ABSTRACT

Title of Thesis: RELATIONSHIPS BETWEEN URBAN FOREST PATCH CHARACTERISTICS AND NEAR-GROUND SOLAR RADIATION IN BALTIMORE, MD

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Forest patches in urban areas perform multiple ecological functions that can aid in regulating microclimate, managing stormwater flows, and improving air quality. Many of these functions and services are driven by solar radiation inputs below the forest canopy. However, the relationships between near-ground solar radiation and urban forest patch characteristics are not well studied or understood. For this thesis, we estimated near-ground solar radiation in six forest patches in Baltimore, MD, USA using hemispherical photographs to calculate global site factor (GSF). In addition, we determined patch compactness, as well as the origin, slope, aspect, distance from edge, and degree of invasion at each sampling site. Results show that patch attributes affect solar radiation inputs, although the strength of the relationships between GSF and the studied patch characteristics vary between sites. The identified patterns in

near-ground solar radiation can be used to inform effective conservation and management of urban forest patches.

RELATIONSHIPS BETWEEN URBAN FOREST PATCH CHARACTERISTICS AND NEAR-GROUND SOLAR RADIATION IN BALTIMORE, MD

by

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List of Abbreviations

BAF	Basal Area Factor
BES	Baltimore Ecosystem Study
CFHS	Carroll, Fendal, Herun, Sinai
DifAb	Diffuse radiation above the canopy
DifBe	Diffuse radiation below the canopy
DirAb	Direct radiation above the canopy
DirBe	Direct radiation below the canopy
GSF	Global Site Factor
LTER	Long-Term Ecological Research

Chapter 1. Introduction.

Vegetation and green infrastructure mitigate the negative effects of adverse conditions often associated with urban environments by providing ecosystem services such as climate regulation (Bonan, 1997; Oke, 1989), air filtration (Escobedo and Nowak, 2009; Cavanagh, 2009), stormwater retention (Berland et al., 2017), erosion control (Pincetl et al., 2013), and human health benefits (Salmond et al., 2016; Bolund and Hunhammar, 1999). Of the vegetation types comprising green infrastructure, the urban forest, which can be defined as all trees and woodlands contained within a city (Nowak et al., 2001; Roman et al, 2018), is a particularly consequential component of urban ecosystems due to its dominance in the urban landscape and to the large biomass of trees relative to other forms of vegetation (Samson, 2017; Steenberg et al., 2019; Davies et al., 2011). In temperate and tropical regions, much of the urban forest consists of forest patches, areas of contiguous canopy that are predominantly self-organizing and experience ecological processes similar to their non-urban counterparts (Kowarik and Körner, 2005; Pregitzer et al., 2019; Ogden et al., 2019).

The complex structure and vegetation density of urban forest patches make them well-suited for alleviating the high air temperatures that define urban heat islands (Yokohari et al., 2001; Chen and Jim, 2008). The cooling benefits of forest patches are largely a result of tree evapotranspiration, which converts energy from solar radiation into latent heat rather than sensible heat (Grimmond and Oke, 1991; Bowler et al., 2010; Qiu et al., 2017), thus lowering the air temperature and providing a cooling effect that can extend more than 1000 meters beyond a forest patch boundary

(Oke, 1989; Upmanis et al., 1998; Yokohari et al., 2001). In addition to its influence on evapotranspiration and temperature regimes, near-ground solar radiation, or insolation, is important for ecological and pedological processes such as plant growth, photosynthesis, soil water budgets, and carbon cycling (Schleppi and Paquette, 2017; Rasmussen et al., 2005; Huxman et al., 2005).

