Optimizing co-benefits of the urban forest using a GIS-based urban forest benefits model

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A GIS-decision support tool called the Urban Forest Benefits Model (UFBM) is discussed. The model provides decision makers, municipal planners, and urban foresters with the ability to prioritize their greening efforts so as to maximize the net environmental, economic and social co-benefits to their community. The model’s focus centres around a spatial technique developed in this research that maximizes the co-benefits of trees as they relate to land use. There were three key objectives associated with this research: (1) to develop an inventory and framework of urban forest benefits calibrated for a specific city; (2) to develop a prioritized list of the city’s sustainability goals and identify how greening efforts contribute toward these goals; and (3) to develop the GIS-based UFBM that will assist with the sequencing of greening activities (planting, maintenance, and protection) in order to optimize community co-benefits and attain long-term sustainability goals. Seven tasks were chosen for a customized case study application in Thunder Bay, Ontario, a medium-sized, cold-climate city. The combination of these tasks identified priority sites for strategic greening investments in Thunder Bay. The UFBM provides a new model for managing urban forests and is customizable and designed for use in other jurisdictions.

Keywords: urban forestry, sustainability, GIS, planning, benefits, green infrastructure

Introduction

Urban trees are commonly referred to as ‘green infrastructure’ because they provide a benefit to society similar to other ‘hard infrastructure’ (e.g., benches, culverts, roads). Studies focused on green infrastructure and its benefits are providing communities with an understanding of the value of urban forests, and are demonstrating green infrastructure’s contributions toward more sustainable urban environments. A dramatic increase in land pressure and other urban problems in Canada and the US have provided a platform on which to showcase the value of green infrastructure in cities. Over the past three decades, urban forests have been shown to provide significant solutions to urban challenges such as mitigating the effects of urban sprawl and social inequalities, reducing stormwater runoff and water management costs, moderating microclimates, calming traffic, stabilizing and denaturing air and soil pollutants, and reducing noise (Dwyer et al. 1992; Bourne 2000; Pulford and Watson 2003; Li et al. 2005; Day and Dickinson 2008; Escobedo and Nowak 2009; Morani et al. 2011; Norton et al. 2015). Increasingly, using both social and applied research approaches, a wide range of the environmental goods and services produced by urban forests are being quantified (Dwyer and Miller 1999; Nowak and Dwyer 2007; Wolf 2008).

Maximizing the net level of benefits from trees in urban areas has long been a focus of concern for professionals and researchers (Clark et al. 1997). Commonly, higher levels of benefits can be achieved when a tree’s structure is altered in a man-
ner that results in more leaf area (Nowak et al. 2008). More leaf area, for example by providing the conditions and care to allow trees to mature and increase in size (Nowak et al. 2008). Larger, fuller trees have more leaf area, which allows them to perform more services like filtering air, cooling hot urban areas, capturing rainfall, and stabilizing soil. Suitable tree species and micro-site selection also influence the level of net benefits provided.

Although under studied, the spatial placement of trees is another variable influencing a tree’s ability to perform multiple-functions and thus significantly increase co-benefits to be gained by a single tree at one location. Depending on the spatial positioning of green infrastructure and its proximity to certain land-use classes (e.g., commercial, residential), its benefits can be maximized and targeted toward the needs of a community. While studies and models (e.g., i-Tree Tools) focusing on urban forest benefits have existed for nearly two decades (Dwyer and Miller 1999; Nowak et al. 2002; Nowak et al. 2008; Wang et al. 2008; Kirnbauer et al. 2009), few models have used geographical information systems (GIS) to optimize the multi-functional benefits of urban forests.

The Urban Forest Benefits Model (UFBM) involves a variety of elements that make it unique in comparison to existing models. First, the UFBM is highly adoptable and relevant to both small and large communities even those with limited urban forest budgets. Second, the model is simple to apply as it involves just three main stages. It uses a group/stakeholder process and other interdisciplinary methods that can process social benefits efficiently. Third, the UFBM creates priority maps (outputs) that have a fine enough resolution and contain information relevant to arborists and field staff, and can integrate long-term community and sustainability goals. The methods used within the UFBM to develop these priority maps are based on urban forest services and are derived, in part, from frameworks such as the Forestry Opportunity Spectrum (Raciti et al. 2006) and other urban tree canopy (UTC) studies (e.g., Locke et al. 2010). The priority maps are presented through the development of two indices—the Maintenance Index (MI) and the Planting Index (PI). The Maintenance Index identifies priority sites throughout a community that need maintenance and protection investments to allow for the continued provision of multiple key services by trees. The Planting Index demonstrates spatially where trees should preferably be planted to optimize the predetermined co-benefits to a community.

