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Impervious surface thresholds for urban tree site selection

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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

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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.

									Tree Condition		
City, State	Latitude (°)	Temp(°C)	n	Impervious surface (%)		*M. tenebricosa* abundance		Nearest Neighbor (m)	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.

had healthy leaves with mostly full to full canopies.

Background temperature data (800 m^2 temperature spatial grids of monthly 30-yr normals) was sourced from the PRISM Climate Group at Oregon State University (http://prism.oregonstate.edu, 21 April 2017). We calculated mean annual and seasonal (mean minimum winter [December, January, February], mean maximum summer [June, July, August]) temperature by extracting surface temperature values from temperature grids at each study tree's location.

2.3. Statistical analyses

All statistical analyses were performed in R version 3.3.2 (R Core Team, 2016). When considering all cities, we modeled *M. tenebricosa* abundance as a function of impervious surface cover and background temperature with a quadratic regression. We created three models, one for each background temperature variable, and retained the one with best fit: mean minimum winter temperature. Within cities, *M. tenebricosa* abundance was modeled as a function of impervious surface using linear regression.

Across cities, we modeled tree condition as a function of impervious surface cover or *M. tenebricosa* abundance as main effects with background temperature as a covariate. Within-city models contained only main effects. We used ordinal logistic regression, *polr* function of the 'MASS' package (Venables and Ripley, 2013), for all tree condition models, where tree condition was ordered Good to Fair to Poor. The model with best fit (i.e., the greatest likelihood ratio index) was retained. Tree condition thresholds were identified from the model intercepts (Guisan and Harrell, 2000) and are delineated as the value of impervious surface where the most likely tree condition transitioned from one condition to another (i.e., Good to Fair, Fair to Poor).

3. Results

Across all cities, *M. tenebricosa* abundance was a function of impervious surface cover and mean winter temperature ($F_{3,259} = 20.7$, *adj.* $R^2 = 0.18$, $P < 0.001$; Table A1). Within cities, *M. tenebricosa* abundance was a function of impervious surface cover in 4 of 8 study cities, those occurring in mid latitudes of the study (Table A2).

Overall, *M. tenebricosa* abundance was a significant, but modest (*likelihood ratio index* = 0.205) predictor of tree condition. Considering cities individually, *M. tenebricosa* abundance was a significant predictor ($P < 0.001$) of tree condition for 4 of the 8 study cities (Table A3). Impervious surface cover was consistently a significant predictor of tree condition across and within cities ($P < 0.001$), and the likelihood ratio index for each of these models was always greater when using impervious surface as compared to *M. tenebricosa* abundance as the predictor (Table A4). While tree condition was a function of impervious cover, background temperature was not a significant covariate, indicating that the effect of impervious cover on tree condition was not modulated by background temperature in the study cities.

Impervious surface planting thresholds for *A. rubrum* were identified across and within each city (Fig. 1). Considering all cities, we found the Good to Fair threshold at 36% impervious surface cover, and Fair to Poor at 61%. Within cities, the thresholds ranged from 29–44% for Good to Fair and 54–69% for Fair to Poor, with mid-latitude study cities generally transitioning to Poor condition at lower percentages of impervious surface cover.