Insolation in urban forest patches and its corresponding ecological processes can be greatly affected by the heterogenous landscape matrix within which a patch is embedded (Fig. 1) (McDonnell et al., 1997; Ogden et al., 2019). The context, fragmentation, and high edge-to-interior ratios of urban forest patches make them subject to greater inputs of energy (Saunders et al., 1991), pollutants (Lovett et al.,

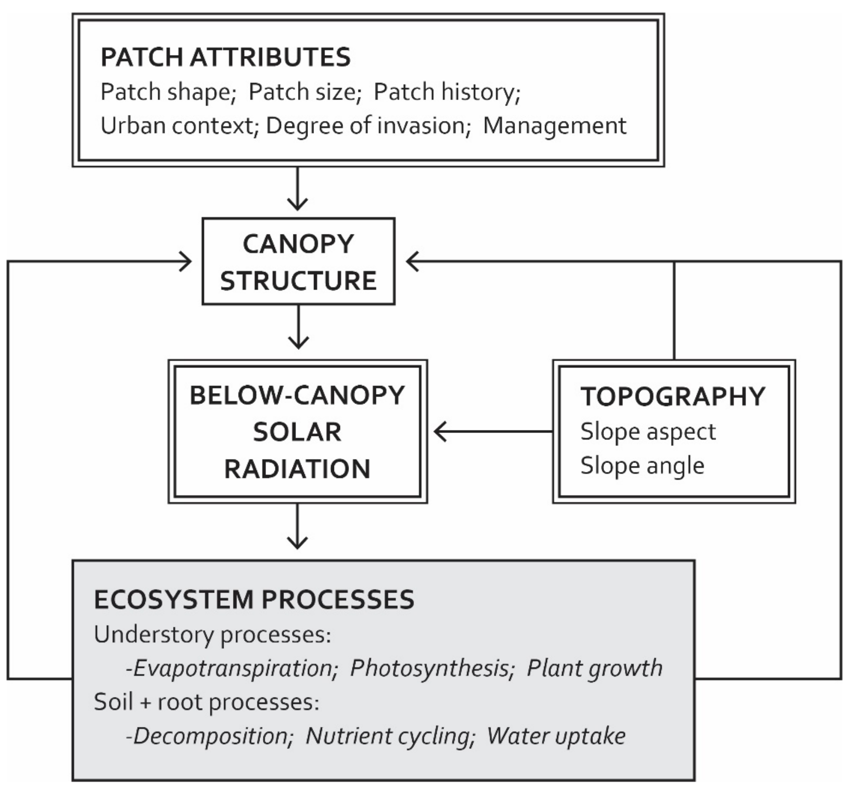

Fig. 1.1. Schematic diagram of relationships and linkages among urban forest patch attributes, solar radiation, and ecosystem processes. Patch attributes, canopy structure, and topography influence below-canopy solar radiation and therefore understory, soil, and root processes. Variables selected for this study are denoted by a double outline around their box. Ecosystem processes (shown in gray) result in the provision of urban ecosystem services.

2000; Carreiro, 2008), and species from the surrounding environment (McKinney, 2002). For example, forest patches bordered by roads and buildings may have open edges that receive more solar radiation than forest interiors. The drier conditions near patch edges can extend well beyond the patch boundary and alter the composition of understory vegetation up to 30 meters into the forest patch (Hamberg et al., 2009). Changes in vegetation composition in response to the high-light environments and disturbed soils near patch edges include an increased presence of invasive vines and other non-forest species (Harper et al., 2005; Guirado et al., 2006). Once established at patch edges, invasive species can propagate and disperse throughout an entire patch (Wiser et al., 1998; Cole and Weltzin, 2005). High levels of invasion are especially prevalent in urban environments, where the flow of non-native propagules from adjacent land uses can result in the colonization of exotic species (Hobbs, 1988; Honnay et al., 1999; Cadenasso and Pickett, 2001). Such species, which often thrive in human-disturbed environments, can overtake remnant vegetation, reduce tree growth, and further increase solar radiation inputs near patch edges and throughout urban forest patches (Matthews et al., 2016). Because opportunities for invasion typically originate in adjacent land uses and at patch boundaries where solar radiation inputs are higher, the edge-to-interior ratio, or compactness, of forest patches may affect solar radiation inputs (Štajerová et al., 2017; Geiger et al., 2009).