**Project objectives and background**

As indicated above, the UFBM uses GIS to prioritize locations for tree planting and tree maintenance activities in city forest locations. The UFBM aims to dramatically enhance the co-benefits derived from trees by identifying locations that allow green infrastructure to be as multi-functional as possible. It also targets important land-use areas that allow urban forest services to complement and support intended community planning goals. The model evolved out of the need to understand how urban forests might be better integrated into community planning strategies to alleviate the existing sustainability problems faced by cities. The UFBM developed in this research is unique in comparison to other models mentioned earlier as it integrates the mitigating, multi-functional goods and services of trees with the sustainability objectives tailored or customized to a specific community and explicitly uses GIS to highlight priority areas.

The UFBM is a combination of computer-based (GIS) and non-computer based (focus groups) components used to prioritize greening investments at a neighbourhood scale in a manner that maximizes the biophysical and socioeconomic returns to the community. Additionally, it provides urban planners and urban foresters the means to demonstrate where trees can help simultaneously achieve a variety of community sustainability objectives (e.g., climate change adaptation, mitigation of stormwater runoff, and increase in active transportation). Active transportation “refers to any form of human-propelled transportation such as walking, cycling, in-line skating or skateboarding” (Government of Canada 2017) and is increasingly the focus of planning efforts at improving community and personal health (e.g. City of Thunder Bay 2016).

This article discusses the conceptual approach in developing the UFBM and its application to Thunder Bay. There are three key objectives associated with the research: (1) to develop an inventory and framework of urban forest benefits calibrated to the case study city; (2) to develop a prioritized list of Thunder Bay’s sustainability goals and identify how greening efforts contribute toward these goals; and (3) to develop spatial greening schemes using GIS that will sequence planting, maintenance, and protection efforts in order to optimize community benefits and attain long-term community sustainability goals. In meeting the third of these objectives the article presents two GIS based index models—the Maintenance Index and Planting Index.

**Study area**

Thunder Bay is a small to medium-sized city with a metropolitan population of approximately 121,600 (Statistics Canada 2017), located in Northwestern Ontario. It has a total land area of 2,556 km² and an average population density of 47.6 persons/km². Thunder Bay was created in 1970 through the amalgamation of the two former cities of Port Arthur and Fort William, now commonly referred to respectively as the North Core and South Core (Figure 1). Over the past few decades, Thunder Bay has faced many urban challenges similar to those of large urban centres in Canada and the US, such as urban sprawl, economic decline, and the decay of downtown and inner city neighbourhoods. Unique to Thunder Bay is the existence of two struggling downtown cores, amidst the backdrop of the loss of well-paying blue collar employment in the forestry and grain-handling sectors since the 1990s. The economic activity that once thrived in the two downtown cores has been directed to a new focal point in the Intercity area and is meant to bring the two cities together both physically and economically (Randall and Lorch 2007; EarthWise Thunder Bay 2008).
Thunder Bay was an ideal location for the case study due to its array of social, economic and environmental challenges. It was also selected because the lead author has firsthand experience working as an urban forest professional at the City of Thunder Bay and is familiar with the city’s tree inventory and related datasets required for this research.

Conceptual model: Methods and data requirements

The primary objective of the Urban Forest Benefits Model (UFBM) was to identify urban sites for greening that would provide the greatest positive impact to the community—this impact being an aggregated index of the numerous socio-economic and environmental benefits available from an urban forest. The conceptual approach of the developed UFBM consists of three main stages (Figure 2), and provides the methods and framework required to replicate the model in other jurisdictions. The ‘standard tasks’ within the model are those informed by current practice and professional urban forestry literature, while the ‘link table’ tasks are those included for the Thunder Bay case study. Other cities would be able to develop other ‘link table tasks’ based on their own needs developed through the focus group process. The next section describes the methods employed within the developed conceptual model (i.e., Stages 1 to early Stage 3 in Figure 2). The aggregated results in the formulation of two indices—the Maintenance Index and the Planting Index (i.e., end of Stage 3 on Figure 2)—are discussed later in the results portion of the article.

Focus groups

Focus groups and group interviews are effective and innovative methods of generating wisdom in complex research environments (Morgan 1996; Gibbs 1997; Beckett et al. 2000). For example, by utilizing the pooled knowledge of a group of experts, a researcher can avoid the costs of duplicating primary research of forest benefits that has been developed elsewhere. The development of the UFBM involved the use of two focus groups (i.e., Stage 1 in Figure 2). Based on the compilation of urban forest benefits found in the literature, a first focus group was created comprising local professionals and experts in the fields of urban forestry and landscape architecture. The discussions of this focus group provided a stronger sense of certainty regarding the urban forest functions that clearly benefited the community—an important first step which determined if and how the multitude of benefits documented in the literature apply in Thunder Bay.

