Impervious surface thresholds for urban tree site selection

Michael G. Just[a],[*],[1], Steven D. Frank[a],[1], Adam G. Dale[b]

[a] Department of Entomology and Plant Pathology, North Carolina State University, Raleigh, NC 27695, USA
[b] Entomology and Nematology Department, University of Florida, Gainesville, FL 32611, USA

ABSTRACT

Impervious surfaces are a ubiquitous urban feature that increase temperature and tree drought stress and are a demonstrated indicator of *Acer rubrum* L. tree condition and insect pest abundance. We examined the relationship between *A. rubrum* condition, impervious surface cover, and *Melanaspis tenebricosa* (Comstock) abundance, a primary herbivore of urban *A. rubrum*, in eight cities across the southern distribution of *A. rubrum*. We predicted that the effects of warming, due to impervious surface, would be greater in warmer southern cities than in cooler northern cities. We found that impervious surface was a robust predictor of tree condition, but this effect was not significantly affected by background temperature. *Melanaspis tenebricosa* abundance was a function of impervious surface and background temperature, with greatest abundances occurring at mid latitudes. Based on these relationships, we developed impervious surface thresholds to inform site selection for *A. rubrum* throughout the southeastern USA. Planting criteria based on habitat characteristics should maximize urban tree longevity and services provided.

1. Introduction

Trees are an important part of urban landscapes. They provide multiple ecosystem services that improve both human (Sanesi et al., 2011) and environmental health (Aber, 1992; Escobedo and Nowak, 2009). Urban trees provide aesthetic beauty (Price, 2003), provide people with a sense of well-being (Bratman et al., 2015), generate higher property values (Donovan and Butry, 2010; Pandit et al., 2013), and their canopy cover is correlated with safer neighborhoods (Kondo et al., 2017). Urban trees also filter air and water (Aber, 1992; Escobedo and Nowak, 2009), cool the environment via direct shade and transpiration (Bowler et al., 2010; Balogun et al., 2014), and sequester carbon (Nowak et al., 2013) in addition to other services (McPherson et al., 1997). Unfortunately, urban trees are often subject to stress and insect pest infestations that can reduce physiological functions, growth, and ecosystem services (Meineke et al., 2013; Dale and Frank, 2014a; Youngsteadt et al., 2014). A primary challenge in mitigating these factors and designing more sustainable urban landscapes is selecting plant species that will thrive with minimal pesticide, water, or other non-renewable inputs. To meet this challenge, landscape planners and maintenance professionals must be able to predict how location-specific conditions will affect long-term tree health.

Trees planted in urban landscapes are often surrounded by impervious surface — a common urban land-cover class — such as roadways, parking lots, and sidewalks. Trees surrounded by impervious surfaces have much shorter life expectancies than trees grown in parks or natural areas (Watson et al., 2014) and impervious surface cover is correlated with many tree stressors, including drought conditions, inadequate soil volumes, pollutants, and warmer temperatures (Timilsina et al., 2014; Guo et al., 2015; Mullaney et al., 2015b; Chen et al., 2017), which can lead to poor performance and hastened death. For example, the soil beneath impervious surfaces is regularly very compact (e.g., 95% Proctor) to provide structural support to the impervious surface that rests upon it. Urban trees roots are often unable to sufficiently penetrate urban soils resulting in inadequate uptake of water and nutrients (Grabosky et al., 2001), even in soils with adequate water and nutritional content. Moreover, the lack of plant available water in compact soils may be exacerbated by urban warming that increases water demand, further reducing tree performance. (Meineke and Frank, 2018).

Impervious surface cover is also a predictor of insect pest abundance and tree condition in urban areas (Dale et al., 2016). For example, as little as 2 °C of urban warming can increase insect pest abundance 200-fold and reduce tree condition from 'Good' to 'Poor' indicating a decline in overall structure and health (Dale and Frank, 2014b). Likewise, urban warming can reduce tree physiological functions like photosynthesis and, consequently, growth and carbon sequestration (Vogt et al., 2015; Meineke et al., 2016). Thus, it is imperative to select the

right tree for the right place to ensure long-term tree health and the fulfillment of landscape designs and planning goals.

Identifying and using urban tree planting sites with salubrious conditions during landscape planning is necessary to maximize tree longevity and minimize maintenance costs (Mullaney et al., 2015a; Vogt et al., 2015). Previous research in Raleigh, NC, USA has shown that higher proportions of impervious surface cover adjacent to red maples (*Acer rubrum* L.) increases tree canopy temperature (Dale and Frank, 2014b), water stress (Dale and Frank, 2017), and the abundance of gloomy scale (*Melanaspis tenebricosa* (Comstock)); a primary *Acer* spp insect pest in the eastern US (Metcalf, 1912). The combination of these factors worsens tree condition (Dale et al., 2016). From this work, impervious surface thresholds for tree condition based on the proportion of impervious surface surrounding a tree (20 m radius) were developed for Raleigh, NC. For example, at or below 32% impervious cover surrounding a tree, the most likely condition for an *A. rubrum* individual was Good, whereas at sites with greater than 62% impervious cover were most often Poor.