Patch histories may also influence solar radiation inputs, as they determine the age, successional pathways, and species composition of urban forest patches (Zipperer et al., 1997). Forest patches can originate as either remnant patches, which we define as areas that existed as forested in 1927, having been reforested postlogging, or regenerated patches, which have grown on sites once cleared for development and were reforested after 1927 following agricultural abandonment (Fig. 1.2). Remnant sites are older and tend to be dominated by large-diameter trees, while regenerated sites generally contain younger trees and early successional species (Nowak, 1994; Zipperer et al., 1997). As such, remnant patches are projected to have a higher biomass accumulation and leaf area index than regenerated ones (Zipperer et al., 1997), and thus below-canopy solar radiation inputs may be higher in regenerated patches (Barbier et al., 2008). The difference in species composition between the two patch types can also affect insolation. For example, Zipperer (2002) found that regenerated patches were dominated by sugar maple (*Acer saccharum*), Norway maple (*Acer platanoides*), and boxelder (*Acer negundo*), while remnant sites primarily contained *A. saccharum* and black oak (*Quercus velutina*). The canopy structures of these species differ from one another, resulting in variance in near

Fig. 1.2. Forest patches in Baltimore can be classified as (a) remnant sites that have been forested since their initial clearing, typically for lumber, in the mid-1800s, or as (b) regenerated sites that were cleared for agriculture or development in the early 1900s and were later abandoned and reforested. Patch origin was determined based on aerial photographs from 1927, with sites that were non-forested at that time classified as regenerated.

ground solar radiation among species (Canham et al., 1994). Therefore, dissimilarities in species composition between remnant and regenerated patches may also cause patch origin to influence solar radiation inputs.

In addition to edge proximity, vine invasion, compactness, and patch origin, variations in topography can affect near-ground solar radiation, with shallow, south-facing slopes in the northern hemisphere receiving more direct radiation than north-facing ones during summer months (Geiger et al., 2009; Zou et al., 2007). As a result, slopes on northern aspects tend to be cool and moist while those on southern aspects tend to be warm and dry (Pope and Lloyd, 1975). Microclimate variations resulting from topographic differences can affect canopy cover and the distribution of vegetation (Hack and Goodlett, 1960; Whiteman et al., 1989), further contributing to the influence of slope and aspect on below-canopy radiation.

Despite the influence of urban characteristics and fine-scale variability in species composition and topography on insolation, few have studied these attributes and their interactions in the urban core (but see Dacanal and Labaki, 2011; Li et al., 2018). Rather, scholars have studied relationships between forest cover and urban microclimate at a regional scale using remote sensing images (e.g., Li et al., 2012; Kong et al., 2014; Tian et al., 2014; Ren et al., 2016). While regional-scale observations provide insight into landscape factors that contribute to changes in solar radiation inputs across space, they do not address smaller-scale shifts in near-ground solar radiation within urban forest patches themselves. Understanding gradients in solar radiation at the spatial scale of patches and trees is essential for recognizing, interpreting, and addressing variations in ecosystem structure and function across forest patches, especially in stands subject to anthropogenic influences (Foster et al., 1992; Hardiman et al., 2018).

In this study, we assess the effects of multiple urban and forest characteristics on near-ground solar radiation in forest patches in Baltimore, MD, USA. For this purpose, we chose patch origin, patch compactness, aspect, slope, distance to patch edge, and vine invasion as the primary factors that may influence solar radiation inputs. Our objective was to answer the following questions: (1) how do patch histories influence solar radiation below the forest canopy; (2) what is the effect of patch shape on near-ground insolation; (3) how do solar radiation inputs change from the exterior to the interior of forest patches; and (4) do interactions among topographic variables, vine invasion, and proximity to the forest edge determine patch microclimates? By exploring the relationships between multiple patch attributes and near-ground solar radiation, we highlight that the spatial heterogeneity inherent in urban forest stands affects microclimate and therefore the benefits that the urban forest provides to cities.