A second focus group identified and ranked the sustainability goals of the City that would ultimately be used in the link
Figure 2
The conceptual model of the UFBM is comprised of three stages: 1) focus group and link table development, 2) task identification, and 3) GIS analysis and consolidation of tasks. A GIS model was developed for the seven listed tasks resulting in the identification of ‘hot spots’ or priority locations for tree planting, maintenance and protection.

Table discussed below. This focus group comprised of senior administrators and other professionals, such as city managers, community decision makers (e.g., health unit, active transportation), and urban planners, provided a holistic perspective needed for this step of the model. Prior to the second focus group meeting, a literature review of the City’s major guiding documents was completed in order to identify the core goals and direction of the City that pertain to sustainability. Various documents were used, such as the Thunder Bay Official Plan (City of Thunder Bay 2005), the Community Environmental Action Plan (Earthwise Thunder Bay 2008) and the Mayor’s Strategic Plan (City of Thunder Bay 2007). Although other plans exist within the community, these three were chosen because of the broad range of people and comprehensive set of goals they represent, including their foci on subjects like education, the environment and public health.

In reviewing the above guiding documents, those sustainability goals of the city having potential to be supported by an urban forest benefit (as substantiated by the literature) were selected and compiled in a tabular framework. For example, if a particular air quality improvement goal could be fully or partially accomplished by the services of an urban forest it was included in the framework. Each goal summarized in the framework was classified on the basis of sustainable development principles into one of three categories, namely (1) social capital, (2) environmental capital, and (3) economic capital. A ranking exercise was then carried out with the second focus group to establish a level of priority for the community with regards to the sustainability goals identified in the framework. Creating a calibrated list of urban forest benefits and a priority list of sustainability goals was essential in order to complete the link table process, that is, to isolate a set of achievable forest management tasks that would address specific sustainability goals of the City.

Link table
The link table within the UFBM is a comprehensive process that included the use of a Delphi group to measure the level of connection, however small or large, between an urban forest benefit and a particular sustainability goal (Table 1). For example, a goal of increasing active transportation in a community is influenced by the ability of trees to beautify the neighbourhood, to reduce noise, to calm traffic, and to protect pedestrians. The link table provided a means of identifying the benefits that most strongly contributed toward a particular sustainability goal. If a
Table 1
Link table showing extent of agreement or disagreement about connections between urban forest benefits (column headings) and sustainability goals (row headings)

<table>
<thead>
<tr>
<th>Extent of Agreement</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - strongly disagree</td>
<td>Trees make corridors more attractive and appealing and connect a community with the locality</td>
</tr>
<tr>
<td>2 - disagree</td>
<td>Trees positively affect tourism through influence on consumer behaviour and beautification</td>
</tr>
<tr>
<td>3 - possibly agree</td>
<td>Trees lead to temperature reduction and other microclimatic effects</td>
</tr>
<tr>
<td>4 - agree</td>
<td>Trees attract business investment through increased aesthetics and through increased traffic/tourism</td>
</tr>
<tr>
<td>5 - strongly agree</td>
<td>Trees provide corridor between roads and sidewalks protecting pedestrians and giving the perception of safety</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summary Benefit → Sense of Place</th>
<th>Tourism</th>
<th>Air Temp / Microclimate</th>
<th>Attract Business Investment</th>
<th>Pedestrian Safety</th>
<th>Erosion and Slope Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefit Category → Beautification and Design</td>
<td>Economic Development</td>
<td>Air Quality</td>
<td>Economic Development</td>
<td>Public Health And Safety</td>
<td>Lands</td>
</tr>
<tr>
<td>Benefit Section → Social Benefits</td>
<td>Biophysical Benefits</td>
<td>Social Benefits</td>
<td>Social Benefits</td>
<td>Social Benefits</td>
<td>Biophysical Benefits</td>
</tr>
</tbody>
</table>

**Goals Selected by Focus Group**

**Economic Development**
Support the creation of a positive climate for business, institutions and employees in order to develop a diversified growing economy; city will rely more on secondary and tertiary support industry, retail and service functions, and small business, rather than the traditional sources of employment

<table>
<thead>
<tr>
<th>Economic Development</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

**Downtown Core**
Maintain and enhance the downtown areas as unique focal points of activity, interest and identity for residents and visitors through the provision of the fullest range of urban functions and amenities

<table>
<thead>
<tr>
<th>Downtown Core</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
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<td>4</td>
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<tr>
<td>3</td>
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<td>2</td>
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<tr>
<td>5</td>
<td>3</td>
<td>1</td>
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</tbody>
</table>

**Sustainability Goals**

**Intensification / Housing**
Encourage efficient residential land use within the city by facilitating the creation of new residential accommodation within existing buildings or on previously developed serviced land

