

## Influence of seasonality and vegetation type on suburban microclimates

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**Abstract** Urbanization is responsible for some of the fastest rates of land-use change around the world, with important consequences for local, regional, and global climate. Vegetation, which represents a significant proportion of many urban and suburban landscapes, can modify climate by altering local exchanges of heat, water vapor, and CO<sub>2</sub>. To determine how distinct urban forest communities vary in their microclimate effects over time, we measured stand-level leaf area index, soil temperature, infrared surface temperature, and soil water content over a complete growing season at 29 sites representing the five most common vegetation types in a suburban neighborhood of Minneapolis–Saint Paul, Minnesota. We found that seasonal patterns of soil and surface temperatures were controlled more by differences in stand-level leaf area index and tree cover than by plant functional type. Across the growing season, sites with high leaf area index had soil temperatures that were 7°C lower and surface temperatures that were 6°C lower than sites with low leaf area index. Site differences in mid-season soil temperature and turfgrass ground cover were best explained by leaf area index, whereas differences in mid-season surface temperature were best explained by percent tree cover. The significant cooling effects of urban tree canopies on soil temperature imply that seasonal changes in leaf area index may also modulate CO<sub>2</sub> efflux from urban soils, a highly temperature-dependent process, and that this should be considered in calculations of total CO<sub>2</sub> efflux for urban carbon budgets. Field-based estimates of percent tree cover were found to better predict mid-season leaf area index than satellite-derived estimates and consequently offer an approach to scale up urban biophysical properties.

**Keywords** Urban ecology · Plant functional type · Leaf area index · Soil temperature · Surface temperature · Phenology

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## Introduction

Vegetation alters local, regional, and global climate in part by controlling the exchanges of energy, water and carbon between land and the atmosphere (Foley et al. 2003). Plants exert direct control over land–atmosphere exchanges of water and carbon through the physiological processes of transpiration, photosynthesis, and respiration. In addition, plants indirectly control these land–atmosphere fluxes through biophysical properties, such as albedo, surface roughness, and leaf area index (LAI) or vegetation density, that drive changes in local microclimates (Smith and Johnson 2004; Tanaka and Hashimoto 2006).

In urban and suburban areas, vegetation cover has been shown to be important for explaining spatial differences in urban and suburban evapotranspiration rates (Grimmond and Oke 1999; Spronken-Smith 2002), net CO<sub>2</sub> exchange (Soegaard and Møller-Jensen 2003; Moriwaki and Kanda 2004), and microclimate characteristics (Bonan 2000; Byrne et al. 2008; Huang et al. 2008). For example, Spronken-Smith (2002) found that residential neighborhoods in Christchurch, New Zealand with high vegetation cover had greater evapotranspiration rates than did neighborhoods with less vegetation cover. Grimmond and Oke (1999) showed that the variability among North American cities in evapotranspiration rates was related to differences in the percent cover of vegetated surfaces, in addition to differences in precipitation and irrigation inputs. Determining the causes of spatial variation in CO<sub>2</sub> fluxes in cities is relatively more complex, and depends on housing density and traffic volume (Nemitz et al. 2002; Coutts et al. 2007); however Moriwaki and Kanda (2004) showed that tree cover played an important role in driving the summertime CO<sub>2</sub> sink observed in a residential area of Tokyo, Japan. Previous studies have also found that vegetation cover and composition influence urban microclimate characteristics, such as air temperature, soil temperature, and surface temperature (Bonan 2000; Byrne et al. 2008; Huang et al. 2008). These ideas have been extended by several recent studies showing that the density of vegetation or LAI plays an important role in explaining the spatial variation in urban surface temperatures as well (Hardin and Jensen 2007; Jenerette et al. 2007). LAI provides a measure of the total amount of leaf surface area that can exchange heat, water, and CO<sub>2</sub> with the atmosphere, whereas percent cover provides only a measure of the presence or absence of vegetation. Percent vegetation cover, however, is a relatively easier metric to assess in urban areas using a variety of methods, including field-based inventories, aerial photographs, and satellite imagery (Walton et al. 2008).

Land surface models, which represent land–atmosphere exchanges of energy, water and carbon, are rarely parameterized for urban and suburban ecosystems, in part because these landscapes are so spatially complex (Pielke and Avissar 1990). Accounting for the direct and indirect climate effects of distinct urban ecological communities and plant compositions would greatly advance the development of these models. Plant functional types (*e.g.* evergreen needle-leaved trees or deciduous broad-leaved trees) offer a way to organize ecologically distinct groups of plants that represent major differences in physiology, biophysical properties, and leaf phenology (Reich et al. 1998), and are currently used to model the direct and indirect climate effects of vegetation in natural and agricultural ecosystems (Foley et al. 1998). Leaf phenology, or seasonal variation in LAI, is one of the most important ways by which different types of plants can influence the physical environment over time (Arora and Boer 2005). For example, evergreen trees have relatively constant leaf area throughout the year, while deciduous trees show much greater seasonal variability in leaf area. These seasonal differences in LAI influence the amount of solar radiation intercepted by the canopy, and transpiration and photosynthesis rates, over the course of the growing season.

In this study, we examined how distinct urban forest communities vary in their microclimate effects over the course of the growing season. We measured both the vegetation type differences and seasonal patterns of stand-level LAI, soil temperature, infrared surface temperature, and soil water content over a full growing season in a suburban residential neighborhood of Minneapolis–Saint Paul, Minnesota. Our objectives were to: 1) determine how seasonal patterns of leaf development and microclimate are influenced by plant functional type; 2) determine how seasonal changes in LAI modulate urban forest microclimates; 3) evaluate the ability of percent tree cover and LAI to explain the variation in mid-season microclimates and percent ground cover among suburban vegetated areas; and 4) evaluate the ability of satellite-derived and field-based estimates of tree cover to predict and scale up the variation in urban biophysical properties in a suburban neighborhood.

## Methods

### Study area and site selection

In the Upper Midwest region of the United States, urban and suburban land use represents a significant percentage (over 14%) of the regional land surface. Suburban, low density residential land use, in particular, is increasing more rapidly than any other land-use type in the region (Radeloff et al. 2005). Our study area was located in a first-ring suburban neighborhood in the Minneapolis–Saint Paul metropolitan area in east-central Minnesota. The landscape (approximately 9 km<sup>2</sup>) was a single-family residential area located at the border of Saint Paul and the suburbs of Roseville, Falcon Heights, and Lauderdale. Vegetated surfaces represented over 50% of the landscape, consisting of isolated trees, forested patches, and open turfgrass lawns.