Chapter 2. Materials and Methods.

2.1 Study sites

Baltimore, Maryland is located in the Patapsco River Watershed and comprises two physiographic provinces, the Piedmont Plateau and the Atlantic Coastal Plain. The former is characterized by deep, well drained soils underlain by semi-basic or mixed-basic and acidic rocks; the latter has well drained soils underlain by sandy, gravelly, or clayey sediment (US Forest Service, 2016). Baltimore has 27.4% tree canopy coverage (Baltimore City Recreation & Parks, 2018), with forest patches – areas of canopy larger than 0.1 hectares – comprising more than a third of the city's total tree canopy (Avins, 2013). In June, July, and August, when trees are in full leaf-out, the daily average total solar radiation in Baltimore ranges from 5169 to 6313 watt-hours per square meter (Wh/m^2). Between 1991 and 2010, the 20-year daily average was 5747 Wh/m^2, 55 percent (3135 Wh/m^2) of which was direct radiation, while 45 percent (2612 Wh/m^2) was diffuse radiation (Sengupta et al., 2018).

We selected six forest patches in Baltimore in which to study the effects of patch origin, topography, edge environments, and invasion on near-ground solar radiation (Fig. 2.1, Table 2.1). The sites were chosen from 40 patches that are being studied and characterized as part of a collaboration between the University of Maryland, Baltimore County (UMBC), the US Forest Service, and Baltimore Green Space (Fig. 2.1) (Baker et al., *unpub. manuscript*). Over the past six years, these groups have collected data on soil characteristics, hydrologic function, and species composition at

Fig. 2.1. Physiographic provinces and the location of forest patches being studied and characterized in Baltimore, MD, denoted by circles. Large, numbered circles represent the six selected site and correspond with aerial photographs (right, to scale) and details in Table 1 (below).

Table. 2.1. Characteristics of selected forest patches. Patch numbers correspond to values in Fig. 2.1.

No.	Patch Name	Location	Area (ha)	Length (m)	Width (m)	No. of Points	Landform(s)
1.	Carroll	Southwest	4.4	190	95	25	Ridge
2.	Fendal	Northwest	13.8	700	170	69	Between two ridges, contains small valley
3.	Forest Glen	West	9.8	300	260	72	Ridge and valley
4.	Herun	Northeast	9.9	430	130	57	Ridge and valley
5.	Sinai	Northwest	8.6	550	180	34	Ridge; adjacent to valley
6.	Village Square	Northwest	5.5	590	80	62	Slope between ridge and valley

sampling sites located at the intersection points of a 35- to 40- meter grid projected onto each forest patch.

Because there is great variability in the scale and features of the 40 studied forest patches, we selected six sites that shared several characteristics; all studied patches are located in the Piedmont Plateau physiographic province, are larger than three hectares, are at least 75 meters wide, contain more than 20 sampling points, and are not fragmented by roads or buildings (Fig. 2.1, Table 2.1).

The dominant tree species in the surveyed forest patches include tuliptree *(Liriodendron tulipfera)*, white oak *(Quercus alba)*, red maple *(Acer rubrum)*, red oak *(Quercus rubrum)*, American beech *(Fagus grandifolia)*, and green ash *(Fraxinus pennsylvanica)*. While more than 90 percent of the tree species present are native to North America, about 56 percent of the groundcover species are non-native. Common non-native species include vines such as English ivy *(Hedera helix)*, Japanese honeysuckle *(Lonicera japonica)*, porcelain berry *(Ampelopsis brevipedunculata)*, and oriental bittersweet *(Celastrus orbiculatus)* (Baker et al., *unpub. manuscript*; Phillips et al., 2019).