<table>
<thead>
<tr>
<th>Intensification / Housing</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
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<td>3</td>
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<td>3</td>
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</table>

**Needs of Special Groups**
Encourage consideration of the needs of special groups, and in particular persons with disabilities, in the design and construction of buildings and other facilities

<table>
<thead>
<tr>
<th>Needs of Special Groups</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
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<tbody>
<tr>
<td>4</td>
<td>1</td>
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<td>1</td>
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<td>3</td>
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<tr>
<td>2</td>
<td>3</td>
<td>1</td>
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</table>

**Active Transportation (AT)**
Improve the number of people walking, biking, or travelling by other human-powered means

<table>
<thead>
<tr>
<th>Active Transportation (AT)</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
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<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>5</td>
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<td>2</td>
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<td>1</td>
<td>1</td>
<td>3</td>
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</table>

**Open Space Areas**
Achieve a highly integrated system of recreational areas and trails throughout the city

<table>
<thead>
<tr>
<th>Open Space Areas</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
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<tr>
<td>1</td>
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<td>1</td>
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</tbody>
</table>

**Green Building**
Achieve long-term savings to the citizens of Thunder Bay through reduced operating and life-cycle costs of municipal and private facilities

<table>
<thead>
<tr>
<th>Green Building</th>
<th>Social Benefits</th>
<th>Biophysical Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
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</table>
particular connection was strong (i.e., a particular sustainability goal of a community can be, in part or in whole, accomplished through the function of an urban forest), then a link table process identified this connection as a ‘multi-functional link task’ that was then modeled using GIS to influence greening activities and maximize benefits. The link table process focused on the most urgent sustainability aims of a community and provided a balanced approach to sustainability, by choosing an array of tasks that focus on the economic, social, and environmental aspects of city living. The link table, an example of which is shown in Table 1, contained over 30 sustainability goals and 50 benefits. As mentioned earlier, the Delphi group helped to confirm the strengths of the key linkages between the sustainability goals and potential benefits derivable from the urban forest. In this case study, the members of the Delphi group were drawn from the education, environment, public health and urban forest sectors.

Compiling tasks

The second stage of the UFBM identifies the various standard tasks and link table tasks selected (Stage 2 in Figure 2). Each of these tasks is represented by a spatial greening regime, that is, a map that prioritizes greening activities in order to accomplish a particular sustainability goal (e.g., air pollution reduction, traffic calming). The UFBM is comprised of three task categories, namely multi-functional link tasks, multi-functional standard tasks, and standard tasks. The term ‘multi-functional’ denotes that the task can be used in the model with other tasks to identify sites where trees perform multiple key functions and produce higher net benefits. The advantage resulting from multi-functional tasks are that they can be stacked on top of each other in a spatial environment in order to identify those locations with maximum co-benefits and are here referred to as ‘spatially optimized services’. The term ‘standard’ denotes that the task is a commonly applied management activity performed by a manager of the urban forest. These standard tasks include routine greening (planting, maintenance and protection) strategies which may have been employed in a community prior to their using the UFBM, such as targeting new housing developments for planting, or for tree replacements due to emerald ash borer damage. For example, if a community routinely managed their urban forest to mitigate stormwater effects, such a task would be considered a standard multi-functional task. The standard tasks for this study were determined through consultation with the City of Thunder Bay’s city forester as a subset of those routinely used urban forest management practices.

GIS analysis

A GIS model was developed for each of the standard and multi-functional tasks in the UFBM, resulting in the identification of ‘hot spot’ maps (or priority locations) for increasing or protecting existing leaf area. Each task was modeled individually using ESRI’s ArcGIS software and employed a grid of one-hectare pixels to define the forest management areas of the city. A one-hectare resolution was deemed to be large enough to present a broad overview of the city while providing small enough management areas for onsite planning and design. This resulted in an independent set of maps demonstrating recommended locations to plant, maintain and protect trees to ensure optimal levels of leaf area and benefits to the community were achieved. These maps were then combined to form a final comprehensive map demonstrating optimum locations for greening.