We used true color aerial orthophotos with 0.15 m resolution (State of Minnesota 2006) to identify potential study sites that had dimensions of approximately 30 m×30 m and were representative of the five most common vegetation types in the area (Table 1). These five vegetation types consisted of three distinct plant functional types, deciduous broad-leaved trees, evergreen needle-leaved trees, and cool-season turfgrass lawns. We included two categories of deciduous tree cover because we observed a wide range of cover among the deciduous sites. We divided the deciduous sites into those having sparse or low cover (DL), with ≤40% tree cover, and those having high cover (DH), with ≥60% tree cover. Using two levels of deciduous tree cover allowed us to evaluate the relative importance of plant functional type versus percent tree cover in influencing urban biophysical properties. We did not find a wide range of tree cover in areas dominated by evergreen species, so we could not employ a full-factorial experimental design. We selected sites that were approximately 30 m×30 m in area because that size was large enough to minimize edge effects in ground-based optical LAI measurements but small enough to encompass relatively homogenous stands of the different vegetation types. The area of the sites also corresponds approximately to the pixel sizes of satellite remote sensing imagery that is commonly used for mapping urban features over extensive areas (*e.g.*, 30-m Landsat or 20-m SPOT). Based on a spring field survey, we verified the vegetation composition of potential sites and eliminated those sites with significant discontinuities in vegetation type, steep slopes that would complicate optical LAI measurements, or obstacles such as large fences. We selected sites where the ground cover was dominated by turfgrass because that was the most common ground cover type in the area. We did not stratify sites based on land management practices (*e.g.*, fertilization, irrigation, mowing, or pruning) because our 30 m×30 m sites encompassed the land of

**Table 1** Forest characteristics of 29 suburban study sites, grouped by vegetation type. Data are means  $\pm 1$  standard deviation. The species listed represent  $>60\%$  of the trees counted in each vegetation type and are listed alphabetically

Vegetation type	Label	Number of Sites ( <i>n</i> )	Tree Cover (%)	Basal Area ( $\text{m}^2 \text{ha}^{-1}$ )	Tree Height (m)	DBH (cm)	Tree Species
Open turfgrass lawns	OP	7	0	0	NA	NA	NA
Deciduous tree canopy, low cover	DL	5	21 ( $\pm 11$ )	6 ( $\pm 10$ )	7 ( $\pm 4$ )	11 ( $\pm 10$ )	<i>Acer ginnala</i> <i>Magnolia spp.</i>
Deciduous tree canopy, high cover	DH	7	83 ( $\pm 7$ )	146 ( $\pm 91$ )	11 ( $\pm 5$ )	19 ( $\pm 18$ )	<i>Acer negundo</i> <i>Acer saccharinum</i> <i>Fraxinus pennsylvanica</i> <i>Quercus alba</i>
Evergreen tree canopy	EG	5	56 ( $\pm 21$ )	147 ( $\pm 69$ )	14 ( $\pm 3$ )	33 ( $\pm 11$ )	<i>Picea glauca</i> <i>Pinus nigra</i>
Mixed deciduous and evergreen tree canopy	MX	5	71 ( $\pm 16$ )	48 ( $\pm 19$ )	11 ( $\pm 4$ )	24 ( $\pm 12$ )	<i>Acer platanoides</i> <i>Betula papyrifera</i> <i>Picea glauca</i> <i>Tsuga canadensis</i>

multiple owners and because our replicate sites in each vegetation type were intended to broadly represent the landscape as a whole. For each of the 29 selected sites, we obtained permission to access the property through personal communication with homeowners.

#### LAI and microclimate measurements

During the 2006 growing season, from leaf-out in April until leaf senescence in November, we measured a suite of biophysical variables weekly at each site. All measurements were collected at the geographic center of the site. Stand-level LAI (leaf area per plot area) was measured using an optical plant canopy analyzer (model LAI-2000, LI-COR, Lincoln, Nebraska, USA) on days when sky conditions were overcast or on clear sky days when the solar angle was low to avoid direct sunlight hitting the sensor. Because our LAI measurements reflect stand-level values, they represent the combined effects of the canopy density of tree-covered areas and the percent tree cover at each site. To prevent interference with the measurements, a  $270^\circ$  view cap was used to block the  $90^\circ$  horizontal angle of the sensor's view that was nearest to the operator. Each LAI measurement consisted of one above-canopy reading and the mean of four below-canopy readings taken in the cardinal directions at a distance of 1 m from the center point of each site, and at a height of 1 m above the ground. The above-canopy readings recorded the background light conditions and were collected in nearby open areas, such as sports fields or large parking lots without obstructions blocking the sky view. The LAI-2000 optical sensor consists of five detectors arranged in concentric rings, each with a different field of view. To ensure that the field of view of each LAI measurement was within the boundaries of each site, we used only the four inner rings ( $0$  to  $58^\circ$  from zenith). Tree canopies were the dominant source of leaf area to these stand-level LAI measurements, as understory vegetation was rarely present above the 1-m measurement height.

Seasonal LAI dynamics at each site were modeled by fitting two piecewise logistic curves to the LAI measurements (Zhang et al. 2003). At sites with evergreen tree canopies, both measured and modeled LAI were corrected for leaf clumping using a correction factor of 1.6, according to the manufacturer's recommendations for the LAI-2000. At sites with deciduous tree canopies, modeled and measured LAI were corrected for the influence of stems and branches, or wood area index (WAI), which varies seasonally with leaf development and senescence (Breda 2003). The modeled LAI curves were used to establish a WAI correction factor ( $\alpha$ ) that varied from zero during the middle of the growing season to unity outside the growing season (Dufrene and Breda 1995). The WAI was defined as the leaf-off LAI measurement collected at each site in November 2006. LAI at deciduous sites was corrected using  $LAI_{\text{corr}} = LAI - (\alpha \text{ WAI})$ . At sites with mixed tree canopies, measured and modeled LAI were divided into two pools, evergreen LAI and deciduous LAI, based on the proportion of evergreen and deciduous tree cover. The proportion of each tree cover type was estimated using a leaf-off aerial photograph with a 0.15 m resolution (State of Minnesota 2006) and separately digitizing the evergreen and deciduous tree canopies within an 18-m radius of each site's center point, which corresponded to the average field of view of the LAI measurements. The evergreen and deciduous LAI pools were separately corrected using the methods described above for pure evergreen and pure deciduous stands, then summed to calculate the corrected LAI at mixed sites.