2.2. Photograph acquisition

We estimated transmittance of solar radiation below the canopy through the analysis of hemispherical photographs taken in each forest patch. Hemispherical photographs capture plant canopies through an extreme wide-angle lens placed beneath the canopy, facing upwards (Anderson, 1964). The images display a full hemisphere of visible sky and provide a permanent record of canopy geometry, which can be used to determine canopy characteristics and the light environment below the canopy (Hall et al., 2017; Rich, 1990).

To study the variation in solar radiation regimes across the forest patches, we took between ten and twenty-eight hemispherical photographs in each patch during the summer of 2020. Photographs were collected at alternating intersection points of the established sampling grid (Fig. 2.2). In total, 127 sites were sampled, with 10 at Carroll, 27 at Fendal, 27 at Forest Glen, 28 at Herun, 18 at Sinai, and 17 at Village Square. Variability in the number of sampling sites among the forest patches was a result of variation in the size and shape of the patches.

Following the recommendations of Fournier et al. (2017) and Beckschäfer et al. (2013), photographs were taken during a 45- to 60-minute timeframe at dusk, when sky conditions were uniform and skylight was diffuse, yet bright enough to capture a contrast between the sky and the foliage. All photographs were collected using a Canon EOS 80D camera (Huntington, NY, USA) fitted with a SIGMA 4.5 mm F2.8

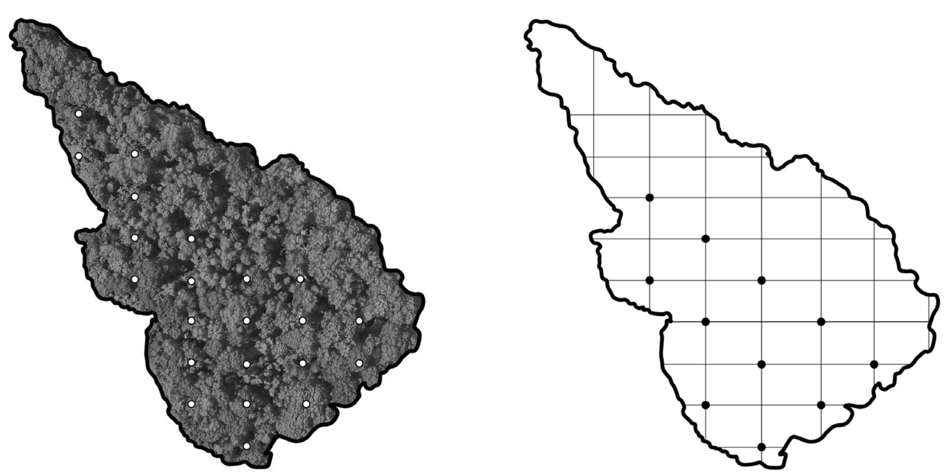

Fig. 2.2. Patch sampling regime. Existing sampling sites in Carroll (left) are denoted by white dots; photographs were taken at alternating intersections along the existing sampling grid (right).

EX DC circular fisheye lens (Kawasaki-shi, Kanagawa, Japan). At each sampling site, the camera was positioned on a tripod at breast height, 1.37 meters above ground level. We then oriented the camera towards North, levelled it, pointed the lens directly upward, and took several photographs (Fig. 2.3). To ensure that a clear, sharp depiction of canopy openings was captured in the photograph, we took an auto-exposed photograph, then reviewed that image using the camera's "highlight alert" playback mode. In this mode, the overexposed areas of the image are marked as blinking lights. If areas of the image were overexposed, we adjusted the exposure incrementally until no warning lights appeared and no part of the image was overexposed (Beckschäfer et al., 2013).