The analysis required for each task was determined by the type of task and the available data, but in most instances followed a common methodological approach as generalized in Table 2. Since the standard and multi-functional tasks incorporated a broad array of social, economic and environmental issues (e.g., planning for children’s journeys to and from school, planning for special needs groups), the required data were similarly broad. For example, completion of the stormwater standard task required a variety of data such as public and private tree cover, impervious and pervious cover, and aerial imagery. From these inputs, analysis was performed to determine problematic stormwater areas, and ultimately to demonstrate areas that would benefit from increased tree care, protection or planting to enhance existing tree cover. Other tasks needed details on business or school locations and census data. With respect to a set of steps within a given task, if an adequate methodology already existed in the literature and was found to be suitable, for example Nowak et al.’s (2002) Priority Planting Index, it was used in the UFBM. If no methodology existed, one was developed. A general methodology for each task is found in Table 2.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Identify the task.</td>
<td>Identified through various methods in Stage 2 of the conceptual model (Figure 2).</td>
</tr>
<tr>
<td>2. Explore the variables that could be used to determine and fulfill the task.</td>
<td>Explore the possible variables and types of data inputs required for the task (e.g., population density, business locations, tree cover). Use existing methodologies if available.</td>
</tr>
<tr>
<td>3. Select the variables and prepare the data.</td>
<td>From the list of all possible variables that influence the task, select the variables that can be supported by the data that is available.</td>
</tr>
<tr>
<td>4. Choose methods and tools.</td>
<td>Choose the methods and tools to perform the necessary measures to identify greening locations based on the selected variables.</td>
</tr>
<tr>
<td>5. Display the data on the map or perform analysis (if required).</td>
<td>Using GIS, the data for each criterion are represented on the map (e.g., business and school locations). Depending on the type of data and the criterion, analysis may also be needed using ArcGIS tools.</td>
</tr>
<tr>
<td>6. This step is reserved for the final compilation of all tasks together to identify priority greening locations.</td>
<td>Using the weighted linear combination method to assign weights to each task (according to Focus Group Two) to identify areas where the urban forest will simultaneously attain multiple benefits within a community.</td>
</tr>
</tbody>
</table>
Measuring existing tree cover

Key to the development of the Planting Index (discussed below) was an up-to-date tree inventory of both publically and privately-owned trees. An updated inventory of publically-owned trees was acquired from the City of Thunder Bay while the extent and distribution of privately-owned trees were inventoried via remote sensing using ERDAS’ Stereo Analyst and ESRI’s ArcGIS. The private trees included those in the front, back and side yards of individual properties as well as forest stands (i.e., collections of trees located in relatively unmaintained environments within the city) (Figure 3). Two sets of high-resolution aerial imagery were acquired for the study area. The Ontario Ministry of Natural Resources provided 40 cm resolution near-infrared ADS40 imagery (leaf-off) and the City of Thunder Bay provided visible spectrum SID 20 cm QUAD (leaf-on). Both sets of imagery were flown in 2008 and provided a strong aerial image bank needed for the inventory. The following attributes using Stereo Analyst were collected for each privately-owned tree: tree location, visible canopy width (class), and tree type (conifer or deciduous).

Results

The UFBM as conceptualized earlier was applied using a case study approach for Thunder Bay. In this conceptualization, a total of seven management tasks were identified (Figure 2) including three standard tasks and four link table tasks. A fuller description of the seven tasks is provided below, including a rationale for their inclusion in the UFBM and the variables used to model their potential benefits. The results from each of these tasks are combined as two indices—the Maintenance Index and the Planting Index.

Tasks chosen for the case study application

Stormwater. The stormwater multi-functional standard task was selected to produce a priority greening planting scheme to reduce the peak, volume, and rate of stormwater runoff by targeting the highest concentration of impervious cover in Thunder Bay. This task focused primarily on environmental and economic capital. It was chosen because large tracts of impervious cover, combined with a network of drainage infrastructure designed to carry stormwater long distances, have created a host of water quality and maintenance issues for municipalities (Dwyer and Miller 1999; Goonetilleke et al. 2005), including Thunder Bay (North Shore Remedial Action Plan 2011). Trees capture rainfall and reduce runoff, and create favourable soil conditions that allow rainwater to permeate into and replenish groundwater (Wissmar et al. 2004). In addition, trees reduce the amount of pollutants entering streams and rivers, increase the quality of aquatic habitats, and ultimately replace or minimize the need for expensive hard infrastructure to manage the runoff (Dwyer and Miller 1999; Nowak 2006; Mullaney et al. 2015).

Priority Planting Index. The Priority Planting Index (PPI) is an index developed by researchers at the US Forest Service Northeastern Research Station (Nowak et al. 2002). It ranks tree planting locations based on population densities, tree stocking, and...
trees per capita. The intended results lead to a priority planting scheme to increase tree cover so as to benefit the greatest number of people. Many municipalities have used the PPI since its conception, providing recommendations for targeting planting locations in highly populated areas. Due to its wide acceptance and use by large and small municipalities alike, and its application in a variety of studies (Raciti et al. 2006; Morani et al. 2011), it was included in the UFBM as a standard task.

