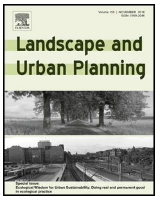
Landscape and Urban Planning 157 (2017) 457–467

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



Where to plant urban trees? A spatially explicit methodology to explore ecosystem service tradeoffs

E.W. Bodnaruk[a,*], C.N. Kroll[a], Y. Yang[b], S. Hirabayashi[c], D.J. Nowak[d], T.A. Endreny[a]

[a] *Department of Environmental Resources Engineering, State University of New York, College of Environmental Science and Forestry, Syracuse, NY 13210, USA*
[b] *USDA Forest Service Northern Research Station & The Davey Institute, Syracuse, NY 13210, USA*
[c] *The Davey Institute, The Davey Tree Expert Company, Syracuse, NY 13210, USA*
[d] *USDA Forest Service Northern Research Station, Syracuse, NY 13210, USA*

HIGHLIGHTS

- Tree planting scenarios were developed to meet Baltimore's goal of 40% tree cover.
- Each scenario optimized a single ecosystem service, benefit, or proxy.
- Tradeoffs between scenarios were evident.
- Differences in ecosystem services and benefits between scenarios were quantified.
- Methodology could be expanded into a decision support system for urban forestry.

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 18 August 2016
Accepted 27 August 2016

Keywords:
Urban forestry
Ecosystem services
Tradeoffs
Priority planting
Spatial pattern

ABSTRACT

Urban trees can help mitigate some of the environmental degradation linked to the rapid urbanization of humanity. Many municipalities are implementing ambitious tree planting programs to help remove air pollution, mitigate urban heat island effects, and provide other ecosystem services and benefits but lack quantitative tools to explore priority planting locations and potential tradeoffs between services. This work demonstrates a quantitative method for exploring priority planting and ecosystem service tradeoffs in Baltimore, Maryland using spatially explicit biophysical iTree models. Several planting schemes were created based on the individual optimization of a number of metrics related to services and benefits of air pollution and heat mitigation ecosystem services. The results demonstrate that different tree planting schemes would be pursued based on the ecosystem service or benefit maximized, revealing tradeoffs between services and priority planting locations. With further development including consideration of additional ecosystem services, disservices, user input, and costs of tree planting and maintenance, this approach could provide city planners, urban foresters, and members of the public with a powerful tool to better manage urban forest systems.

1. Introduction

Urban land cover and the global proportion of urban residents are increasing; by 2050, 86% of people in industrialized countries and 64% in developing countries are predicted to be urban dwellers (DESA, 2010). Urbanization can lead to many negative environmental effects that adversely impact humans and ecosystems including urban stream degradation (Elmore & Kaushal, 2008; Klocker, Kaushal, Groffman, Mayer, & Morgan, 2009), increased runoff and nutrient export (Duan, Kaushal, Groffman, Band, & Belt, 2012; Morgan, Kline, & Cushman, 2007), elevated species extinctions (Alberti et al., 2003), increased human exposure to air pollutants (Zhang, Shou, & Dickerson, 2009), the urban heat island effect (Imhoff, Zhang, Wolfe, & Bounoua, 2010; US EPA, 2008), and increased material consumption and energy use (Torrey, 2004). At the same time, cities have also advanced human well-being and have great potential for resource efficiency (Alberti et al., 2003; Seto, Sánchez-Rodríguez, & Fragkias, 2010).

---

* Corresponding author at: 1 Forestry Drive, 321 Baker Labs, Syracuse, NY 13210 USA.
E-mail addresses: ebodnaruk@gmail.com (E.W. Bodnaruk), cnkroll@esf.edu (C.N. Kroll), yyang31@syr.edu (Y. Yang), Satoshi.Hirabayashi@davey.com (S. Hirabayashi), dnowak@fs.fed.us (D.J. Nowak), te@esf.edu (T.A. Endreny).

http://dx.doi.org/10.1016/j.landurbplan.2016.08.016

The shifting paradigm recognizing humanity as part of nature has led to a focus on maintaining or enhancing ecosystem services as a means to manage environmental challenges and promote human health and well-being (Halpern et al., 2013; Roy, Byrne, & Pickering, 2012). Changes in land cover, vegetation, and human activities can provide ecosystem services which help alleviate some of the impacts of urbanization. Urban trees remove air pollution, mitigate urban heat island effects, and provide other ecosystem services (Nowak, Hirabayashi, Bodine, & Hoehn, 2013; Thomas & Geller, 2013; Wang et al., 2012). Increased recognition of the multiple ecosystem services and benefits provided by trees has encouraged municipal tree planting programs such as those in Los Angeles, New York City, Baltimore, and elsewhere around the world (Pataki et al., 2011).

Trees can be strategically planted and managed to optimize desired ecosystem services using knowledge of the heterogeneous urban landscape and human demographics. For instance, a location with high levels of air pollutants and high population density could be an optimal location to plant trees to improve health (Cabaraban, Kroll, Hirabayashi, & Nowak, 2013; Hirabayashi, Kroll, & Nowak, 2011; Morani, Nowak, Hirabayashi, & Calfapietra, 2011). Incomplete knowledge of the spatial and temporal variation of environmental parameters, ecosystem services, and human demographics and activities poses a challenge to more effective urban forest management (Jenerette, Harlan, Stefanov, & Martin, 2011; Pataki et al., 2011; Thomas & Geller, 2013). Priority planting methodologies have been developed (Locke et al., 2011; Locke, Grove, Galvin, O'Neil-Dunne, & Murphy, 2013; Morani et al., 2011), but have not quantified ecosystem services, benefits, or tradeoffs needed for a comprehensive decision-making context (Haase et al., 2014). The goal of this work is to demonstrate a spatially explicit modeling methodology that can explore priority planting based on multiple ecosystem services, benefits, the potentially complex tradeoffs between them (Carpenter et al., 2009; Rodríguez et al., 2006) and with further development, monetary and resource costs. This work explores optimal planting locations and tradeoffs for the mitigation of two common urban environmental stressors: air pollution and the urban heat island.