On each sampling day, we collected microclimate measurements between 08:00 and 17:00 h by taking the mean of four readings in the cardinal directions at a distance of 1 m from the center point of each site. Soil temperature at 10 cm depth was measured using a thermister temperature probe (model Acorn Temp 5, Oakton, Vernon Hills, Illinois, USA, accuracy  $\pm 0.2^\circ\text{C}$ ). Surface temperature of the ground cover was measured using an infrared radiometer (model IRTS-P, Campbell Scientific, Inc., Logan, Utah, USA, accuracy  $\pm 0.3^\circ\text{C}$ ) held 0.5 m directly above the surface. Soil water content was measured at 5 cm depth using a frequency-domain reflectometer (model ML2x ThetaProbe, Delta-T Devices, Ltd., Cambridge, England, accuracy  $\pm 1\%$ ). Because soil and surface temperature vary throughout the day with changes in solar radiation and weather, our spot measurements collected at different times of day could not be directly compared among sites. Instead, we used continuous temperature measurements at a nearby climate station to normalize all of the spot measurements so that they could be compared among the sites. We analyzed all temperatures as the difference between each spot measurement at each site and the temperature recorded at the same time point at the climate station. The climate station was located within our study area ( $< 1$  km from all measured sites) in an open turfgrass lawn, which was representative of low-maintenance lawns in the area—it was not irrigated and it was mowed approximately once per week with clippings left to decompose on the surface. The temperature of the upper 5 to 10 cm soil layer was continuously measured using two linear platinum resistance temperature probes (model STP-1, REBS, Inc., Seattle, Washington, USA, accuracy  $\pm 0.5^\circ\text{C}$ ). Air temperature was continuously measured 1.4 m above the ground using a sonic anemometer (model CSAT3, Campbell Scientific, Inc., accuracy  $\pm 0.025^\circ\text{C}$ ). The sonic temperature was corrected following Schotanus et al. (1983) to calculate the actual air temperature. Half-hour averages of the reference temperature measurements were recorded using a datalogger (model CR1000, Campbell Scientific, Inc.). We present results as relative soil temperature (site soil temperature minus reference soil temperature) and relative surface temperature (site surface temperature minus reference air temperature). Although soil temperature measurements collected at 10 cm depth were referenced against soil temperature averaged over 5 to 10 cm depth, and surface temperature measurements were referenced against air temperature, these relative temper-

atures remove the effects of diurnal changes in solar radiation and weather and provide a meaningful way to compare the microclimate effects of vegetation type.

#### Percent tree and ground cover measurements

Field-based measurements of percent tree cover were made following the U.S. Forest Service Forest Inventory and Analysis (FIA) urban forest inventory pilot protocols (USDA Forest Service 2005) and represent a visual estimate to the nearest 5%. Each estimate was made from under the tree canopy on a 7.3 m radius (167 m<sup>2</sup>) plot centered at each study site's center point. Satellite-derived estimates of percent tree cover at each site were obtained from a land-cover classification of a QuickBird (2.4 m resolution) multispectral image acquired on July 26, 2006 that had an accuracy of 87% for the tree class (J. Wu, personal communication). The center point of each study site was geo-referenced using post-processed coordinates from a global positioning system (model GS20, Leica Geosystems AG, Heerbrugg, Switzerland) and overlaid on the land-cover map in a geographic information system (ArcMap, version 9.2, ESRI, Redlands, California, USA). Percent tree cover was calculated from the number of pixels that were classified as tree-covered within an 18 m buffer around each site's center point, approximating the field of view of our LAI measurements.

Ground cover was measured once in August 2006 at each site using a 60 cm×60 cm aluminum quadrat with 121 point-intersections. At each point-intersection, ground cover was categorized as turfgrass, broad-leaved weed, or bare soil. Percent ground cover of each type was determined as the mean of four readings in the cardinal directions at a distance of 1 m from the center point of each site.

#### Data analysis

Statistical analyses were performed using the R statistical language (version 2.7.1, R Development Core Team). Seasonal patterns of LAI and microclimate variables were analyzed using linear mixed effects models with vegetation type and day of year (DOY) as fixed factors, and site as a random factor. The mid-season period of the growing season was defined as DOY 166 to 251, when the LAI at individual sites was neither increasing nor decreasing over time. Coefficients of variation and mid-season means of LAI and microclimate variables were analyzed using analysis of variance (ANOVA) tests. Significant ANOVAs ( $\alpha=0.05$ ) were followed by a Tukey's Honestly Significant Difference (HSD) post-hoc test ( $\alpha=0.05$ ) to perform multiple comparisons of means. The effects of LAI on microclimate variables across the growing season were analyzed using stepwise backward elimination of linear mixed effects models (Akaike Information Criterion  $\Delta < 3$ ) with vegetation type and LAI as fixed effects, and site as a random factor. The effects of mean mid-season LAI and percent tree cover on mean mid-season variables were analyzed using simple linear-regression. Open vegetation classes by definition have a stand-level LAI=0 and thus were not included in any analyses involving LAI.

## Results

### Seasonal patterns of LAI and microclimate

The 2006 growing season (April to November) was warmer and drier than the local 30-year climate averages (National Climatic Data Center 2004). During June and July, air

temperature was 2.5°C warmer than the 30-year average and rainfall was 5.4 cm below average. During our measurements from April to November, air temperature at the reference turfgrass site ranged from a low of -8°C to a high of 37°C, and soil temperature ranged from 2°C to 33°C (Fig. 1). Most of the large precipitation events (over 10 mm) occurred in July and August (Fig. 1).

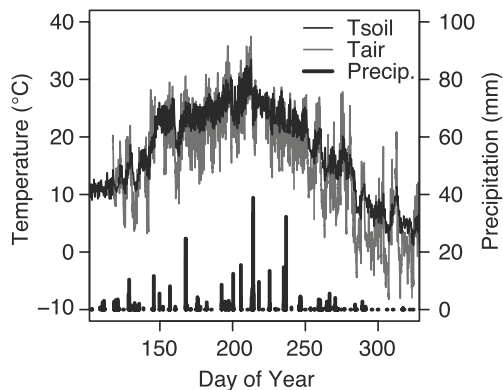
Over the course of the growing season, stand-level LAI differed significantly among the four forested vegetation types (Fig. 2a,  $F_{3,19}=6.44$ ,  $P=0.004$ ). The coefficient of variation of LAI across the growing season was significantly different among vegetation types ( $F_{3,19}=17.51$ ,  $P=0.0001$ ) and lower at evergreen sites (c.v.=16%) than at deciduous low (43%), deciduous high (40%), or mixed sites (34%). All sites reached maximum LAI by DOY 166 and leaf senescence began on average by DOY 266. Mean mid-season LAI differed significantly among vegetation types (Fig. 3a,  $F_{3,19}=6.06$ ,  $P=0.005$ ) and, on average, mid-season LAI was highest at mixed sites (4.2 m<sup>2</sup> m<sup>-2</sup>) and lowest at deciduous low sites (1.2 m<sup>2</sup> m<sup>-2</sup>). Mid-season LAI at mixed sites, however, was not significantly different from evergreen or deciduous high sites.