Emerald ash borer crisis planning. This standard task was selected to reduce the impact of ash loss once the emerald ash borer (EAB) (Agrilus planipennis) reaches Thunder Bay. Planning involves prioritizing schemes to increase greening activities in areas with high concentrations of ash cover and where no insecticide treatment would be prescribed for the ash. The task is to infill high concentration areas of present ash tree populations to offset the loss of tree cover and associated benefits in the near future. It was chosen primarily because the EAB is an invasive, non-native beetle and has been identified as one of the most destructive forest insects ever to invade North America (Province of Ontario 2014). The beetle is approaching Thunder Bay and the threat of extensive damage to the city’s ash tree population is real and significant (Vescio 2010).

Economic development. The economic development multi-functional link task was chosen to produce a priority-greening scheme based on business density that could increase tree cover so as to benefit the greatest number of businesses across Thunder Bay. It was also chosen as it is recognized that urban vegetation can support the well-being of people and stimulate urban business districts (Wolf 2004a; 2005; 2008; Yanick et al. 2010). Trees can help mitigate the effects of negative moods and stress, which are commonplace among shoppers and business people (Gullone 2000; Joye et al. 2010). They can impact consumer purchasing behaviour in a positive manner and increase the work ethic and productivity of business people. Wolf and others have concluded that greener enhances the perceived aesthetic qualities of urban areas and the appeal of commercial/retail districts (McPherson et al. 2006; Velarde et al. 2007; Wolf 2008; Joye et al. 2010).

Downtown core greening. This multi-functional link task was chosen to increase tree cover so as to benefit the greatest number of businesses and people in Thunder Bay’s two downtown cores, and to ultimately help establish more attractive, functional, and prosperous downtowns. Trees play an important role in improving the aesthetics of downtown neighbourhoods. Their presence in business areas can stimulate value and the perception of value, and can provide a welcoming facade to attract customers and tourists (Wolf 2006). In Thunder Bay, the downtown cores are arguably more important than other areas of the city in stimulating the growth and health of the business sector. This is because healthy, vibrant downtown cores are significant assets and are essential for the life of communities (Jacobs 1961; City of Thunder Bay 2005).

Children’s journey to and from school. This multi-functional link task was chosen to identify the need for additional tree cover along Thunder Bay roads to benefit and encourage children to walk or bike to school. It was chosen because trees play a significant part in growing strong healthy communities that embrace a culture of active-commuting to and from school (Wolf 2004b). This index was an attempt to help prioritize greening activities so as to benefit the largest number of people who walk and bike to school. It also serves as a means to encourage and increase active-commuting rates in youth who live close to schools. The direct and indirect benefits provided by green infrastructure, most notably trees, in regards to commuting by active transportation are numerous. One of the strongest forces is an increase in streetscape aesthetics. Beautified streetscapes are more attractive and are used more frequently by pedestrians (Wolf 2004b). The more people actively commute on a street, the more people use that street, and the safer the street becomes. The safety of children also increases through the integration of trees that safeguard youth from traffic while functioning as traffic-calming devices (Wolf and Bratton 2006). As pedestrian traffic increases, so do social interactions among neighbours and their community. These kinds of social interactions are valuable for the development of children (Taylor et al. 2001).

Trees also affect the biophysical environment and can lead to a variety of benefits for youth as pedestrians. Trees moderate the extreme temperatures in both summer and winter and provide shade from harmful UV rays (Raciti et al. 2006). The air and noise filtering capacity of green infrastructure can also be significant (Beckett et al. 2000; Escobedo and Nowak 2009) and creates more pleasant and healthy routes to and from school. Consequently with an increase in active transportation, the number of cars and congestion on roads and associated harmful emissions are reduced.

Needs of special groups. This multi-functional link task was selected to identify the need for additional tree cover required along Thunder Bay roads in proximity to care homes for people with special needs. It is primarily meant to increase the aesthetics, safety, and cleanliness around care home neighbourhoods and to moderate extreme temperatures, traffic and noise. Similar to children and the elderly, people with special needs (i.e., physically or mentally disabled) are often particularly vulnerable to land-use and transportation infrastructure designs. Until recent support for social equality in cities, many people with special needs had their mobility restricted due to hostile urban conditions. Temperature extremes, excessive traffic noise and pollution, and poorly designed infrastructure frequently restrict the mobility and independence of people with disabilities (Gant 1997).

Since the late 20th century, trees and other green infrastructure have been recognized for their therapeutic effects. Hospitals, geriatric centres, drug rehabilitation centres, care homes for the disabled and prisons have used trees and sensory gardens in healing because of the widespread benefits to patients and prisoners (Maller et al. 2009). Many studies have since reported that patients heal more quickly from physical and psychological trauma when exposed to urban green spaces, and have found that patients have increased motivation for physical exercise and have more social interactions (Gullone 2000; Rappe 2007; Maller et al. 2009). More specifically, Park et al. (2010) have demonstrated that exposure to urban green spaces promotes lower concen-
The restorative benefits of trees also directly and indirectly occur through a decrease in traffic noise and pollution, a reduction in temperature and wind extremes, and a decrease in exposure to UV light. These factors, mitigated by trees, play a significant role in determining if a resident will go outside. They can also help increase the overall well-being of a patient and increase the effectiveness of their therapy.