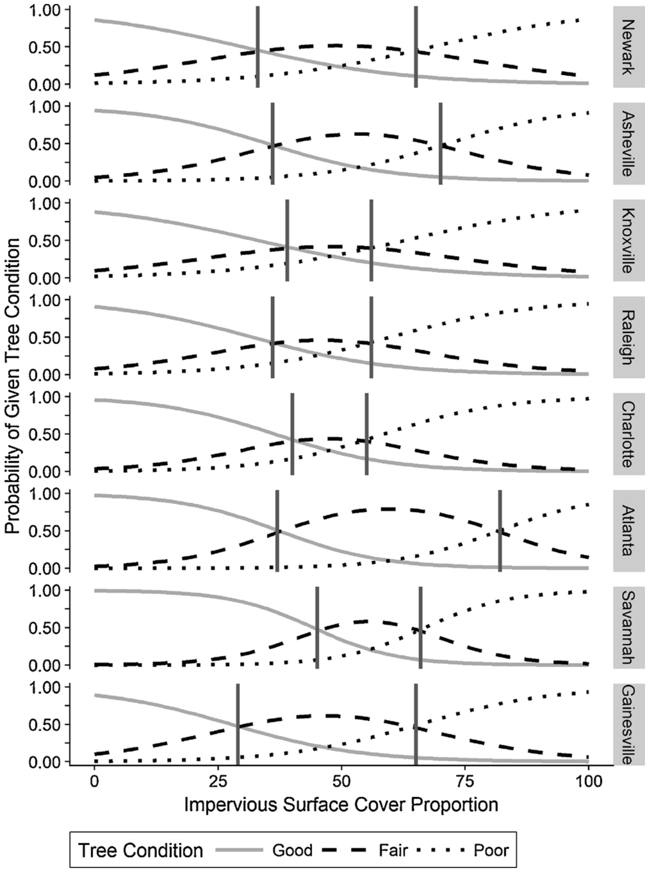

Fig. 1. Impervious surface cover thresholds for *Acer rubrum* plantings. These plots demonstrate the value of impervious cover at which the tree condition with the greatest probability of occurrence transitions from Good to Fair (left vertical bar) and Fair to Poor (right vertical bar). Tree condition probabilities (Good [solid gray line], Fair [dashed black line], Poor [dotted black line]) are derived from an ordinal logistic regression for each city, where tree condition is a function of the proportion of impervious surface cover within a 20 m radius of the planting site. Plots are arranged top to bottom in ascending order of mean winter temperature.

4. Discussion

Understanding how location-specific characteristics affect tree condition is necessary to make informed planning decisions about tree placement and maintenance in urban areas. In this study, we examined the effect of *M. tenebricosa* abundance (a primary insect pest of *Acer* spp) and impervious surface cover (a ubiquitous and important driver of tree health within urban areas) on *A. rubrum* condition in cities that differed in background temperature across the southern distribution of *A. rubrum*. We found that the percentage of impervious surface surrounding *A. rubrum* planting sites was a good predictor of tree condition across the southeastern USA and should be considered a useful criterion for urban landscape designs that include *A. rubrum*. Considering all study cities, the odds of an individual *A. rubrum* transitioning to a worse condition were 1.07 times greater with each percentage increase in impervious surface cover. Thus, within the southeastern USA, landscape professionals can expect *A. rubrum* individuals planted at sites with 36% or less impervious surface cover (~20 m radius) to be in good condition.

We hypothesized that the effect of impervious cover on tree condition would differ based on the background temperature at the tree's geographic location and would thus require different impervious surface thresholds. Trees surrounded by large percentages of impervious surface tend to be more water stressed due to higher temperatures, less soil moisture availability, and increased transpiration; these conditions or their combined effects can reduce tree growth and health (Cregg and Dix, 2001). As in other studies, we found that *M. tenebricosa* abundance was positively correlated with impervious surface (Dale and Frank, 2014b, 2017). Additionally, we found that *M. tenebricosa* abundances were a function of impervious cover and background temperature, with greatest abundances in the middle of the temperature distribution of our study cities. However, *M. tenebricosa* are not vagile and cannot flee from inclement temperatures. This suggests that while *M. tenebricosa* has a southern USA distribution, the combination of urban heat and warmer background temperature may be too hot for *M. tenebricosa* (Fig. 1). Yet, *M. tenebricosa* abundance was not a robust predictor of tree condition, and background temperature was not a significant covariate in our model predicting tree condition with impervious surface as our predictor. Thus, for *A. rubrum* urban planning and planting purposes, regional temperature appears to be less important than impervious surface cover in its southern distribution.