Relative soil temperature differed significantly among the five vegetation types over the course of the growing season (Fig. 2b,  $F_{4,25}=20.68$ ,  $P<0.0001$ ). Soil temperature at all sites was lower than at the turfgrass reference site throughout the growing season. This was true even for our open lawn sites, which we attributed to small differences in the depths sampled by the buried soil temperature sensors at the reference site compared to our spot measurements at the other sites. In addition, the soil at the turfgrass reference site was very dry during mid-summer from lack of irrigation and low rainfall, whereas irrigation practices were variable across the open study sites. Mid-season soil temperatures differed significantly among vegetation types (Fig. 3b,  $F_{4,25}=18.24$ ,  $P<0.0001$ ) and, on average, mid-season soil temperatures at deciduous high, evergreen, and mixed sites were 2.8°C cooler than at deciduous low and open sites.

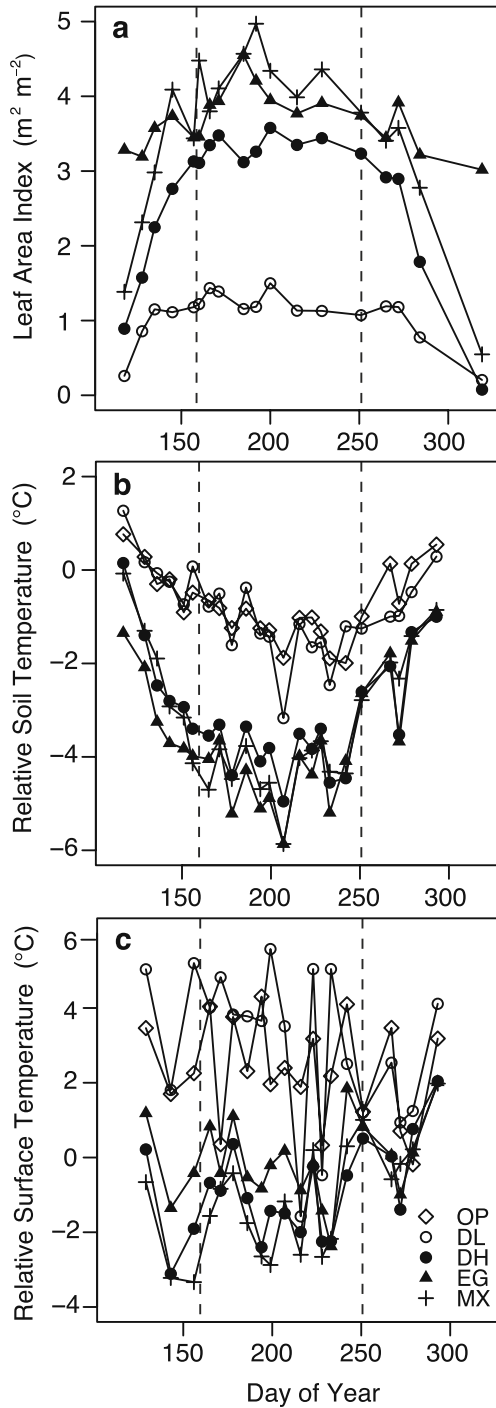
Relative infrared surface temperature differed significantly among the five vegetation types over the course of the growing season (Fig. 2c,  $F_{4,25}=8.07$ ,  $P=0.0003$ ). Mean mid-season infrared surface temperature also differed significantly among vegetation types (Fig. 3c,  $F_{4,25}=5.73$ ,  $P=0.002$ ) and, on average, mid-season surface temperatures at deciduous high and mixed sites were 4.6°C cooler than deciduous low sites.

Soil water content did not differ significantly among vegetation types over the course of the growing season ( $F_{4,25}=0.48$ ,  $P=0.75$ ).

**Fig. 1** Environmental conditions during the 2006 growing season at the open turfgrass reference site. Air temperature was measured 1.4 m above the surface and soil temperature was measured over the upper 5–10 cm deep soil layer

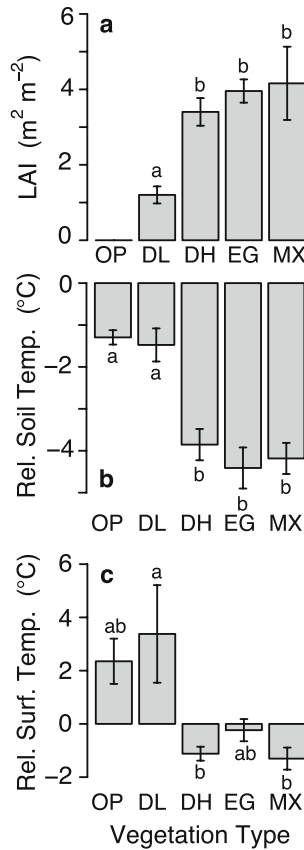


**Fig. 2** Seasonal patterns during the 2006 growing season of measured **a** stand-level leaf area index, **b** soil temperature at 10 cm depth, and **c** infrared surface temperature of the ground cover of five suburban vegetation types: open turfgrass lawns (OP), deciduous tree canopy with low cover (DL), deciduous tree canopy with high cover (DH), evergreen tree cover (EG), and mixed deciduous and evergreen tree cover (MX). Each symbol represents the mean of all sites of a given vegetation type. The spot temperature measurements at the sites are expressed relative to the temperature recorded at the same time point at a climate station located in an open turfgrass area. The *dashed vertical lines* at Julian days 166 and 251 mark the mid-season period





**Fig. 3** Mean mid-season **a** stand-level leaf area index, **b** soil temperature at 10 cm depth, and **c** infrared surface temperature of five suburban vegetation types: open turfgrass lawns (OP), deciduous tree canopy with low cover (DL), deciduous tree canopy with high cover (DH), evergreen tree cover (EG), and mixed deciduous and evergreen tree cover (MX). Error bars represent  $\pm 1$  standard error. Lowercase letters indicate significantly different means based on a Tukey HSD multiple comparisons test. Mid-season is defined as the period between Julian days 166 and 251