2.3. Photograph analysis

Photographs were analyzed using HemiView canopy analysis software (HemiView 2.1, Delta-T Devices, Cambridge, UK) to determine the proportion of total solar

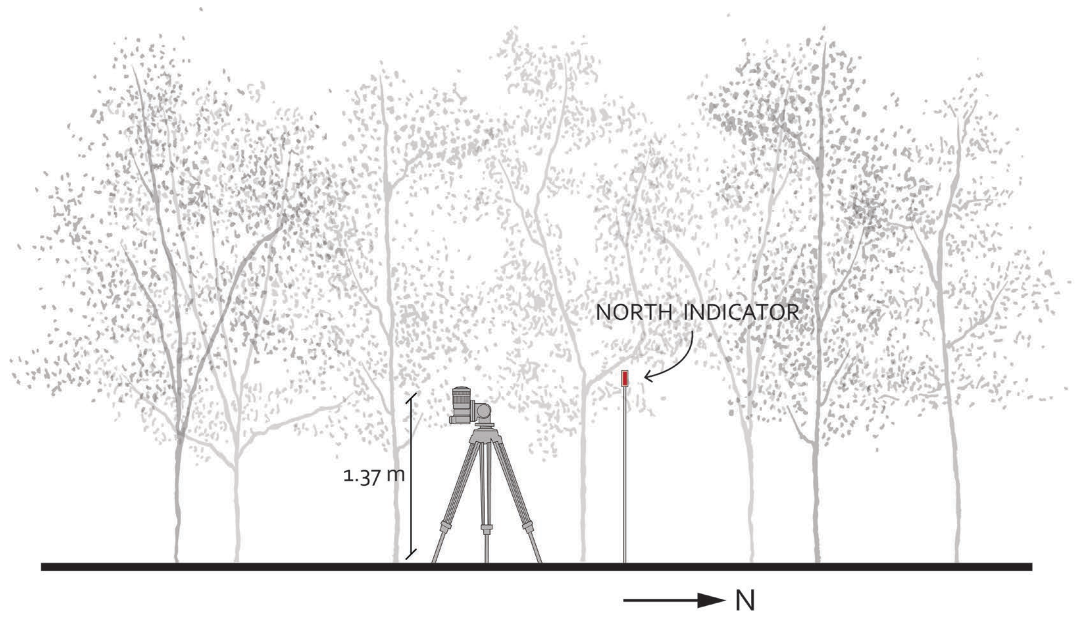

Fig. 2.3. Schematic diagram of camera positioning below the forest canopy. The camera was positioned on a tripod 1.37 m above ground level with the lens pointed upward and the bottom oriented towards North. The direction of North was marked in the field by a North indicator.

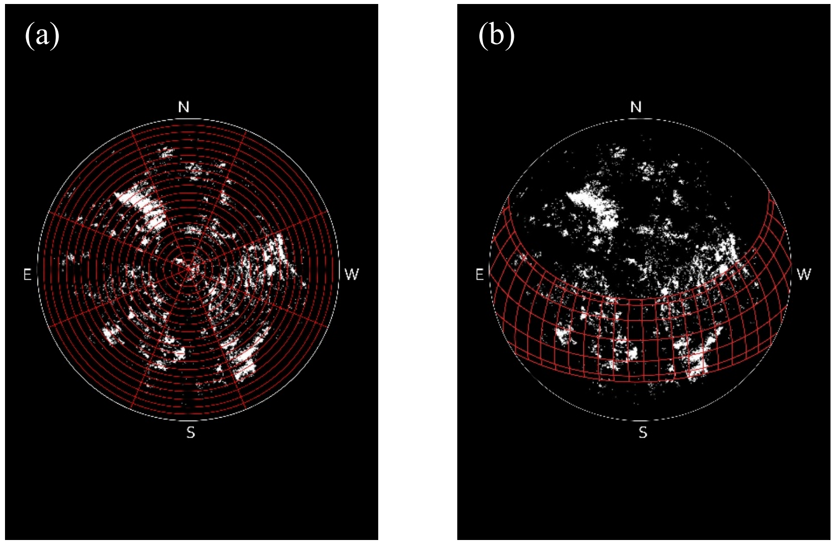

Fig. 2.4. Sky sectors superimposed over hemispherical photographs, used to determine diffuse and direct radiation below the canopy: (a) skymap divisions defined by zenith and azimuth angles, used to calculate diffuse radiation inputs; (b) sunmap divisions defined by the sun's path, used to calculate direct radiation inputs.