5. Conclusion

A straightforward way to maximize urban tree health and to ensure longevity of tree-provided services is to put the right tree in the right place. Our impervious surface thresholds, which identify transitions in *A. rubrum* expected condition — Good to Fair at 36% impervious surface cover and Fair to Poor at 61% — are one way to guide putting the right tree in the right place within the southeastern USA. When available, city-specific thresholds (e.g., Fig. 1) may provide additional insight. Moreover, this research provides a general framework for developing species-specific planting site recommendations based on location-specific conditions, such as pit soil volume, soil pH (affected by deicing solutions or concrete weathering), or salinity levels (increased salt levels can create drought-like conditions), that may be more important for some species or cities. However, we contend that impervious surface is likely a good predictor of tree condition for other cities and tree species given its ubiquity in urban locations. Specific recommendations for species, locations, or both can be easily incorporated into urban tree planning decisions and will complement existing local expertise and industry standards.

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Appendix

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Table A1
Quadratic model details for predicting *Melanaspis tenebricosa* abundance by impervious surface cover (%) and mean minimum winter temperature (°C) across all study cities.

Parameter	Estimate ± SE	*t*
Intercept	0.28 (0.1)	2.30*
Impervious surface (%)	0.01 (0.0)	5.11***
Mean Winter Temp (°C)	0.07 (0.02)	3.10**
Mean Winter Temp^2 (°C)	−0.02 (0.01)	−4.48***

* P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

Table A2
Melanaspis tenebricosa abundance ($\log_{10}[x+1]$) as a function of impervious surface cover (%) by study city.

		overall model					
City, State	n	F	Adj. R2	term	Estimate	SE	t
Newark, DE	36	1.0	0.00	intercept	0.52	0.2	2.3*
				impervious surface	0.00	0.0	−1.0
Asheville, NC	35	9.7**	0.2	intercept	−0.33	0.2	−1.6
				impervious surface	0.01	0.0	3.1**
Knoxville, TN	36	7.6**	0.16	intercept	−0.20	0.3	−0.6
				impervious surface	0.01	0.0	2.8**
Raleigh, NC	32	9.6**	0.22	intercept	0.08	0.4	0.2
				impervious surface	0.02	0.0	3.1**
Charlotte, NC	30	27.1***	0.47	intercept	−0.69	0.3	−2.2*
				impervious surface	0.03	0.0	5.2***
Atlanta, GA	31	1.6	0.02	intercept	0.39	0.4	0.9
				impervious surface	0.01	0.0	1.3

(*continued on next page*)

Table A2 (*continued*)

		overall model					
City, State	n	F	Adj. R2	term	Estimate	SE	t
Savannah, GA	30	0.4	−0.02	intercept	0.23	0.4	0.7
				impervious surface	0.00	0.0	0.6
Gainesville, FL	35	4.2*	0.09	intercept	−0.03	0.2	−0.2
				impervious surface	0.01	0.0	2.1*

Cities are listed in ascending order of mean winter temperature. * $P \le 0.05$, ** $P \le 0.01$, *** $P \le 0.001$.

Table A3
Ordinal logistic regression model results for predicting tree condition as a function of *Melanaspis tenebricosa* abundance ($\log_{10}[x+1]$).

