects plant growth	Gilbertson and Bradshaw 1985; Craul 1992, 1999; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Zimmerman et al. 2005; Jutras et al. 2010; Millward et al. 2011; Lawrence et al. 2012
	Volume	Insufficient soil volumes restrict proper root growth and limit tree size at maturity	Craul 1992, 1999; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Millward et al. 2011
Climate	Temperature	Variable urban microclimates and heat islands stress and damage urban trees; global climate warming and increasing freeze-thaw events adversely influence tree condition	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Nitschke and Innes 2008; Lindner et al. 2010
	Precipitation	Both drought events and excessive precipitation adversely affect tree condition and cause mortality, especially among newly-established trees	Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Nitschke and Innes 2008; Lindner et al. 2010
	Storm events	Severe storm events can cause broken limbs and windthrow, with structural damage possible both above and below the ground	Hauer et al. 1993, 2011; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Sieghardt et al. 2005; Lopes et al. 2009; Staudhammer et al. 2011

condition and ecosystem function and (or) cause tree mortality, thereby reducing ecosystem service supply (Table 1). These might range from site-level environmental degradation (e.g., soil compaction, construction activity, and proximity to infrastructure; Koeser et al. 2013) to ecosystem-level stress from the combined effects of density and land use (Konijnendijk et al. 2005).

A great deal of the stress on urban trees can be associated with infrastructure and the built environment (Trowbridge and Bassuk 2004). The geometry and density of buildings and other urban structures affects the irradiation (i.e., sunlight available for photosynthesis and plant growth) and the microclimate of urban areas, which can negatively affect tree growth in heavily built-up areas (Jutras et al. 2010). Moreover, the extent of impervious surfaces (e.g., concrete and asphalt) restricts the land area available for urban forest establishment (Tratalos et al. 2007). Tree proximity to, and potential conflict with, infrastructure (e.g., overhead wires) can also be an indirect source of stress due to management practices associated with removing conflicts (Trowbridge and

Table 2. Potential indicators of urban forest sensitivity.

Category	Indicator	Description	Source
Structure	Diameter at breast height	Smaller, newly established trees have higher rates of mortality; Larger, mature trees are frequently in poor condition and sensitive to storm damage	Hauer et al. 1993, 2011; Staudhammer et al. 2001; Konijnendijk et al. 2005; Jutras et al. 2010; Lu et al. 2010; Roman and Scatena 2011; Lawrence et al. 2012; Koeser et al. 2013; Steenberg 2015
	Structural diversity	Even-aged, immature urban forests are sensitive to higher mortality rates; Even-aged, overmature urban forests are sensitive to widespread senescence, age-related decline, storm disturbance, and mortality	McBride and Jacobs 1979; Hauer et al. 1993, 2011; Staudhammer et al. 2001; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Laćan and McBride 2008; Lopes et al. 2009
Composition	Species	Tree species have variable sensitivities to urban conditions (e.g., air pollution, de-icing salts, restricted growing space; microclimate effects)	Hauer et al. 1993, 2011; Staudhammer et al. 2001; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Jutras et al. 2010; Lu et al. 2010; Lawrence et al. 2012; Koeser et al. 2013; Steenberg 2015
	Species diversity	Low species diversity, especially in localized pockets, increases sensitivity to species-, genus-, and family-specific pests and other stressors	McBride and Jacobs 1979; Hauer et al. 1993, 2011; Staudhammer et al. 2001; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Laćan and McBride 2008
Condition	Tree condition	Trees in poor condition are more sensitive to other stressors and disturbances and have higher rates of decline and mortality	Dreistadt et al. 1990; Hauer et al. 1993, 2011; Staudhammer et al. 2001; Konijnendijk et al. 2005; Lopes et al. 2009; Lu et al. 2010; Koeser et al. 2013; Steenberg 2015

Bassuk 2004). Land use has also been found to be highly influential on both tree mortality and ecosystem structure (Nowak et al. 2004), especially those with greater intensity of use and higher density (e.g., commercial and industrial land uses). Exposure to social stressors associated with both land use intensity and land management practices also cause intentional and unintentional physical damage to trees (Lu et al. 2010).

Pollution and environmental contaminants negatively affect tree biology and urban forest ecological processes. Despite the amelioration of urban air pollution by trees (Nowak and Dwyer 2007), tree physiology is simultaneously degraded by airborne pollutants. For example, tropospheric or ground-level ozone reduces plant photosynthetic rates and hinders biomass accumulation (Sitch et al. 2007). The chemical properties of urban soils are also commonly altered to varying degrees in cities. Soil contamination with heavy metals and de-icing salts, low nutrient availability due to leaf-litter removal, and altered pH levels are all common urban stressors of trees (Craul 1992; Zimmerman et al. 2005). However, the relationship between urban forest function and urban soils is far more complex. Soil degradation and loss is a frequent scenario in urban areas do to rapid development and poor practices like grading and topsoil removal (Craul 1999; Millward et al. 2011). Soils are vital for sustaining urban trees, as they provide the rooting medium and essential water and nutrients for above-ground growth (Craul 1992, 1999). Moreover, physical soil properties are often negatively affected by urbanization due to the loss of soil structure caused by compaction and surface sealing (Craul 1992, 1999). The loss of soil structure can result in restricted root growth and degraded water infiltration, hindering overall tree condition and growth (Hanks and Lewandowski 2003). Insufficient soil volumes to sustain proper root growth are also a common occurrence in land uses with an abundance of development and impervious surfaces (Trowbridge and Bassuk 2004).

Outside of a city's human population, the primary biological threats to urban trees are from insects and pathogens (Konijnendijk et al. 2005; Laćan and McBride 2008). Both urban and hinterland forests are subject to insects and pathogens. However, trees that are stressed, as many are in the urban environment, are more susceptible to infestation and decline (Armstrong and Ives 1995). Moreover, urban areas are frequently subject to invasive forest pests and diseases that have been introduced as a result of global trade and the warming climate (Dukes et al. 2009). A well-known example that decimated urban tree populations is the Dutch elm disease (*Ophiostoma novo-ulmi*), and more recently the emerald ash borer, which is currently afflicting ash populations in Canada and the United States (Herms and McCullough 2014). The frequency and severity of these biological invasions in urban areas is also projected to increase in the near future.