Differences in albedo, heat capacity, and thermal emissivity between the natural and built environment as well as reduced tree and vegetative cover (i.e. less shade and evapotranspiration) result in higher urban surface and air temperatures compared to rural surroundings, known as the urban heat island (Grimm et al., 2008; Imhoff et al., 2010; US EPA, 2008). The urban heat island exacerbates regional heat waves and is also of concern in a warming climate (Ye et al., 2011). Pre-existing medical conditions, age, and socioeconomic factors such as low income, poor housing, and lack of access to air conditioning are known to exacerbate risks of heat-related mortality (Hess, Saha, & Luber, 2014; Huang et al., 2011). Exposure to air pollutants and excessive heat in the urban environment are significant causes of hospitalizations and mortality (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Jenerette et al., 2011; Jerrett et al., 2009). Fine particulate matter ($PM_{2.5}$) and ozone (O_3) can cause asthma, respiratory disease, and premature mortality (Kheirbek et al., 2012). In the urban setting, air pollution is often exasperated due to industrial and transportation activities as well as the urban heat island (Zhang et al., 2009).

There are several challenges to defining, classifying, and valuing ecosystem services in ways that are useful for decision making (De Groot, Alkemade, Braat, Hein, & Willemen, 2010; Fisher, Turner, & Morling, 2009; Gómez-Baggethun & Barton, 2013). This work distinguishes between ecosystem services and the specific benefits they provide to humans, demonstrating different optimal planting schemes for a service as opposed to the benefit it provides. For instance, air pollutant removal via dry deposition occurs wherever there are trees, but the benefit to humans may be a more logical focus for decision making (Boyd & Banzhaf, 2007; Fisher et al., 2009; Kumar, 2010). Further, ecosystem services can support other services (Millennium Ecosystem Assessment, 2005) or can directly provide one or several benefits. Tracking benefits can therefore avoid problems of under- or over-counting services (Boyd & Banzhaf, 2007; Fisher et al., 2009; Kumar, 2010).

This work utilizes spatially explicit biophysical models based on the i-Tree suite of tools (i-Tree, 2014). i-Tree tools have been used by hundreds of researchers, urban foresters, and others around the world to quantify urban forest structure and ecosystem services. Using i-Tree models, we calculate heat mitigation and pollution removal ecosystem services and benefits (or their proxies) for current, increasing, and one decreasing increment of tree cover in Baltimore, Maryland. This allows us to quantify spatially explicit ecosystem service and benefit gradients, the services and benefits obtained from incremental changes in tree cover in different locations across Baltimore. Using the results of this localized gradient approach, we determine priority planting schemes optimized for individual services and benefits constrained to Baltimore's goal of 40% tree cover (Tree Baltimore, 2014). Similarities and differences between optimized tree planting schemes are explored, as well as tradeoffs between the services and benefits provided. The gradient results also provide insight on which trees are most important to protect or maintain particular services or benefits. With further development, this methodology could be used by municipalities and stakeholders around the world to better utilize a growing body of spatial demographic and biophysical data and to improve urban forest management, increase urban forest ecosystem services and benefits, or prioritize specific desired objectives or services.

2. Methods

2.1. Study area: Baltimore, Maryland

Baltimore is the site of a National Science Foundation urban long term social ecological research (LTSER) project aiming to understand the social and ecological trajectories of urban and urbanizing areas (Grove et al., 2013). The city is known to have a pronounced urban heat island effect (Brazel, Selover, Vose, & Heisler, 2000) exacerbated by warm winds carried into the city from suburban sprawl or upstream urbanization (Zhang et al., 2009). The Chesapeake Bay and Baltimore's urban streams are also significantly impacted by urbanization (Elmore & Kaushal, 2008), and the city's pollutant emissions far exceed those of neighboring counties (Boone, Fragkias, Buckley, & Grove, 2014).

The 2010 US Census divides Baltimore into 200 tracts and 653 block groups. High resolution imagery of Baltimore's land cover from the US Forest Service's Urban Tree Canopy (UTC) assessment project reveals that Baltimore has 24% tree cover, 18.9% short vegetation, 1.5% bare soil, 12.2% water, and 43.4% impervious surfaces (Grove & O'Neil-Dunne, 2009) (Fig. 1). The city's Baltimore Sustainability Plan includes a goal of establishing 40% tree cover by 2040 (Tree Baltimore, 2014).

2.2. Potential tree cover and tree cover gradients

Areas with short vegetation and bare soil land cover in Baltimore were identified as areas where tree cover could potentially increase. While cities could convert impervious surfaces to tree cover, the additional complication and expense of such a conversion warranted that such practices not be considered in this initial analysis. The spatial distribution of actual and potential tree cover was quantified using GIS and varied in scale according to the requirements of two spatially explicit models: a) the Pasath air temperature model (Yang, Endreny, & Nowak, 2013) that was run on a 370 m raster