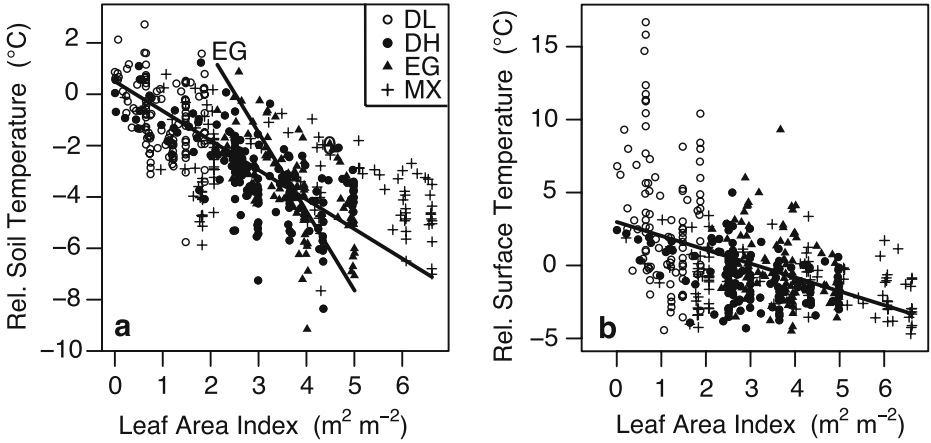


#### Seasonal effects of LAI on microclimate

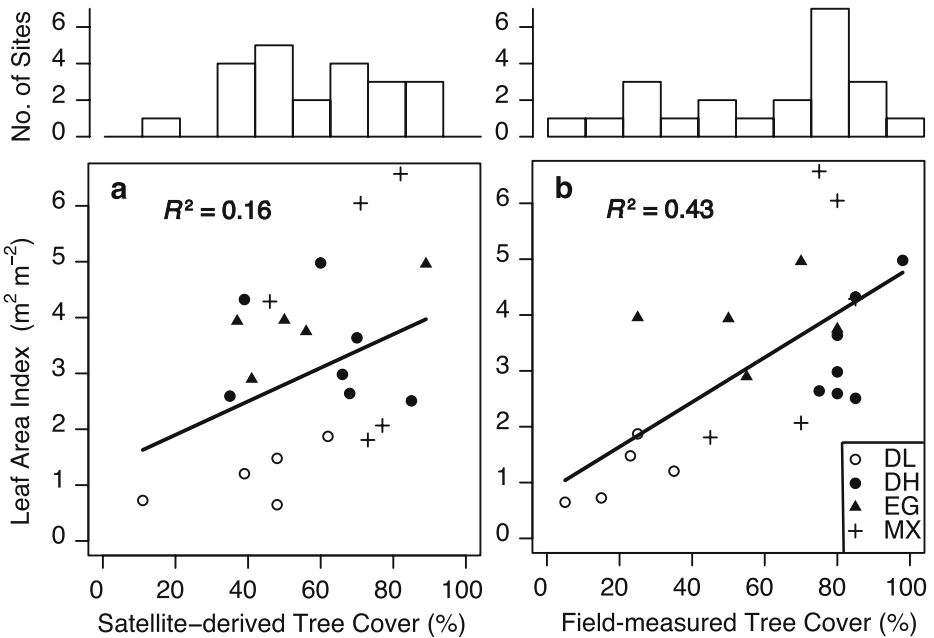
Over the course of the growing season, relative soil and surface temperature were negatively correlated with stand-level LAI (Fig. 4). The slopes and intercepts of the response of relative soil temperature to increasing LAI were not significantly different among deciduous and mixed sites, but were significantly different among evergreen sites and deciduous/mixed sites (Fig. 4a). The best-fit mixed-effects model, determined using the Akaike Information Criterion, for relative soil temperature at deciduous and mixed sites was  $y = -1.15 \text{ LAI} + 0.50$ , while the best-fit model for relative soil temperature at evergreen sites was  $y = -3.07 \text{ LAI} + 7.72$ . The slopes and intercepts of the response of relative surface temperature to increasing LAI, however, were not significantly different among vegetation types (Fig. 4b). The best-fit mixed-effects model for relative surface temperature at all sites was  $y = -0.95 \text{ LAI} + 2.98$ .

#### Site differences in LAI and microclimate

Across all sites, mid-season LAI was positively correlated with both satellite-derived estimates of percent tree cover (Fig. 5a,  $R^2=0.16$ ,  $P=0.06$ ) and field-based measurements of percent tree cover (Fig. 5b,  $R^2=0.43$ ,  $P<0.001$ ). Satellite-derived percent tree cover varied



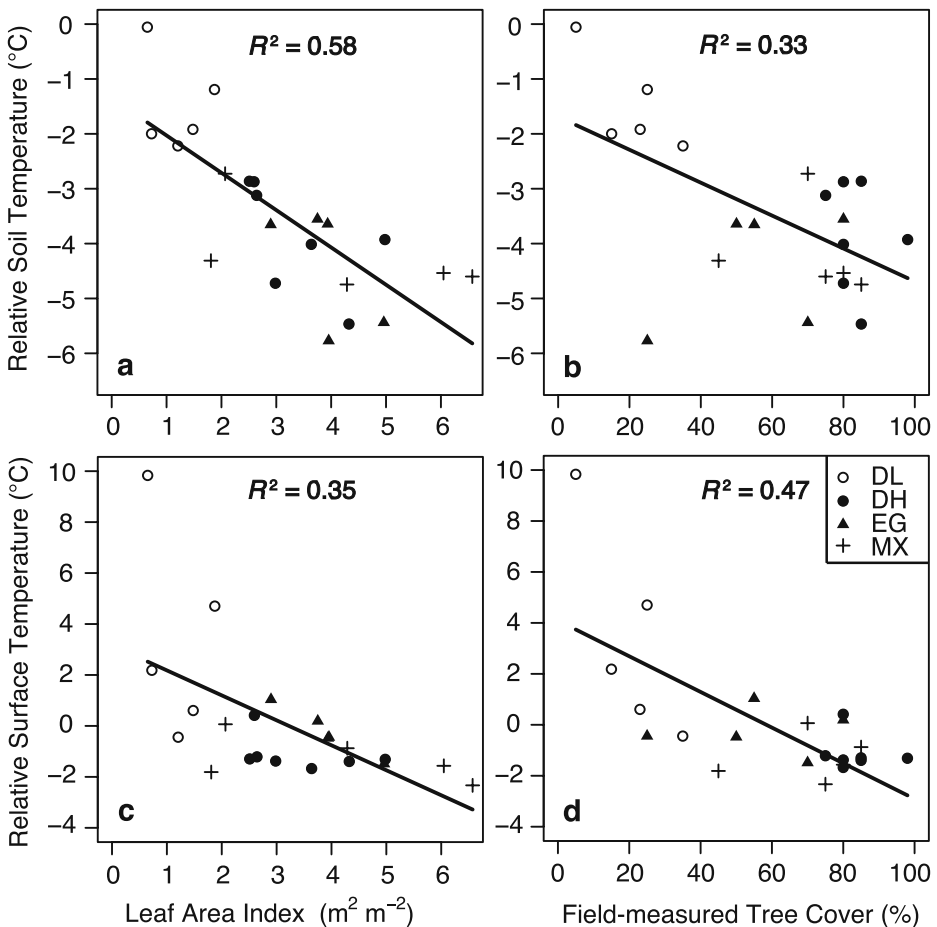
**Fig. 4** Relationships between modeled stand-level leaf area index and **a** relative soil temperature, and **b** relative surface temperature during the 2006 growing season. Each symbol represents a measurement at a single time point at an individual study site. Lines represent the best model fit after stepwise backwards elimination of linear mixed-effects models, where site is a random factor