		overall model					
City, State	n	χ^2	likelihood ratio index	term	Estimate	SE	Wald Z
Newark, DE	37	3.5	0.10	y > =Fair	0.81	0.4	1.9
				y > =Poor	−0.93	0.4	−2.2*
				M. tenebricosa	1.13	0.6	1.8
Asheville, NC	35	13.4***	0.36	y > =Fair	0.51	0.4	1.2
				y > =Poor	−1.45	0.5	−3.0**
				M. tenebricosa	7.68	4.5	1.7
Knoxville, TN	36	16.7***	0.42	y > =Fair	0.38	0.4	0.9
				y > =Poor	−1.40	0.5	−2.9**
				M. tenebricosa	2.04	0.7	2.9**
Raleigh, NC	32	11.8***	0.35	y > =Fair	−0.28	0.6	−0.5
				y > =Poor	−2.11	0.7	−2.9**
				M. tenebricosa	1.53	0.5	3.1**
Charlotte, NC	30	6.9**	0.24	y > =Fair	0.48	0.5	0.9
				y > =Poor	−0.93	0.5	−1.8
				M. tenebricosa	1.18	0.5	2.4*
Atlanta, GA	31	3.0	0.11	y > =Fair	1.12	0.6	2.0*
				y > =Poor	−1.14	0.6	−2.0*
				M. tenebricosa	0.73	0.4	1.7
Savannah, GA	30	0.3	0.01	y > =Fair	1.24	0.5	2.4*
				y > =Poor	−0.16	0.5	−0.3
				M. tenebricosa	0.34	0.6	0.6
Gainesville, FL	37	3.5	0.10	y > =Fair	0.21	0.4	0.6
				y > =Poor	−1.72	0.5	−3.4***
				M. tenebricosa	2.22	0.9	2.4*
All	266	53.3***	0.21	y > =Fair	0.58	0.2	3.7***
				y > =Poor	−1.13	0.2	−6.7***
				M. tenebricosa	1.20	0.2	6.6***

Cities are listed in ascending order of mean winter temperature. * $P \le 0.05$, ** $P \le 0.01$, *** $P \le 0.001$.

Table A4
Ordinal logistic regression model results for predicting tree condition as a function of impervious surface cover (%).

		overall model					
City	n	χ^2	likelihood ratio index	term	Estimate	SE	Wald Z
Newark, DE	37	15.5***	0.39	y > =Fair	−1.71	0.9	−1.9
				y > =Poor	−4.00	1.1	−3.6***
				impervious surface	0.06	0.0	3.4***
Asheville, NC	35	25.0***	0.57	y > =Fair	−2.79	1.0	−2.8***
				y > =Poor	−5.59	1.4	−4.1***
				impervious surface	0.08	0.0	3.9***
Knoxville, TN	36	16.4***	0.41	y > =Fair	−2.00	1.0	−2.1*
				y > =Poor	−3.78	1.1	−3.5***
				impervious surface	0.06	0.0	3.4***
Raleigh, NC	32	15.1***	0.43	y > =Fair	−2.28	1.1	−2.4*
				y > =Poor	−4.28	1.3	−3.4***
				impervious surface	0.07	0.0	3.3***
Charlotte, NC	30	16.4***	0.48	y > =Fair	−3.11	1.4	−2.3*
				y > =Poor	−4.99	1.6	−3.2***
				impervious surface	0.09	0.0	3.2***
Atlanta, GA	31	25.4***	0.64	y > =Fair	−3.62	1.6	−2.3*
				y > =Poor	−7.94	2.1	−3.7***
				impervious surface	0.10	0.0	3.6***

(*continued on next page*)

Table A4 (*continued*)

City	n	overall model		term	Estimate	SE	Wald Z
		χ^2	likelihood ratio index				
Savannah, GA	30	23.4^{***}	0.62	y > =Fair	−5.23	1.9	-2.8^{**}
				y > =Poor	−7.90	2.3	-3.5^{***}
				impervious surface	0.12	0.0	3.5^{***}
Gainesville, FL	37	15.5^{***}	0.39	y > =Fair	−2.10	0.8	-2.8^{**}
				y > =Poor	−4.98	1.2	-4.3^{***}
				impervious surface	0.08	0.0	4.0^{***}
All	266	152.1^{***}	0.49	y > =Fair	−2.28	0.4	-6.4^{***}
				y > =Poor	−4.64	0.5	-10.4^{***}
				impervious surface	0.07	0.0	10.2^{***}

Cities are listed in ascending order of mean winter temperature. * $P \leq 0.05$, ** $P \leq 0.01$, $^{***}P \leq 0.001$.

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