3.2. Sensitivity

Sensitivity is the degree of system response to forcing from a stressor or disturbance in the urban environment and determines the magnitude of potential impacts (i.e., loss of ecosystem services) in response to exposure (Turner et al. 2003*a*). Urban forest sensitivity is influenced by a variety of factors, including species composition, age structure, and tree condition (Table 2). Ecosystem, species, and genetic diversity are key determinants of urban forest sensitivity to insects and pathogens (Laćan and McBride 2008). Furthermore, trees in poor condition that are already under stress are more susceptible to the effects of insects and pathogens (Armstrong and Ives 1995). While urban forests tend to have higher species richness than pre-settlement forests, there is frequently poor spatial distribution of species diversity and a tendency for single-species dominance in localized pockets (McBride and Jacobs 1979; Nock et al. 2013). Moreover, tree species are highly variable in their tolerance to urban conditions and poor tree condition due to improper site selection is a common phenomenon (Trowbridge and Bassuk 2004).

Urban forest age and structural diversity are also an important component of sensitivity, as an abundance of overmature trees can result in widespread tree senescence and mortality in a short time period. Older trees and even-aged forests are also more susceptible to storm damage and windthrow (Mitchell 1995; Lopes et al. 2009). Conversely, younger and newly planted urban trees

Table 3. Potential indicators of urban forest adaptive capacity.

Category	Indicator	Description	Source
Social	Income	More affluent Individuals have more resources to invest in stewardship activities; Income is positively correlated with urban forest amenities across cities	Martin et al. 2004; Grove et al. 2006, 2014; Troy et al. 2007; Landry and Chakraborty 2009; Boone et al. 2010; Pham et al. 2013; Steenberg 2015
	Housing value	Housing value is often indicative of affluence, but also of property size and available space for tree establishment and growth	Troy et al. 2007; Boone et al. 2010; Grove et al. 2014
	Homeownership	Homeowners have direct legal control over the landscaping and management practices on their properties	Grove et al. 2006, 2014; Troy et al. 2007; Landry and Chakraborty 2009; Boone et al. 2010; Pham et al. 2013; Steenberg 2015
	Education	Higher education is associated with affluence and engagement in stewardship activities, and is positively correlated with urban forest amenities across cities	Troy et al. 2007; Boone et al. 2010; Pham et al. 2013; Steenberg 2015
	Stewardship	Local organizations, residents associations, and households that engage in stewardship activities contribute to the maintenance and enhancement of urban trees and forests	Martin et al. 2004; Konijnendijk et al. 2005; Troy et al. 2007; Boone et al. 2010; Lu et al. 2010; Lawrence et al. 2012
	Municipal policies	Municipal tree protection and conservation by-laws, strategic and operational management plans, and public education and outreach contribute to the maintenance and enhancement of the urban forest resource	Kenney and Idziak 2000; Trowbridge and Bassuk 2004; Konijnendijk et al. 2005; Conway and Urbani 2007
Environmental	Open green space	The amount of open green space is indicative of the total area available for tree establishment and urban greening initiatives	Konijnendijk et al. 2005; Grove et al. 2006, 2014; Tratalos et al. 2007; Troy et al. 2007; Landry and Chakraborty 2009; Pham et al. 2013; Steenberg 2015
	Existing tree canopy	Extensive tree canopy cover is indicative of an intact urban forest and higher levels of ecosystem service supply	Martin et al. 2004; Konijnendijk et al. 2005; Grove et al. 2006, 2014; Tratalos et al. 2007; Troy et al. 2007; Landry and Chakraborty 2009; Pham et al. 2013; Steenberg 2015
	Forested area	Continuous and naturalized forested areas have high levels of ecosystem service supply and require fewer management interventions	Nowak et al. 2004; Konijnendijk et al. 2005; Tratalos et al. 2007; Millward et al. 2011; Nowak and Greenfield 2012

have far higher associated mortality rates (Roman and Scatena 2011). Arguably, ecosystem-scale urban forest sensitivity to various urban stressors and disturbances is an understudied phenomenon.

3.3. Adaptive capacity

The adaptive capacity of a social–ecological system is its ability to function while stressed or to adapt its conditions to reduce vulnerability (Adger 2006). It is determined by both inherent environmental and social components (Lindner et al. 2010). The social dimension of adaptive capacity within urban forest ecosystems is in-part a function of the economic wealth and education of city residents and their likelihood of engaging in stewardship activities (Table 3). Populations with a greater access to resources, a greater capacity to self-organize, and a higher level of education will have greater adaptive capacity (Grove et al. 2006; Manzo and Perkins 2006; Boone et al. 2010; Pham et al. 2013; van Heezik et al. 2013). Neighbourhoods with higher levels of wealth, homeownership, education will therefore likely have a greater capacity to maintain, improve, and prevent decline in the supply of urban forest ecosystem services (Martin et al. 2004; Grove et al. 2006; Troy et al. 2007). However, while wealth, homeownership, and education are frequently correlated, homeownership and education have a more variable relationship with tree cover and stewardship activities (Pham et al. 2013; Steenberg et al. 2015).

Neighbourhoods with resident associations, community groups, business improvement areas, and other social structures that are aware of urban forest issues are also more likely to engage in stewardship and lobby municipal governments to enhance their urban forest (Martin et al. 2004; Manzo and Perkins 2006; Conway et al. 2011). Homeownership again may also present a more nuanced example of adaptive capacity, as homeowner behaviour regarding landscaping practices can be influenced by neighbourhood-wide trends (i.e., the neighbourhood effect) and the presence of residence associations (Grove et al. 2006; Conway et al. 2011).

With regards to social adaptive capacity, an important distinction exists between citizen- and community-led, bottom-up processes and government-led, top-down processes that also influence urban forests. Government policies and practices also influence the spatial distribution and structure of urban forests through management, regulation, incentive programs, and public education and outreach designed to protect and (or) enhance trees and green spaces (Heynen et al. 2006; Conway and Urbani 2007; Kendal et al. 2012). For instance, municipal tree protection by-laws/ordinances that regulate tree removal on private land are in place in many large municipalities (Conway and Urbani 2007). The existence of a municipal urban forestry program and corresponding public investment in urban forests (e.g., tree planting, maintenance, and removal) are especially influential drivers on public property (e.g., streets and parks; Heynen et al. 2006; Kendal et al. 2012). As a result, there can be both spatial heterogeneity and inequalities in the access to urban forest amenities in areas with less public space (Heynen et al. 2006).