**Fig. 5** Comparing **a** satellite-derived and **b** field-based tree cover measurements as predictors of modeled mid-season LAI. Each symbol represents an individual study site. Histograms show the tree cover distribution determined by each method

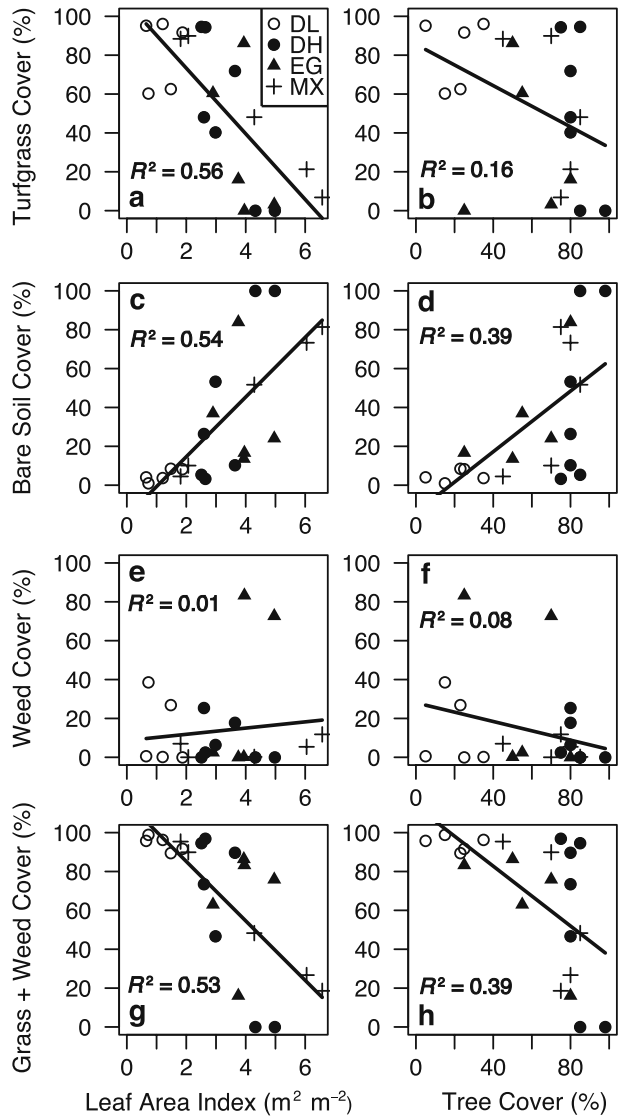
over a narrower range than did the field-based measurements and it poorly predicted site differences in mid-season LAI.

Mid-season relative soil and surface temperatures across all sites were negatively correlated with both mid-season LAI (Fig. 6a,  $R^2=0.58$ ,  $P<0.001$  and Fig. 6c,  $R^2=0.35$ ,  $P=0.004$ , respectively) and field-measured percent tree cover (Fig. 6b,  $R^2=0.33$ ,  $P=0.005$  and Fig. 6d,  $R^2=0.47$ ,  $P<0.001$ , respectively). However, mid-season LAI better predicted mid-season relative soil temperature (Fig. 6a, b) while percent tree cover better predicted mid-season relative surface temperature (Fig. 6c, d). Turfgrass cover and turfgrass + broad-leaved weed cover were both negatively correlated with mid-season LAI (Fig. 7a,  $R^2=0.56$ ,  $P<0.001$  and Fig. 7g,  $R^2=0.53$ ,  $P=0.001$ , respectively) and field-measured tree cover (Fig. 7b,  $R^2=0.16$ ,  $P=0.07$  and Fig. 7h,  $R^2=0.39$ ,  $P=0.002$ , respectively). Broad-leaved weed cover was not correlated with mid-season LAI (Fig. 7e,  $R^2=0.01$ ,  $P=0.62$ ) or field-measured tree cover (Fig. 7f,  $R^2=0.08$ ,  $P=0.21$ ). Conversely, bare soil cover was positively



**Fig. 6** Comparing modeled mid-season LAI and field-based tree cover measurements as predictors of **a, b** mid-season soil temperature, and **c, d** mid-season surface temperature. Each symbol represents an individual study site

**Fig. 7** Comparing modeled mid-season LAI and field-based tree cover measurements as predictors of **a, b** turfgrass cover, **c, d** bare soil cover, **e, f** broad-leaved weed cover, and **g, h** turfgrass + broad-leaved weed cover. Each symbol represents an individual study site



correlated with both mid-season LAI (Fig. 7c,  $R^2=0.54$ ,  $P<0.001$ ) and field-measured tree cover (Fig. 7d,  $R^2=0.39$ ,  $P=0.002$ ). Across all sites, ground cover was better predicted by mid-season LAI than by percent tree cover.

**Discussion**

Seasonal patterns of LAI and microclimate variables

The five vegetation types represented in this study showed distinct seasonal patterns of canopy leaf development and microclimate effects. These seasonal variations in urban

biophysical properties were more strongly related to differences in percent tree cover and canopy density than to plant functional type.