The background temperature of a given geography can modulate the effects of urban warming on tree stress (Wienert and Kuttler, 2005; Way and Oren, 2010). Accordingly, an equal amount of warming or drought in a cool city may be less detrimental than in a hot city, where trees are not only stressed by urban heat but also background temperature. Thus, we hypothesized that impervious surface cover would remain an effective predictor of urban tree condition in additional cities, but that the strength of this effect would vary based on the background climate of the geographic location in which trees were measured. Here, our goal was to develop *A. rubrum* planting site recommendations based on impervious surface thresholds for use by landscape architects, urban foresters, and other landscape professionals in the southeastern USA. This work has the potential to serve as a template to develop urban planting recommendations for tree species in worldwide locations based on location-specific conditions (e.g., impervious surface).

2. Methods

2.1. Study sites

Our study was conducted in eight cities in the southeastern USA (Asheville, NC, Atlanta, GA, Charlotte, NC, Gainesville, FL, Knoxville, TN, Newark, DE, Raleigh, NC, and Savannah, GA) from October 2016 – March 2017 (Table 1). Study cities covered approximately 10 degrees of latitude, with a range of 13.1–20.5 °C in mean annual temperature (Arguez et al., 2010). Our focal species, *A. rubrum,* can flourish under a wide range of environmental conditions and is one of the most widely distributed species in the eastern USA (Abrams, 1998) and *Acer* spp are the most commonly planted street trees in the USA (Raupp et al., 2006).

Tree locations were obtained from city tree inventories; in cities without inventories, local collaborators provided information on locations with planted *A. rubrum*. Using these locations and street maps, we identified potential study locations in ESRI ArcMap 10.1, any tree or location that was within 30 m of a street was retained, this subset ensured that we sampled planted trees. For each city, we then used a stratified random sampling procedure on the subset to select study trees located across a range of impervious surface values. We used remotely-sensed impervious surface estimates for the sampling procedure (Xiam et al., 2011). These procedures resulted in 30–36 study trees per city (total $n = 265$) that occurred across a range of planting site impervious surface proportions (range: 0–100%; mean: 56%). All trees were located on public property and the study-wide mean minimum distance between trees was approximately 326 m.

2.2. Data collection

To determine *M. tenebricosa* abundance, we pruned four randomly selected terminal twigs (30 cm), one from each cardinal direction, from each tree using a pole pruner. In the laboratory, we counted live *M. tenebricosa* adult females using a dissecting microscope per 15 cm of twig. Our statistical unit was an individual tree and we recorded *M. tenebricosa* counts as the mean value of the four twigs. Counts were $\log_{10}(x+1)$ transformed prior to analyses.

We estimated the proportion of land cover that was impervious surface within a ~ 20 m radius (0.126 ha) of each tree using the 'Pace-to-Plant' technique (Dale et al., 2016). This technique utilizes four transects that each originate at the base of a tree and are situated 90° apart from one another. The initial transect is identified as the one with the closest adjacent impervious edge and the transect intersects this impervious edge at 45°. The proportion of impervious cover within ~ 20 m (i.e., 25 paces) of each tree is estimated as the sum of the paces ($x/100$) that occur upon impervious surface. This technique has been tested on a variety of impervious surface configurations and also produces results that are highly correlated (i.e., $R^2 = 0.96$) with those of GIS based analyses (Dale et al., 2016).

Tree condition ratings are a tool commonly used by urban tree professionals as a qualitative, rapid method to estimate overall tree health (e.g., Berrang et al., 1985; Koeser et al., 2014). We used an ordinal rating system to similar to Dale and Frank (2014b), and we assigned each tree a rating of Good, Fair, Poor, or Dead (Dead trees were not included in our analyses). Trees in Poor condition had broken or multiple central leaders, exposed or self-girdling roots, injuries, multiple dead branches, branch tip dieback, sparse canopies, and/or scorched or chlorotic leaves. Fair trees had less severe indicators of tree decline than Poor trees, including the presence of some dead branches, some root exposure, some canopy dieback, and/or wilting or discolored leaves. Good trees had no or minimal dead branches, no injuries, and

Table 1
Study cities and tree characteristics.

City, State	Latitude (°)	Temp(°C)	n	Impervious surface (%)		*M. tenebricosa* abundance		Nearest Neighbor (m)	Tree Condition		
									Good	Fair	Poor
Newark, DE	39.68	13.1	36	55.4 (4.1)	ab	6.4 (3.2)	c	91	9	14	13
Asheville, NC	35.59	13.6	35	54.9 (4.5)	ab	7.7 (4.1)	c	333	10	13	12
Knoxville, TN	35.96	14.3	36	55.2 (4.5)	ab	37.4 (16.0)	bc	104	10	11	15
Raleigh, NC	35.78	15.9	32	53.6 (3.9)	ab	57.9 (17.2)	a	740	8	10	14
Charlotte, NC	35.23	16.1	30	57.5 (4.2)	ab	34.5 (10.2)	ab	332	7	8	15
Atlanta, GA	33.75	16.5	31	69.5 (4.8)	a	33.3 (9.3)	ab	104	5	14	12
Savannah, GA	32.08	19.3	30	66.2 (3.8)	a	6.3 (2.1)	bc	279	6	9	15
Gainesville, FL	29.65	20.5	35	41.0 (4.6)	b	6.9 (3.7)	c	622	13	13	9
All			265	56.3 (1.6)		23.4 (3.6)		326	68	92	105

Mean values are presented for impervious surface cover and *Melanaspis tenebricosa* abundance with standard error of the mean in parentheses. Different letters indicate differences between cities using Benjamini–Hochberg (BH) post hoc comparisons (α = 0.05) on Kruskal–Wallis analysis of variable of interest. Tree condition reports the number of *Acer rubrum* trees per condition rating per city. Cities are listed in ascending order of mean winter temperature.