We describe environmental adaptive capacity in urban forests as a function of tree canopy cover, open green space, and continuous forested area. Existing tree canopy cover characterizes the existing level of ecosystem services and therefore a greater potential of maintaining higher levels of ecosystem service supply through active management (Troy et al. 2007; Nowak and Greenfield 2012; Pham et al. 2013). Conversely, the area of open green space that is available for new tree establishment, either by planting or natural regeneration, is indicative of the capacity for greening initiatives and increasing ecosystem service supply (Troy et al. 2007). Overall ecosystem service supply in a given city is highly influenced by the extent of continuous forest cover located within a city's parks and undeveloped land (Nowak and Greenfield 2012). Moreover, where natural regeneration is possible, the maintenance and enhancement of ecosystem service supply without management intervention (i.e., tree planting) may be possible (Nowak 2012; Nowak and Greenfield 2012). Therefore, the area of continuous forest cover can be seen as an influential component of environmental adaptive capacity.

4. Assessing and analyzing vulnerability

There are numerous quantitative and qualitative approaches to assessing and analyzing vulnerability. Qualitative approaches address the more subjective and perceived nature of urban forest vulnerability where quantification is not feasible or desirable (Cutter 2003; Ordóñez and Duinker 2014; Kok et al. 2015). For instance, scenario analysis is a participatory research tool to explore possible future scenarios and has been used in qualitative vulnerability research (Swart et al. 2004). Quantitative, indicator-based vulnerability assessment frameworks are arguably the more common approach and have been used at multiple scales and in multiple regions to assess potential threats to ecosystem service supply in social–ecological systems (Luers et al. 2003; Turner et al. 2003*b*; Schröter et al. 2005; Metzger et al. 2006, 2008; Lindner et al. 2010).

Deductive, indicator-based assessments of vulnerability involve indicator identification according to existing theory using a defined conceptual framework (Füssel 2010). A deductive approach is useful for complex social–ecological systems with multiple variables of concern at different spatial and temporal scales (Hinkel 2011). Conversely, observation-based, data-driven inductive approaches to vulnerability analysis focus on measurable cause-and-effect relationships between stressors and system components. Inductive approaches tend to be more repeatable and objective than deductive approaches. However, they are limited in scale and cannot reveal all vulnerabilities and potential impacts, especially long-term variability and risk. Most comprehensive studies on system vulnerability employ elements of both approaches, though it is valuable to always begin with a defined conceptual framework (Füssel 2010).

Indicator selection and design for urban forest vulnerability assessment will be scale, context, and place dependent (Adger et al. 2004; Birkmann 2007; Hinkel 2011). For instance, broad-scale assessments of urban forest vulnerability and inequality might focus on socioeconomic indicators while more localized assessments of invasive species introductions might focus on species composition and diversity indicators. The comprehensive review of determinants of urban forest structure and function in Section 3 (Tables 1, 2, and 3) provides possible examples of urban forest vulnerability indicators. However, these are not intended to be a complete set of indicators for vulnerability assessment, as many of them are closely related or scale dependent.

Data availability and measurement feasibility are also important considerations for urban forest vulnerability assessment. Targeting readily available data sources during indicator selection and design is an important consideration if vulnerability frameworks are to be transferable to practitioners. For instance, indicators of the urban forest adaptive capacity concepts discussed earlier would be well suited to national census data and satellite-derived land cover data for social and environmental adaptive capacity, respectively. Sensitivity indicators would be relatively dependent on field data and the availability of tree inventories. Given the numerous, cumulative, and interactive nature of the stressors and disturbances associated with urban forest exposure, the data needs of associated indicators will likely be more challenging. Several exposure indicators might utilize the previously mentioned and widely available data sources, such as land cover data (e.g., imperviousness) and census data (e.g., housing density). However, a priori consideration of specific indicator selection and design, data needs, and spatial scale of assessment is important.

Vulnerability is a temporal phenomenon (Adger 2006), and in the case of urban forest vulnerability it relates to the supply of ecosystem services over time. Potential impacts refer to declines or undesirable and destabilizing changes in ecosystem service supply resulting from exposure to external forcing and internal system sensitivity (Lindner et al. 2010). They therefore require either forward-looking ecological modelling or backward-looking monitoring for quantification. Drawing from established tools for managers that are used for monitoring and modelling can assist in approaching spatial and temporal variability in vulnerability and ecosystem service supply.

The selection, design, and implementation of indicators for the purposes of monitoring has a rich history in both research and practice (e.g., forestry, environmental assessment, ecological restoration). Indicator-based monitoring is especially useful for practitioners and policy makers as a more feasible and cost effective way of evaluating temporal change and trends in managed systems (Rametsteiner et al. 2011). In principle, indicators are variables that are selected for monitoring because they are highly representative of overall system conditions and (or) highly sensitive to changes in system conditions (Noss 1990). For example, top predators that require extensive, intact habitats are used as indicator species of broader ecosystem integrity in ecological monitoring (Noss 1990). In the urban forest context, canopy cover and leaf area are often used as indicators of ecosystem service supply (Kenney 2000). The objective is for indicators to provide insight into the state of a system of interest without having to measure its entirety and to potentially yield an early warning of adverse environmental changes. In industrially managed forests, criteria and indicators are used to monitor performance-based progress towards sustainability goals (Hall 2001). In criteria and indicator frameworks, indicators are aligned with different criteria of sustainability values and goals relating to the ecological, social, and economic conditions of forests and the forest sector (Hall 2001). The criteria and indicator model could be highly applicable to urban forest vulnerability assessment and monitoring, and indeed Kenney et al. (2011) have developed a criteria and indicator framework for strategic urban forest planning.

Forward-looking modelling is the complement to monitoring and can be valuable for examining potential futures under complex and uncertain conditions, such as those found in cities. Ecological modelling involves assumption, abstraction, and aggregation of system conditions using computer-based simulation models so that management and disturbance experiments can be done at broad spatial and temporal scales (Jørgensen and Bendoricchio 2001). One model that is applicable to urban forest vulnerability is i-Tree Forecast, which is part of the i-Tree suite of models developed by the United States Department of Agriculture (USDA) Forest Service and simulates future changes in urban forest structure and function based on user defined-mortality and establishment rates (USDA Forest Service 2013; Steenberg et al. 2016). This model has been used by municipalities to estimate tree planting requirements to meet long-term canopy cover targets under different mortality scenarios (Nowak et al. 2013*a*, 2014).

The overarching purpose of a vulnerability approach in urban forestry is to communicate complex issues to practitioners, policy makers, and communities in accessible ways. Consequently, some form of indicator aggregation is commonly used in addition to analyzing individual vulnerability indicators (Adger et al. 2004). Indicator aggregation can range from standardization and simple linear combination to more complex methods using fuzzy logic or even expert-derived weights (Tran et al. 2002; Eakin and Luers 2006; Birkmann 2007). However, caution should be taken around the loss of transparency and validity with excessive aggregation and the assumptions involved (Adger et al. 2004; Hinkel 2011). There are arguments both for and against aggregation that will be discussed in Section 5.