We found that the five vegetation types represented in this study had distinctly different seasonal patterns of relative soil and surface temperature, yet did not differ in their seasonal patterns of soil water content. Over the course of the growing season, sites with greater tree cover and higher LAI had consistently cooler soil and surface temperatures than did open or low tree cover sites, regardless of plant functional type (Fig. 2b, c). Consistent with this finding, the only significant differences among vegetation types in mid-season relative soil and surface temperatures were between the low tree cover, low LAI sites and high tree cover, high LAI sites (Fig. 3b, c). These differences in relative soil temperatures were largest during the middle of the growing season and minimal at the beginning and end of the growing season, while differences in relative surface temperature were most noticeable during the first half of the growing season. It is more likely that the seasonal dynamics of soil water content are controlled by precipitation events and irrigation practices, which were not sampled systematically in this study. These ideas are consistent with previous studies that have discussed the importance of irrigation as a driver of spatial patterns of soil moisture in urban and suburban landscapes (Scharenbroch et al. 2005; Byrne et al. 2008).

As expected, plant functional types differed in their seasonal LAI dynamics, most markedly with deciduous-dominated sites showing larger variation in LAI across the growing season than evergreen sites (Fig. 2a). However, plant functional types did not explain the large differences in mid-season LAI among sites (Fig. 3a), suggesting that structural characteristics such as percent tree cover, stand density, or species composition are more important for explaining stand-level variability in urban LAI. Consistent with this, the only significant difference we found in mid-season LAI among the vegetation types was between the deciduous low and all other high tree cover sites (Fig. 3a).

Our stand-level LAI measurements obtained with an optical plant canopy analyzer were similar to those found in another urban study from Terre Haute, Indiana (Hardin and Jensen 2007). LAI values at our suburban study sites were also similar to, or slightly lower than, those observed in temperate and boreal forests with tree species similar to those in our study area (Chen et al. 2006; Lindroth et al. 2008). This result is consistent with studies showing that the aboveground biomass of open-grown urban trees can be 20% less than forest-grown trees of the same diameter (Nowak 1994). Stand-level LAI values are also likely reduced in urban and suburban areas because of landscaping practices that maintain park-like spacing between trees and prevent natural succession and canopy closure.

Microclimate variables showed strong functional responses to changes in LAI across the growing season (Fig. 4). Regardless of vegetation type, surface temperature decreased by  $\sim 1^\circ\text{C}$  for every unit ( $\text{m}^2 \text{ m}^{-2}$ ) increase in LAI (Fig. 4b). In other words, surface temperatures under dense tree canopies (e.g., sites with  $\text{LAI}=6 \text{ m}^2 \text{ m}^{-2}$  in Fig. 4b) were reduced up to  $6^\circ\text{C}$ , relative to sparse canopies with near-zero LAI. Soil temperature also declined with increasing LAI. When compared to sparse tree canopies with near-zero LAI, soil temperatures under dense tree canopies (e.g.,  $\text{LAI}=6 \text{ m}^2 \text{ m}^{-2}$ ) were reduced up to  $7^\circ\text{C}$ . However, the slope and intercept of this relationship was significantly different for evergreen-dominated versus deciduous-dominated sites (Fig. 4a). For every unit increase in LAI, soil temperature decreased by  $\sim 3.1^\circ\text{C}$  at evergreen-dominated sites and by  $\sim 1.2^\circ\text{C}$  at deciduous-dominated sites. A possible explanation for the difference at the evergreen sites is that they had much less variation in LAI over the course of the growing season than did the deciduous and mixed sites. All sites with high tree cover (DH, EG, MX) showed a similar range of relative soil temperature (Fig. 2b) due to seasonal changes in solar radiation. Because those changes in relative soil temperature are seasonally correlated with

changes in LAI across the growing season, the small LAI range at evergreen sites resulted in a steeper decline in relative soil temperature with every unit increase in LAI. Alternatively, if our study area had included evergreen sites representing a larger range of LAI, we may have observed a similar soil temperature response to increasing LAI as in other vegetation types. Our interpretation is that while the difference in response of the evergreen sites was statistically significant, it may not have been ecologically significant, especially in light of the fact that we found no vegetation type differences in the relationship between relative surface temperature and LAI (Fig. 4b).

The cooling effects of urban vegetation are well documented and are currently used as environmental design tools to reduce urban heat islands and home energy use (McPherson 1994). Previous field studies have found soil and surface temperatures of residential lawns to be several degrees cooler during the summer than other common ground cover types, such as bark, mulch (Byrne et al. 2008), and native grasses (Bonan 2000). This is largely because of the increased evaporative cooling by transpiring, and often well-irrigated, turfgrasses. Our results support these previous studies and they extend our understanding of how these cooling effects vary among urban vegetation types and over time with canopy leaf development. We found that tree canopies have a greater cooling effect on soils and the surface compared to open turfgrass lawns, which is likely due to the canopy intercepting solar radiation and shading the surface. Trees also have deeper roots and greater leaf area than turfgrasses, leading to greater evapotranspiration. Evapotranspiration from trees, however, occurs at the top of the canopy and does not necessarily mix throughout the vertical volume of air to significantly modify the local temperature surrounding an individual stand of trees (Oke 1989).

The differences in soil temperature we observed among our vegetation types could also have important implications for carbon cycling in urban areas. Because soil respiration rates increase exponentially with soil temperature between 0 and 40°C (Lloyd and Taylor 1994), our results suggest that CO<sub>2</sub> efflux from urban soils may be modulated by seasonal changes in canopy density as well as plant functional type (Fig. 4a). In natural systems, it has been shown that an increase in canopy density mediates soil respiration rates by reducing net radiation at the surface, causing lower soil temperatures (Smith and Johnson 2004; Tanaka and Hashimoto 2006). If we apply Smith and Johnson's (2004) temperature-response equations from a woodland-grassland study to our suburban ecosystem with a mean summer soil temperature of 25°C, the average soil respiration rate under a dense urban tree canopy (e.g. LAI=6 m<sup>2</sup> m<sup>-2</sup>) would be 56% lower than in an open turfgrass lawn (1.85 versus 4.17 μmoles CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>, respectively). Our results suggest that the significant cooling effects of urban tree canopies on soil temperature should be accounted for in urban carbon budgets (Pataki et al. 2006; Churkina 2008). The greatest potential for reduced CO<sub>2</sub> emissions from lower soil respiration rates would be in sites where urban tree canopies occur over grass or bare soil ground covers, rather than impervious surfaces.