radiation received below the canopy relative to that above at each location (global site factor, GSF). For every image, the amount of diffuse radiation transmitted below the canopy was calculated by dividing the photograph into 162 sky sectors defined by zenith and azimuth angles, determining the proportion of visible sky in each sector (gap fraction), and multiplying gap fraction by the total diffuse radiation originating from each sky sector (Fig. 2.4a) (Delta-T Devices Ltd, 1999). To determine the amount direct radiation transmitted below the canopy, each photograph was overlaid by solar tracks that divide the image into 160 sky sectors defined by the path of the sun over the course of each day and throughout the year (Fig. 2.4b). As with diffuse radiation, direct radiation was calculated by multiplying the gap fraction of each sky sector by the direct radiation originating from that sector (Delta-T Devices Ltd, 1999). Global site factor (GSF) was then calculated from the diffuse and direct radiation values using the following equation:

$$GSF = \frac{DifBe + DirBe}{DifAb + DirAb} \quad \text{(Eq. 1)}$$

where *DifBe* is the diffuse radiation below the canopy, *DirBe* is the direct radiation below the canopy, *DifAb* is the diffuse radiation above the canopy, and *DirAb* is the direct radiation above the canopy, all modelled in megajoules per square meter (see Appendix A).

2.4. Forest characteristics and topographic variables

To study the effects of topography and forest characteristics on near ground-solar radiation, we collected data on six predictor variables: patch origin, patch compactness, aspect, slope, distance of sampling sites to the patch edge, and vine invasion (see Appendix B).

As previously mentioned, forest patches in urban areas may originate as either remnant or regenerated sites. For this study, we defined remnant patches as those that were forested in 1927, while regenerated sites were cleared for human use at that time, then abandoned and reforested. Sampled forest patches were classified as remnant or regenerated through the analysis of historical aerial photographs of Baltimore City. Sampling sites that were observed to be forested in photographs from 1927 were classified as remnant, whereas sites that were not forested at that time – most often used instead for agriculture or were grasslands – were classified as regenerated (Baker et al., *unpub. manuscript*).

Patch compactness (K), a measure of patch elongation or circularity, was calculated using the following equation:

$$K = \frac{2\sqrt{\pi * A}}{P} \quad \text{(Eq. 2)}$$

where A is the patch area and P is the patch perimeter (Bosch, 1978; Davis, 1986). Area and perimeter were determined from Google Earth™ (Google Earth Pro 7.3, Google, Mountain View, CA, USA) aerial imagery and measurement tools.

The aspect and slope at each sampling site were determined from a digital elevation model of Baltimore City (Maryland Geographic Information Office, 2015).

To determine the distance of each sampling site from the forest edge, patch boundaries for each sampled patch were drawn using Google Earth™ (Google Earth Pro 7.3, Google, Mountain View, CA, USA) aerial imagery and drawing tools. The distance of a sampling site to the nearest identified patch boundary was then determined using the Euclidean distance spatial analysis tools in ArcMap™ (ArcGIS® 10.8.1, Esri, Redlands, CA, USA).

To quantify vine invasion, at each sampling site, all trees included within a 10 BAF wedge prism were rated based on the Shumaker Vine Invasion Index. Using this six-step rating scale, the extent of vining on each tree stem and canopy was associated with an integer value: no vines on the tree trunk (0), vines on the bottom of the trunk (1), vines on the trunk below the canopy (2), vines growing into the canopy (3), vines covering the majority of the canopy (4), and vines entirely covering the canopy (5) (Fig. 2.5). The Shumaker scores were averaged across all trees to obtain a single vine invasion value for each sampling site. At 23 sites, no trees were included within the prism; as such, no Shumaker scores were determined at these locations.