Lastly, mapping has been shown to be an effective means for communicating vulnerability (O'Brien et al. 2004; Eakin and Luers 2006). This might entail the mapping of individual indicators or overall aggregated indices of vulnerability and its core components (i.e., exposure, sensitivity, adaptive capacity). Moreover, with monitoring and modelling tools, the mapping of vulnerability outcomes (e.g., potential impacts) is also feasible (Metzger et al. 2006). The growing availability and accessibility of data and increasing sophistication of geographic information systems (GIS) and tools for spatial analysis have increased the possibility for the spatial communication of ecosystem vulnerability (Eakin and Luers 2006).

5. Discussion and conclusions

A prominent focus in municipal urban forest policy and management in North America is on urban forest ecosystem services and their associated benefits (Ordóñez and Duinker 2013; Steenberg et al. 2013). There is less attention on potential threats to urban forest ecosystems, and little discussion of overall system vulnerability (Ordóñez and Duinker 2013). In contrast, there are many studies on ecological disturbance and stressors of urban forests, especially street trees, in the research literature (e.g., Jutras et al. 2010; Hauer et al. 2011; Koeser et al. 2013). For instance, Laćan and McBride (2008) created a vulnerability model for urban forests pests. More recently, Ordóñez and Duinker (2014) investigated the vulnerability of urban forests to climate change. Integrating a vulnerability approach into municipal urban forestry programs and policy development could help to bridge some of this gap between research and practice.

The assessment and analysis of vulnerability can also shed light on longer-term processes and unexpected, multi-faceted relationships between ecosystem service supply and risk (Metzger et al. 2006). For instance, residential neighbourhoods with older housing and higher levels of affluence are frequently characterized by large, mature trees and correspondingly high levels of ecosystem service supply (Zipperer et al. 1997; Boone et al. 2010). Despite this adaptive capacity, widespread pest-related decline and mortality are still possible where species diversity is low (Laćan and McBride 2008). Moreover, widespread senescence and age-related mortality is a likely scenario in these older neighbourhoods (Kenney et al. 2011; Steenberg et al. 2013). Conversely, newly constructed suburban housing developments often have higher affluence and an abundance of open green space where tree establishment is possible (Steenberg et al. 2015), and thus high social and environmental adaptive capacity. However, as new development typically involves land clearing, trees may be absent, small, and (or) sparse (Puric-Mladenovic et al. 2000), presenting a scenario of low vulnerability and low levels of ecosystem service supply. These latter examples not only stress the internal variability and complexity of urban forest vulnerability, but also the importance of temporal dynamics and the potential threat of time-lag effects in forest ecosystems associated with disturbance and environmental change.

Vulnerability is one of a large number of theoretical frameworks in the body of research on urban social–ecological systems (Grove 2009; Cumming 2014). While there is an increasing need for frameworks to understand and predict the outcomes of intervention through management and policy in these systems, there is a lack of consensus on which are the most effective (Cumming 2014). The sustainability approach is commonly used in urban planning. Early conceptions of sustainability in urban planning saw sustainability as an achievable and persistent state for cities (Ahern 2011). Resilience theory, which recognizes the more dynamic nature of cities, has since become more prominent and has begun to both replace and supplement this mode of sustainability (Ahern 2011). Moreover, resilience is a commonly used term and framework for researching urban social–ecological systems (Carpenter et al. 2005; Miller et al. 2010). Resilience is a system's ability to recover from a disturbance and change back to a reference state and (or) to maintain that reference state or states while stressed, and has a longer tradition in the natural sciences (Turner et al. 2003*a*).

However, both vulnerability and resilience are fundamentally concerned with the response of complex systems to change and arguably some of their biggest differences are in their disciplinary backgrounds and lexicons (Miller et al. 2010). Importantly, more recent vulnerability research in the arena of global environmental change integrates resilience concepts into a broader definition and conceptual framework of vulnerability. The framework developed by Turner et al. (2003*a*) and used in this paper employs the concept of resilience to describe the attributes and processes that have since been termed adaptive capacity in more recent applications (Metzger et al. 2006, 2008). Arguably, a vulnerability approach to addressing change in social–ecological systems therefore provides a broader and more holistic system picture by explicitly addressing the causes/types of change and not just the system's response to them.

There are certainly several challenges and limitations associated with vulnerability assessment and analysis. Vulnerability is an abstract concept that cannot be measured directly (Turner et al. 2003*a*). Consequently, vulnerability assessment and analysis are nearly always limited by a lack of metrics and available data (Luers et al. 2003). However, for the sake of sustainable management and the amelioration of the negative consequences associated with vulnerable systems, it is necessary to operationalize the concept in some way (Eakin and Luers 2006). Since it is essentially impossible to characterize the entirety of a system in a research or management context, systems must be generalized and abstracted using tools like indicators and ecological models (Jørgensen and Bendoricchio 2001; Turner et al. 2003*a*).

This latter necessity of the omission and reduction of information brings with it several critiques of vulnerability assessment and how its findings can be used. A prominent critique pertains to the use of vulnerability indicators and aggregated indices (Adger et al. 2004; Hinkel 2011). Indicators and indices are the primary way in which vulnerability is communicated to policy makers and in which the effectiveness of management interventions are monitored (Hinkel 2011). However, there is often confusion and even overstatement on what vulnerability indicators can do and a lack of transparency in how they are developed and applied (Eriksen and Kelly 2007). Whether indicators are deductive and based on existing theoretical knowledge, inductive and based on measured observable phenomena, or some combination of these latter two, documentation and full transparency on their selection and application is vital for communicating vulnerability (Eriksen and Kelly 2007; Füssel 2010; Hinkel 2011). Vulnerability indicators are valuable tools for reducing complexity to inform policy, but the spatial, temporal, and analytical scale of reduction must also be weighed (Hinkel 2011). For example, the knowledge omission in reducing a broad-scale and complex phenomenon like global climate change to a single indicator to determine international resource allocation policies for adaptation would most likely be ineffective if not unjust and lack transparency. Ultimately, scientifically valid and transparent indicators are one set of tools for urban forestry that can be used to operationalize complex phenomena like vulnerability to inform policy. They cannot and should not remove all subjectivity and complexity from the decision-making process.