#### Site differences in mid-season microclimate and ground cover

We evaluated two stand-level metrics, LAI and percent tree cover, for their ability to explain spatial differences in mid-season microclimate, as well as mid-season ground cover composition, under the urban forest canopy. Overall, we found that mid-season LAI was a better predictor of both mid-season microclimate and ground cover variables than percent tree cover.

While we found mid-season LAI to be a better predictor of mid-season soil temperature (Fig. 6a, b), we also found that percent tree cover was a better predictor of mid-season

surface temperature (Fig. 6c, d). Because surface temperature is most affected by the direct beam solar radiation penetrating a canopy at a given moment in time, it depends more on the extent and distribution of the canopy (indicated by percent tree cover) than the density of leaves per unit ground area (indicated by stand-level LAI). As a result, over the range of tree cover from 0 to 100%, the mean mid-season surface temperature was reduced by 6°C on average. In contrast, soil temperature is a more integrated measure of a site's energy balance and is more strongly influenced by the total leaf area per unit ground area. A greater mid-season LAI by five units ( $\text{m}^2 \text{m}^{-2}$ ) consequently reduced the average mid-season soil temperature across the sites by an average of 4°C.

Mid-season LAI was also a better predictor of site differences in percent ground cover than was percent tree cover (Fig. 7). The percent cover of turfgrass, in particular, showed the strongest correlation with mid-season LAI (Fig. 7a,  $R^2=0.56$ ). Although turfgrass species are adapted to a variety of light environments, in general turfgrass is less shade tolerant than many broad-leaved weed species (Fry and Huang 2004), which showed no trend with increasing LAI or percent tree cover (Fig. 7e, f). In high light environments, turfgrass can out-compete weed species, but turfgrass is less competitive in low light conditions (Fry and Huang 2004). Additionally, human management prevents competition from broad-leaved weeds through the use of herbicides, which are often applied to open canopy, high light lawns. The cover of turfgrass in urban and suburban areas has been much less frequently quantified (Milesi et al. 2005) than has tree cover, which is relatively easily assessed using forest inventories, aerial or satellite imagery (Nowak et al. 2008). Our results suggest that it would be possible to produce a first-order estimate of the density of turfgrass ground cover by using the more readily available data on urban tree canopies, although the predictive equations would likely need to be developed regionally to account for differences in climate and horticultural practices. Ultimately, this information could be used to account for understory vegetation cover in models of urban land–atmosphere exchanges of energy, water, and carbon (Rivalland et al. 2005).

### Using tree cover to predict site differences in mid-season LAI

In this study, we evaluated the relative performance of two different measures of percent tree cover for predicting site differences in mid-season LAI. Measuring LAI in urban ecosystems is considerably more difficult than in natural forest systems because of numerous methodological constraints, including optical interference from buildings, a limited number of urban-specific allometric equations for trees, and spatially heterogeneous and isolated tree canopies (Peper and McPherson 2003). Although we found stand-level LAI was a better predictor of mid-season microclimates and ground cover than percent tree cover (Figs. 6 and 7), percent tree cover is an easily measured and more commonly used metric for evaluating the extent and distribution of urban forests, as well as the ecosystem services they provide (Nowak et al. 2008; Wang et al. 2008). We found that field-based estimates of percent tree cover were better than satellite-derived estimates at predicting the site-to-site variations in LAI in our suburban study area (Fig. 5). The satellite-derived land-cover map produced a narrower range of tree cover values compared to the field-based inventory using U.S. Forest Service urban forest inventory protocols (USDA Forest Service 2005). Although the field-based measures are more subjective, they take into account gaps within individual tree canopies that are too small to resolve in even high-resolution satellite imagery such as QuickBird (2.4 m). There was still considerable variation around the best-fit linear regression model (Fig. 5b) and, in general, LAI at evergreen sites was under-predicted by 30%, while LAI at deciduous sites was over-predicted by 40%. The

model fit was largely driven by the strong positive relationship between stand-level LAI and field-measured tree cover at levels of <50% tree cover. At sites having >50% tree cover, there was considerable scatter in the relationship and field-measured percent tree cover poorly predicted mid-season LAI. This saturating effect of LAI with field-measured percent tree cover was likely due to the fact that both stand density and species composition contribute to a site's LAI. At sites with low percent tree cover, stand density had the greater influence on stand-level LAI. In contrast, at sites with high percent tree cover, differences in the canopy structure of different plant functional types and species was more important in determining stand-level LAI.

Developing relationships between percent tree cover and mid-season LAI would be a useful step toward scaling up urban biophysical properties and providing the information required to implement complex urban land-surface models. Our results suggest that satellite imagery with a pixel size on the order of 2.4 m is unable to resolve the detailed tree canopy information needed to scale up urban forest biophysical properties. However, metropolitan-scale comparisons of different methods for estimating tree cover have found that high-resolution aerial photography (60 cm ground resolving distance) produces similar estimates to field-based urban forest inventories (Nowak et al. 1996; Walton et al. 2008). This suggests that next-generation, high resolution satellite imaging systems, such as GeoEye-1 (1.65 m multispectral and 0.41 m panchromatic resolution at nadir), could be used to produce maps of urban forest canopy characteristics that would be adequate to model LAI, soil temperature, surface temperature, and ground cover over relatively large urban areas.

## Conclusions

Urban forest vegetation types showed distinct seasonal patterns of stand-level LAI, soil temperature, and surface temperature, which were largely explained by differences in tree cover and changes in LAI, rather than by plant functional type. Over the course of the growing season, sites with higher percent tree cover and greater LAI reduced soil temperatures by up to 7°C and surface temperatures by up to 6°C, relative to sites with near-zero LAI. Because of low variability in LAI over the growing season, soil temperature at evergreen sites was more greatly reduced with every unit increase in LAI than at deciduous-dominated sites. Additionally, we found that site differences in mid-season soil temperature and turfgrass ground cover were better predicted by mid-season LAI, while mid-season surface temperature was better predicted by percent tree cover. The significant cooling effects of urban tree canopies on soil temperature imply that seasonal changes in canopy density may also modulate the CO<sub>2</sub> efflux from urban soils and should be included in urban carbon budgets. To scale up, we found that field-based estimates of tree cover were better than 2.4 m resolution satellite imagery for predicting the mean mid-season LAI values that were important for determining temperatures under the urban forest canopy, but that higher resolution aerial imagery or next-generation satellite sensors may provide a practical approach for larger metropolitan areas and regions.

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