The maintenance index
This section describes construction of the Maintenance Index within the UFBM. Each of the tasks described earlier identifies areas of priority for urban forest maintenance or protection. The Maintenance Index represents an amalgamation of these priority areas. It identifies sites throughout the city where trees would perform multiple key functions and thus produce higher net benefits, hence the need for maintenance and protection especially in priority areas. The Maintenance Index does not account for present tree canopy cover and tree stocking as this is accounted for in the Planting Index discussed separately below.

The Maintenance Index was compiled using a weighted linear combination approach and is presented as Equation 1 where, $MI$ is the Maintenance Index, $SWGI$ is the stormwater greening task’s standardized score, $SNG$ is the special needs greening task’s standardized score, $STGI$ is the school travel greening task’s standardized score, $DCGI$ is the downtown core greening task’s standardized score, $EDGI$ is the economic development greening task’s standardized score, $PPI$ is the priority planting index standardized score, $EABGI$ is the emerald ash borer greening task’s standardized score and $w_j$ is the weight given to each of the seven sub-indices. Values of the Maintenance Index can vary from 0 to 100, where values tending toward 100 have a greater priority for maintenance.

In compiling the Maintenance Index, the contributing task scores (one from each of the seven tasks) were weighted equally rather than placing greater priority (or weight) on one or more tasks. Future research might involve a detailed sensitivity analysis to determine appropriate weighting schemes to explore how alternate weightings of the contributing sub-index scores affect the final Maintenance Index results. Additionally, some users may be inclined to place more weight on specific tasks, for example the standard tasks.

The results of the Maintenance Index for management areas at a resolution of 1 ha are shown in Figure 4. The higher the index score for a given management area, the greater the need to intensify maintenance and protection activities in order to sustain or to enhance the benefits received from tree cover. The index identifies priority locations, regardless of the number of

\[
MI = \frac{(SWGI \times w_j) + (SNGI \times w_j) + (STGI \times w_j) + (DCGI \times w_j) + (EDGI \times w_j) + (PPI \times w_j) + (EABGI \times w_j) \times 100}{\sum w_j}
\]  

(1)

terations of cortisol, lower pulse rate, lower blood pressure, and lower sympathetic nerve activity than do non-treed urban areas. Many of these benefits can be realized by greening the immediate premises because views through windows to greenspace throughout the day can be as valuable to patients with restricted access and mobility (Kaplan 1992; Maller et al. 2009).

The planting index
The Planting Index (PI) is the combination of seven chosen tasks from the Maintenance Index except it accounts for estimates in tree stocking. The spatially optimized services for the Planting Index are represented in Figure 5. The model demonstrated priority areas in both downtown core sections, along with other areas in the northwest and southwest sections of the city.

The tree cover data discussed earlier, and surface cover data provided by the City of Thunder Bay, which demonstrated the spatial extent and distribution of grass cover (soil and other plantable land) in the city, were both used to determine tree stocking, that is, the biologically viable sites to plant trees. The percent tree cover and grass cover were calculated for each 1 ha management area in the study area using the formula of Nowak et al. (2002) and presented as Equation 2. Each variable was standardized on a scale of 0 to 100, with 100 representing management areas with the highest priority for planting (i.e., low tree cover, high grass cover). Generally, areas with low tree stocking levels were identified as areas with greatest priority for tree planting.

\[
TS = 1 - \left[ 100 - \left( \frac{T}{T+G} * 100 \right) \right]
\]  

(2)

where, $TS$ is the tree stocking value (0–1), $T$ is percent tree cover, and $G$ is percent grass cover.

The tree stocking values, standardized on a scale of 0 to 100 were then subtracted from the Maintenance Index, also standardized on scale of 0 to 100, to provide an estimate of the important areas that are most suited for planting trees (i.e., the Planting Index). The Planting Index, therefore, accounted for the amount of pervious and impervious surfaces in the study area, as well as the extent and distribution of existing tree cover. It demonstrated spatially where trees should preferably be planted to optimize the predetermined benefits and attain desired sustainability goals. The index values range between 0 and 100, with highest values indicating the highest priority for planting (i.e., areas with low tree stocking and a high benefit score attained from the Maintenance Index).

\[
PI = MI - TS
\]  