Urban forest ecosystems and their management are now prominent both as a topic of research and as a source of beneficial ecosystem services for citizens, municipal governments, and biodiversity. There is a need for comprehensive frameworks for understanding and assessing potential threats and losses in urban forests. Vulnerability assessment in urban forests can not only identify risk but also address social equity in the distribution of this public amenity (Boone 2010). From a municipal planning and management perspective, neighbourhoods with inequalities in the access to urban forest ecosystem services could be prioritized to build adaptive capacity and thereby ensure equitable access to environmental amenities (Heynen et al. 2006). However, it will be important to include social perspectives and methodologies in future interdisciplinary vulnerability research and assessments. Quantitative, indicator-based frameworks have the benefits of measurability, comparability, and generalizability. However, qualitative approaches, such as scenario analysis, public engagement, and participatory research, can be used to approach the more subtle, subjective, and perceived nature of urban forest vulnerability (Cutter 2003). Ultimately, the two most important functions of vulnerability frameworks are to communicate complex issues to decision makers and stakeholders and to advance the theoretical understanding around the biophysical, built, and social dimensions of urban forest ecosystems.

Acknowledgements

Funding for this project was provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Ryerson University. This research was, in part, conducted and funded during the lead author's Fulbright exchange at the USDA Forest Service's Northern Research Station in Syracuse, New York. Fulbright Canada is a joint, bi-national, treaty-based organization created to encourage mutual understanding between Canada and the United States of America through academic and cultural exchange.

References

Adger, W.N. 2006. Vulnerability. Global Environ. Change, **16**(3): 268–281. doi:10.1016/j.gloenvcha.2006.02.006.

Adger, W.N., Brooks, N., Kelley, M., Bentham, G., Agnew, M., and Eriksen, S. 2004. New indicators of vulnerability and adaptive capacity. Tyndall Centre for Climate Change Research, Norwich, UK.

Ahern, J. 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape Urban Plan. **100**(4): 341–343. doi:10.1016/j.landurbplan.2011.02.

Alberti, M., Marzluff, J.M., Shulenberger, E., Bradley, G., Ryan, C., and Zumbrunnen, C. 2003. Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. BioScience, **53**(12): 1169–1179. doi:10.1641/0006-3568(2003)053[1169:IHIEOA]2.0.CO;2.

Alig, R.J., Kline, J.D., and Lichtenstein, M. 2004. Urbanization on the US landscape: Looking ahead in the 21st century. Landscape Urban Plan. **69**(2–3): 219–234. doi:10.1016/j.landurbplan.2003.07.004.

Armstrong, J.A., and Ives, W.G.H. 1995. Forest insect pests in Canada. NRC Research Press, Ottawa, ON.

Berkes, F., and Folke, C. 1998. Linking social and ecological systems: Management practices and social mechanisms for building resilience. Cambridge University Press, Cambridge, UK.

Binder, C.R., Hinkel, J., Bots, P.W.G., and Pahl-Wostl, C. 2013. Comparison of frameworks for analyzing social-ecological systems. Eco. Soc. **18**(4): 26–44. doi:10.5751/ES-05551-180426.

Birkmann, J. 2007. Risk and vulnerability indicators at different scales: Applicability, usefulness, and policy implications. Environ. Haz. **7**(1): 20–31. doi:10.1016/j.envhaz.2007.04.002.

Blaikie, P., Cannon, T., Davis, I., and Wisner, B. 1994. At risk: Natural hazards, people's vulnerability and disasters. Routledge, London, UK.

Boone, C.G. 2010. Environmental justice, sustainability, and vulnerability. Int. J. Urban Sustainable Dev. **2**(1–2): 135–140. doi:10.1080/19463138.2010.513772.

Boone, C.G., Cadenasso, M.L., Grove, J.M., Schwarz, K., and Buckley, G.L. 2010. Landscape, vegetation characteristics, and group identity in an urban and suburban watershed: Why the 60s matter. Urban Ecosyst. **13**(3): 255–271. doi:10.1007/s11252-009-0118-7.

Burton, I., Kates, R.W., and White, G.F. 1993. The environment as hazard. 2nd ed. Guilford Press, New York. pp. 1–263.

Cadenasso, M.L., Pickett, S.T.A., McGrath, B., and Marshall, V. 2013. Ecological heterogeneity in urban ecosystems: Reconceptualized land cover models as a bridge to urban design. *In* Resilience in ecology and urban design. *Edited by* S.T.A Pickett, M.L. Cadenasso, and Brian McGrath. Springer, New York. pp. 107–129.

Carpenter, S.R., Westley, F., and Turner, M.G. 2005. Surrogates for resilience of social-ecological systems. Ecosystems, **8**(8): 941–944. doi:10.1007/s10021-005-0170-y.

Clark, J.R., Matheny, N.P., Cross, G., and Wake, V. 1997. A model of urban forest sustainability. J. Arboric. **23**(1): 17–30.

Conway, T.M., and Urbani, L. 2007. Variations in municipal urban forestry policies: A case study of Toronto, Canada. Urban For. Urban Greening, **6**(3): 181–192. doi:10.1016/j.ufug.2007.07.003.

Conway, T.M., Shakeel, T., and Atallah, J. 2011. Community groups and urban forestry activity: Drivers of uneven canopy cover? Landscape Urban Plan. **101**(4): 321–329. doi:10.1016/j.landurbplan.2011.02.037.

Craul, P.J. 1992. Urban soil in landscape design. Wiley, New York, NY.

Craul, P.J. 1999. Urban soils: Applications and practices. Wiley, New York, NY.

Cumming, G.S. 2014. Theoretical frameworks for the analysis of social–ecological systems. *In* Social–Ecological Systems in Transition. *Edited by* S. Sakai and C. Umetsu. Springer, Tokyo. pp. 3–24.

Cutter, S.L. 1996. Vulnerability to environmental hazards. Prog. Hum. Geogr. **20**: 529–539. doi:10.1177/030913259602000407.

Cutter, S.L. 2003. The vulnerability of science and the science of vulnerability. Ann. Assoc. Am. Geogr. **93**(1): 1–12. doi:10.1111/1467-8306.93101.

Donovan, G.H., and Butry, D.T. 2010. Trees in the city: Valuing street trees in Portland, Oregon. Landscape Urban Plan. **94**(2): 77–83. doi:10.1016/j.landurbplan.2009.07.019.

Dreistadt, S.H., Dahlsten, D.L., and Frankie, G.W. 1990. Urban forests and insect ecology: Complex interactions among trees, insects, and people. BioScience. **40**(3): 192–198. doi:10.2307/1311364.

Duinker, P.N., Ordóñez, C., Steenberg, J.W.N., Miller, K.H., Toni, S.A., and Nitoslawski, S.A. 2015. Trees in Canadian cities: Indispensable life form for urban sustainability. Sustainability, **7**(6): 7379–7396. doi:10.3390/su7067379.

Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., et al. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Can. J. For. Res. **39**(2): 231–248. doi:10.1139/X08-171.

Eakin, H., and Luers, A.L. 2006. Assessing the vulnerability of social–environmental systems. Annu. Rev. Environ. Resour. **31**: 365–394. doi:10.1146/annurev.energy.30.050504.144352.

Eriksen, S.H., and Kelly, P.M. 2007. Developing credible vulnerability indicators for climate adaptation policy assessment. Mitig. Adapt. Strat. Global Change, **12**(4): 495–524. doi:10.1007/s11027-006-3460-6.

Forsyth, A. 2003. Measuring density: Working definitions for residential density and building intensity. Design Center for American Urban Landscape, University of Minnesota, Minneapolis-Saint Paul, MN.

Füssel, H.-M. 2010. Review and quantitative analysis of indices of climate change exposure, adaptive capacity, sensitivity, and impacts. World Bank, Washington, DC.

Gallopin, G.C. 2006. Linkages between vulnerability, resilience, and adaptive capacity. Global Environ. Change, **16**(3): 293–303. doi:10.1016/j.gloenvcha.2006.02.004.

Gilbertson, P., and Bradshaw, A.D. 1985. Tree survival in cities: The extent and nature of the problem. Arboric. J. **9**(2): 131–142. doi:10.1080/03071375.1985.9746706.

Grove, J.M. 2009. Cities: Managing densely settled social–ecological systems. *In* Principles of Ecosystem Stewardship. *Edited by* C. Folke, G.P. Kofinas, and F.S. Chapin. Springer, New York. pp. 281–294.

Grove, J.M., Cadenasso, M.L., Burch, W.R., Pickett, S.T.A., Schwarz, K., O'Neil-Dunne, J., and Wilson, M. 2006. Data and methods comparing social structure and vegetation structure of urban neighborhoods in Baltimore, Maryland. Soc. Nat. Res. **19**(2): 117–136. doi:10.1080/08941920500394501.

Grove, J.M., Locke, D.H., and O'Neil-Dunne, J.P.M. 2014. An ecology of prestige in New York City: Examining the relationships among population density, socio-economic status, group identity, and residential canopy cover. Environ. Manage. **54**(3): 402–419. doi:10.1007/s00267-014-0310-2.

Grove, J.M., Troy, A.R., O'Neil-Dunne, J.P.M., Burch, W.R., Cadenasso, M.L., and Pickett, S.T.A. 2006. Characterization of households and its implications for the vegetation of urban ecosystems. Ecosystems, **9**(4): 578–597. doi:10.1007/s10021-006-0116-z.

Hall, J.P. 2001. Criteria and indicators of sustainable forest management. Environ. Monit. Assess. **67**(1): 109–119. doi:10.1023/A:1006433132539. PMID: 11339693.

Hanks, D., and Lewandowski, A. 2003. Protecting urban soil quality: examples for landscape codes and specifications. USDA, Natural Resource Conservation Service, Washington, DC.

Hauer, R.J., Hauer, A.J., Hartel, D.R., and Johnson, J.R. 2011. Rapid assessment of tree debris following urban forest ice storms. Arboric. Urban For. **37**(5): 236–246.

Hauer, R.J., Miller, R.W., and Ouimet, D.M. 1994. Street tree decline and construction damage. J. Arboric. **20**(2): 94–97.

Hauer, R.J., Wang, W., and Dawson, J.O. 1993. Ice storm damage to urban trees. J. Arboric. **19**(4): 187–194.

Herms, D.A., and McCullough, D.G. 2014. Emerald ash borer invasion of North America: History, biology, ecology, impacts, and management. Annu. Rev. Entomol. **59**: 13–30. doi:10.1146/annurev-ento-011613-162051. PMID:24112110.

Heynen, N., Perkins, H.A., and Roy, P. 2006. The political ecology of uneven urban green space: The impact of political economy on race and ethnicity in producing environmental inequality in Milwaukee. Urban Aff. Rev. **42**(1): 3–25. doi:10.1177/1078087406290729.

Hinkel, J. 2011. Indicators of vulnerability and adaptive capacity: Towards a clarification of the science–policy interface. Global Environ. Change, **21**(1): 198–208. doi:10.1016/j.gloenvcha.2010.08.002.

Jørgensen, S.E., and Bendoricchio, G. 2001. Fundamentals of ecological modelling. 3rd ed. Elsevier, London, UK.

Jutras, P., Prasher, S.O., and Mehuys, G.R. 2010. Appraisal of key biotic parameters affecting street tree growth. J. Arboric. **36**(1): 1–10.

Kendal, D., Williams, N.S.G., and Williams, K.J.H. 2012. Drivers of diversity and tree cover in gardens, parks, and streetscapes in an Australian city. Urban For. Urban Greening, **11**(3): 257–265. doi:10.1016/j.ufug.2012.03.005.

Kenney, W.A. 2000. Leaf area density as an urban forestry planning and management tool. For. Chron. **76**(2): 235–239. doi:10.5558/tfc76235-2.

Kenney, W.A., and Idziak, C. 2000. The state of Canada's municipal forests — 1996 to 1998. For. Chron. **76**(2): 231–235. doi:10.5558/tfc76231-2.

Kenney, W.A., van Wassenaer, P.J.E., and Satel, A.L. 2011. Criteria and indicators for strategic urban forest planning and management. Arboric. Urban For. **37**(3): 108–117.

Koeser, A., Hauer, R., Norris, K., and Krouse, R. 2013. Factors influencing long-term street tree survival in Milwaukee, WI, U.S.A. Urban For. Urban Greening, **12**(4): 562–568. doi:10.1016/j.ufug.2013.05.006.

Kok, M., Lüdeke, M.K.B., Lucas, P., Sterzel, T., Walther, C., Janssen, P., et al. 2015. A new method for analysing socio-ecological patterns of vulnerability. Reg. Environ. Change, **16**(1): 229–243. doi:10.1007/s10113-014-0746-1.

Konijnendijk, C.C., Nilsson, K., Randrup, T.B., and Schipperijn, J. 2005. Urban forests and trees. Springer, Berlin, Germany.

Konijnendijk, C.C., Ricard, R.M., Kenney, W.A., and Randrup, T.B. 2006. Defining urban forestry — A comparative perspective of North America and Europe. Urban For. Urban Greening, **4**(3–4): 93–103. doi:10.1016/j.ufug.2005.11.003.

Laćan, I., and McBride, J.R. 2008. Pest vulnerability matrix (PVM): A graphic model for assessing the interaction between tree species diversity and urban forest susceptibility to insects and diseases. Urban For. Urban Greening, **7**(4): 291–300. doi:10.1016/j.ufug.2008.06.002.

Landry, S.M., and Chakraborty, J. 2009. Street trees and equity: Evaluating the spatial distribution of an urban amenity. Environ. Plan. A. **41**(11): 2651–2670. doi:10.1068/a41236.

Lawrence, A.B., Escobedo, F.J., Staudhammer, C.L., and Zipperer, W. 2012. Analyzing growth and mortality in a subtropical urban forest ecosystem. Landscape Urban Plan. **104**(1): 85–94. doi:10.1016/j.landurbplan.2011.10.004.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., et al. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manage. **259**(4): 698–709. doi:10.1016/j.foreco.2009.09.023.

Lopes, A., Oliveira, S., Fragoso, M., Andrade, J.A., and Pedro, P. 2009. Wind risk assessment in urban environments: The case of falling trees during windstorm events in Lisbon. *In* Bioclimatology and natural hazards. *Edited by* K. Střelcová, C. Mátyás, A. Kleidon, M. Lapin, F. Matejka, M. Blaženec, et al. Springer, Berlin. pp. 55–74.

Lu, J.W.T., Svenden, E.S., Campbell, L.K., Greenfeld, J., Braden, J., King, K.L., and Falxa-Raymond, N. 2010. Biological, social, and urban design factors affecting young tree mortality in New York City. Cities Environ. **3**(1): 1–15. doi:10.15365/cate.3152010.

Luers, A.L., Lobell, D.B., Sklar, L.S., Addams, C.L., and Matson, P.A. 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environ. Change. **13**(4): 255–267. doi:10.1016/S0959-3780(03)00054-2.

Manzo, L.C., and Perkins, D.D. 2006. Finding common ground: The importance of place attachment to community participation and planning. J. Plan. Lit. **20**(4): 335–350. doi:10.1177/0885412205286160.

Martin, C.A., Warren, P.S., and Kinzig, A. 2004. Neighborhood socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighbourhoods and embedded small parks of Phoenix, Arizona. Landscape Urban Plan. **69**(4): 355–368. doi:10.1016/j.landurbplan.2003.10.034.

McBride, J.R., and Jacobs, D.F. 1979. Urban forest structure: A key to urban forest planning. Calif. Agric. **33**(5): 24.

Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., and Schröter, D. 2006. The vulnerability of ecosystem services to land use change. Agric. Ecosyst. Environ. **114**(1): 69–85. doi:10.1016/j.agee.2005.11.025.

Metzger, M.J., Schröter, D., Leemans, R., and Cramer, W. 2008. A spatially explicit and quantitative vulnerability assessment of ecosystem service change in Europe. Reg. Environ. Change, **8**(3): 91–107. doi:10.1007/s10113-008-0044-x.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., et al. 2010. Resilience and vulnerability: Complimentary or conflicting concepts? Ecol. Soc. **15**(3): 1–25.

Miller, R.W. 1997. Urban forestry: Planning and managing urban greenspaces. Prentice-Hall, New Jersey.

Millward, A.A., Paudel, K., and Briggs, S.E. 2011. Naturalization as a strategy for improving soil physical characteristics in a forested urban park. Urban Ecosyst. **14**(2): 261–278. doi:10.1007/s11252-010-0153-4.

Mitchell, S.J. 1995. The windthrow triangle: A relative windthrow hazard assessment procedure for forest managers. For. Chron. **71**(4): 446–450. doi:10.5558/tfc71446-4.

Nitschke, C.R., and Innes, J.L. 2008. Integrating climate change into forest management in South-Central British Columbia: An assessment of landscape vulnerability and development of a climate-smart framework. For. Ecol. Manage. **256**(3): 313–327. doi:10.1016/j.foreco.2008.04.026.

Nock, C.A., Paquette, A., Follett, M., Nowak, D.J., and Messier, C. 2013. Effects of urbanization on tree species functional diversity in Eastern North America. Ecosystems, **16**(8): 1487–1497. doi:10.1007/s10021-013-9697-5.

Noss, R.F. 1990. Indicators for monitoring biodiversity: A hierarchical approach. Conserv. Biol. **4**(4): 355–364. doi:10.1111/j.1523-1739.1990.tb00309.x.

Nowak, D.J. 2012. Contrasting natural regeneration and tree planting in fourteen North American cities. Urban For. Urban Greening, **11**(4): 374–382. doi:10.1016/j.ufug.2012.02.005.

Nowak, D.J., and Dwyer, J.F. 2007. Understanding the benefits and costs of urban forest ecosystems. *In* Urban and community forestry in the northeast. *Edited by* J.E. Kuser. Springer, New Brunswick. pp. 25–46.

Nowak, D.J., and Greenfield, E.J. 2012. Tree and impervious cover change in U.S. cities. Urban For. Urban Greening, **11**(1): 21–30. doi:10.1016/j.ufug.2011.11.005.

Nowak, D.J., Kuroda, M., and Crane, D.E. 2004. Tree mortality rates and tree population projections in Baltimore, Maryland, U.S.A. Urban For. Urban Greening, **2**(3): 139–147. doi:10.1078/1618-8667-00030.

Nowak, D.J., Hoehn, R.E., Bodine, A.R., Greenfield, E.J., Ellis, A., Endreny, T.A., et al. 2013*a*. Assessing urban forest effects and values: Toronto's urban forest. USDA Forest Service, Northern Research Station, Newton Square, PA.

Nowak, D.J., Hoehn, R.H., Bodine, A.R., Greenfield, E.J., and O'Neil-Dunne, J. 2013*b*. Urban forest structure, ecosystem services, and change in Syracuse, NY. Urban Ecosyst. **2013**, 1–23.

Nowak, D.J., Bodine, A.R., Hoehn, R.E., Ellis, A., Bomberger, K., Crane, D.E., et al. 2014. Assessing urban forest effects and values: Douglas County, Kansas. USDA Forest Service, Northern Research Station, Newton Square, PA.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., et al. 2004. Mapping vulnerability to multiple stressors: climate change and globalization in India. Global Environ. Change, **14**(4): 303–313. doi:10.1016/j.gloenvcha.2004.01.001.

Ordóñez, C., and Duinker, P.N. 2013. An analysis of urban forest management plans in Canada: Implications for urban forest management. Landscape Urban Plan. **116**: 36–47. doi:10.1016/j.landurbplan.2013.04.007.

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

Pham, T.-T.-H., Apparicio, P., Landry, S., Séguin, A.-M., and Gagnon, M. 2013. Predictors of the distribution of street and backyard vegetation in Montreal, Canada. Urban For. Urban Greening, **12**(1): 18–27. doi:10.1016/j.ufug.2012.09.002.