(3)

where $PI$ is the Planting Index (0-100), $MI$ is the Maintenance Index, $TS$ is tree stocking. If TS > MI, then PI=0.
Figure 4
A map displaying the values of the Maintenance Index (MI) for management areas for most of the City of Thunder Bay. Each grid cell represents 1 hectare. Higher values (darker management areas) indicate a need for more focused maintenance and protection.
Figure 5
A map displaying the values of the Planting Index (PI) for management areas for most of the City of Thunder Bay. Each grid cell represents 1 hectare. Higher values (darker management areas) indicate a need for more focused tree planting. The management areas in the PI account for current tree stocking values.
Discussion and conclusion

This article develops a model that spatially optimizes the multifunctional services of green infrastructure in a community. The model is customizable and designed for potential use in other jurisdictions. The medium-scale (i.e., block scale or 100 x 100 m) of modeling within the UFBM and its use of commonly available GIS software to determine planting sites, make it compatible with existing smaller-scale models such as Kirnbauer et al. (2009) and i-Tree™ Design (Hirabayashi et al. 2011) in helping determine planting sites around homes and buildings. However its main purpose is to demonstrate how a municipality might strategize investments in its urban forest to maximize benefits while attaining a variety of sustainability goals. Figure 6 provides an example of how the UFBM output ranks the relative importance of priority planting areas. In this example, two 1-ha pixels are highlighted in the Thunder Bay north core which have Planting Index values approaching 100. Other areas of this older downtown core (darker red shades) are also recommended priority areas for planting (Figure 6). The UFBM developed in this research is the first of its kind to integrate the mitigating, multifunctional goods and services of trees with the tailored sustainability objectives of a community. The model brings together multidisciplinary techniques, and is carried out using interdisciplinary methods.

With resource and budgetary limitations faced by municipalities, the prototype UFBM provides a variety of benefits to communities. Decision makers are now provided with the tools to green their cities in an intelligent, cost-effective manner that maximizes benefits based on the needs of their communities. Urban foresters have the means to modify their existing comprehensive tree planting and maintenance regimes, or create new ones. For example, each city neighbourhood can be ranked based on the average score of its management areas. This ranking exercise provides an output of the neighbourhoods that should have increased frequency of, or increased resources, for pruning. Cities are often subdivided into annual pruning zones, with equal pruning priority assigned to each. Figure 7 demonstrates an example of defining five pruning zones for Thunder Bay based on the average score of its management areas. Zone 5 indicates the highest priority zone that commands more pruning resources and attention to provide a larger return on investment, while zones 1 and 2 have lesser priority due to current city priorities and status of the urban forest and street trees within these areas. This kind of priority-planning approach provides an opportunity to demonstrate new ways of integrating green infrastructure into the urban fabric and could inspire and persuade decision makers to increase funding toward greening initiatives.
Figure 7
Recommended frequency and resources allocated to pruning across sampled Thunder Bay neighbourhoods. Scores from the UFBM allows decision makers to create pruning cycles based on city-defined priorities and maximizing benefits from the urban forest. High priority zones for more frequent pruning are zones 4 and 5, including Downtown PA, Vickers and West End neighbourhoods.
or provide targeted tax incentives or rebates to homeowners and businesses in high priority areas.

Spatially optimizing urban forest services, as performed in the UFBM, also creates a culture of political and public support by demonstrating visually how an urban forest program contributes toward a municipality’s core vision and how it bolsters the mission of other progressive community planning strategies such as Smart Growth and climate change adaptation. The UFBM process requires multidisciplinary coordination and as a result can increase buy-in and vital collaboration from other municipal departments and community groups, normally lacking within municipal urban forest programs.

With accurate, visual representations of the urban forests’ influence on the goals of the community, the UFBM also creates better training, empowerment and development opportunities for field technicians, and thereby increases the effectiveness and the meaningfulness of fieldwork. Field workers are more informed about enhancing particular key benefits and are able to make better decisions in regards to site design, layout and species selection to facilitate the greatest potential of the targeted UFBM benefit(s).

Lastly, spatially optimized services can be used to inspire decision makers to identify and introduce new approaches to create spaces for trees through brownfield conversions, planting pit developments, and hardscape land conversions, especially in high priority areas.

The benefits-based model provided in this article presents a new comprehensive standard for managing the urban forest and other green infrastructure. The urban forest is highly proficient at benefiting a community’s economic, social and environmental capital. This model demonstrates the benefit of shifting the management of green infrastructure to a spatial environment in order to optimize co-benefits according to land use and other program and sustainability goals.

Acknowledgments

This research was supported, in part, by funding from MITACS Canada, The Canadian Tree Fund, and the City of Thunder Bay. We gratefully acknowledge Dr. Ulf Runesson for providing access to Lakehead University’s Natural Resource Management GIS and Remote Sensing Laboratory used for part of this study. Much of the public forest and base layer data for this research were graciously provided by the City of Thunder Bay. We also very much appreciate the comments received from two anonymous reviewers whose suggestions have greatly improved the manuscript.

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