Pickett, S.T.A., and Grove, J.M. 2009. Urban ecosystems: What would Tansley do? Urban Ecosyst. **12**(1): 1–8. doi:10.1007/s11252-008-0079-2.

Puric-Mladenovic, D., Kenney, W.A., and Csillag, F. 2000. Land development pressure on peri-urban forests: A case study in the Regional Municipality of York. For. Chron. **76**(2): 247–250. doi:10.5558/tfc76247-2.

Rametsteiner, W., Pülzl, H., Alkan-Olsson, J., and Frederiksen, P. 2011. Sustainability indicator development — Science or political negotiation. Ecol. Indicat. **11**(1): 61–70. doi:10.1016/j.ecolind.2009.06.009.

Roman, L.A., and Scatena, F.N. 2011. Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, U.S.A. Urban For. Urban Greening, **10**(4): 269–274. doi:10.1016/j.ufug.2011.05.008.

Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., et al. 2005. Ecosystem service supply and vulnerability to global change in Europe. Science. **310**(5752): 1333–1337. doi:10.1126/science.1115233. PMID:16254151.

Sen, A.K. 1984. Resources, values, and development. Blackwell, Oxford, UK.

Sieghardt, M., Mursch-Radlbgruber, E., Paoletti, E., Couenberg, E., Dimitrakopoulus, A., Rego, F., et al. 2005. The abiotic growing environment: Impact of urban growing conditions on urban vegetation. *In* Urban forests and trees. *Edited by* C. Konijnendijk, K. Nilsson, T.B. Randrup, and J. Schipperijn. Springer, Berlin, Germany. pp. 281–323.

Sitch, S., Cox, P.M., Collins, W.J., and Huntingford, C. 2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature. **448**(7155): 791–794. doi:10.1038/nature06059. PMID:17653194.

Staudhammer, C.L., and LeMay, V.M. 2001. Introduction and evaluation of possible indices of stand structural diversity. Can. J. For. Res. **31**(7): 1105–1115. doi:10.1139/x01-033.

Staudhammer, C., Escobedo, F., Lawrence, A., Duryea, M., Smith, P., and Merritt, M. 2011. Rapid assessment of change and hurricane impacts to Houston's urban forest structure. Arboric. Urban For. **37**(2): 60–66.

Steenberg, J.W.N. 2015. Urban forest vulnerability and its implications for ecosystem service supply at multiple scales. Doctoral dissertation, Environmental Applied Science and Management, Ryerson University, Toronto, ON.

Steenberg, J.W.N., Duinker, P.N., and Charles, J.D. 2013. The neighbourhood approach to urban forest management: The case of Halifax, Canada. Landscape Urban Plan. **117**: 135–144. doi:10.1016/j.landurbplan.2013.04.003.

Steenberg, J.W.N., Millward, A.A., Duinker, P.N., Nowak, D.J., and Robinson, P.J. 2015. Neighbourhood-scale urban forest ecosystem classification. J. Environ. Manage. **163**: 134–145. doi:10.1016/j.jenvman.2015.08.008. PMID:26311086.

Steenberg, J.W.N., Millward, A.A., Nowak, D.J., Robinson, P.J., and Ellis, A. 2016. Forecasting urban forest ecosystem structure, function, and vulnerability. Environ. Manage. In press. doi:10.1007/s00267-016-0782-3.

Swart, R.J., Raskin, P., and Robinson, J. 2004. The problem of the future: Sustainability science and scenario analysis. Global Environ. Change, **14**(2): 137–146. doi:10.1016/j.gloenvcha.2003.10.002.

Tardieu, L., Roussel, S., Thompson, J.D., Labarraque, D., and Salles, J.M. 2015. Combining direct and indirect impacts to assess ecosystem service loss due to infrastructure construction. J. Environ. Manage. **152**: 145–157. doi:10.1016/j.jenvman.2015.01.034.

Tran, L.T., Knight, C.G., O'Neill, R.V., Smith, E.R., Riitters, K.H., and Wickham, J. 2002. Fuzzy decision analysis for integrated environmental vulnerability assessment of the mid-Atlantic region. Environ. Manage. **29**(6): 845–859. doi:10.1007/s00267-001-2587-1. PMID:11992175.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., and Gaston, K.J. 2007. Urban form, biodiversity potential, and ecosystem services. Landscape Urban Plan. **83**(4): 308–317. doi:10.1016/j.landurbplan.2007.05.003.

Trowbridge, P.J., and Bassuk, N.L. 2004. Trees in the urban landscape: Site assessment, design, and installation. Wiley, Hoboken.

Troy, A.R., Grove, J.M., O'Neil-Dunne, J.P., Pickett, S.T., and Cadenasso, M.L. 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. Environ. Manage. **40**(3): 394–412. doi:10.1007/s00267-006-0112-2. PMID:17602257.

Turner, B.L, Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., et al. 2003*a*. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. **100**(14): 8074–8079. doi:10.1073/pnas.1231335100. PMID:12792023.

Turner, B.L., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., et al. 2003*b*. Illustrating the coupled human–environment system for vulnerability analysis: Three case studies. Proc. Natl. Acad. Sci. U.S.A. **100**(14): 8080–8085. doi:10.1073/pnas.1231334100. PMID:12815106.

Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., and Zelson, M. 1991. Stress recovery during exposure to natural and urban environments. J. Environ. Psychol. **11**(3): 201–230. doi:10.1016/S0272-4944(05)80184-7.

United Nations. 2014. World urbanization prospects — The 2014 revision [online]. Available from http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf [accessed 29 February 2016].

USDA Forest Service. 2013. i-Tree applications [online]. Available from http://itreetools.org/applications.php [accessed 29 February 2016].

van Heezik, Y., Freeman, C., Porter, S., and Dickinson, K.J.M. 2013. Garden size, householder knowledge, and socio-economic status influence plant and bird diversity at the scale of individual gardens. Ecosystems, **16**(8): 1442–1454. doi:10.1007/s10021-013-9694-8.

Zimmerman, E.M., Jull, L.G., and Shirazi, A.M. 2005. Effects of salinity and freezing on *Acer platanoides*, *Tilia cordata*, and *Viburnum lantana*. J. Environ. Hort. **23**(3): 138–144.

Zipperer, W.C., Sisinni, S.M., Pouyat, R.V., and Foresman, T.W. 1997. Urban tree cover: An ecological perspective. Urban Ecosyst. **1**(4): 229–246. doi:10.1023/A:1018587830636.