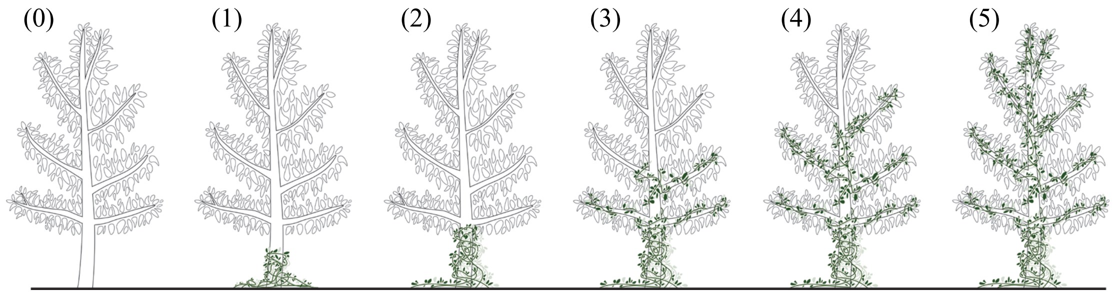

Fig. 2.5. Schematic diagram of vine invasion on trees and the corresponding Shumaker Vine Invasion Index value. Based on this indexing system, trees with no vines growing on them are given a score of zero; trees with vines growing on the bottom of the trunk receive a score of one; trees with vines growing on the trunk but below the canopy receive a score of two; trees with vines growing into the canopy receive a score of three; trees with vines covering the majority of the canopy are given a score of four; and trees with vines completely covering the canopy receive a score of five.

2.5. Statistical analyses

2.5.1. Influence of patch origin on global site factor

Due to the non-normality of the GSF data, we used a Mann-Whitney U test to assess the influence of patch origin (remnant (n = 94) or regenerated (n = 33)) on near-ground solar radiation. We used MATLAB (R2020b, MathWorks®, Natick, MA, USA) to perform this analysis.

2.5.2. Comparisons of global site factor between forest patches

We used a Kruskal-Wallis test to assess variability in near-ground solar radiation among the sampled forest patches. Based on these results, we conducted Nemenyi post-hoc tests for pair-wise comparisons to identify forest patches in which solar radiation inputs were significantly different from the other patches.

To assess the influence of patch compactness on near-ground solar radiation, we performed a linear regression analysis of the median GSF of each patch against its compactness. We used MATLAB (R2020b, MathWorks®, Natick, MA, USA), R

(4.0.2, R Foundation for Statistical Computing, Indianapolis, IN, USA), and RStudio (1.3.1073, RStudio, Inc., Boston, MA, USA) to perform these analyses.

2.5.3. Relationships among topography, forest characteristics, and global site factor

We used a multiple linear regression model to assess the influence of aspect, slope, distance to edge, and vine invasion on near-ground solar radiation. To meet model assumptions, we log-transformed global site factor and slope angle, and square-root-transformed distance to patch edge and Shumaker Vine Invasion Index. Because no Shumaker score was determined at 23 sampling locations, we ran two regression models: one for global site factor on aspect, slope, and distance to patch edge (n = 127), and one for global site factor on aspect, slope, distance to patch edge, and vine invasion, with sampling sites for which there was no Shumaker score excluded (n_{shum} = 104). Variance inflation factors (VIFs) of less than 1.84 suggest that multicollinearity among predictor variables was sufficiently low (see Appendix C).

From comparisons of global site factor between forest patches, we found that two patches – Forest Glen and Village Square – received solar radiation inputs that were significantly different ($P < 0.05$) from the other five patches. Based on these results, we ran both regression models four times, once each for all forest patches (n = 127, n_{shum} = 104), Forest Glen (n = 27, n_{shum} = 15), Village Square (n = 17, n_{shum} = 8), and Carroll, Fendal, Herun, and Sinai, hereafter referred to as CFHS (n = 83, n_{shum} = 81). We used R (4.0.2, R Foundation for Statistical Computing, Indianapolis, IN, USA) and RStudio (1.3.1073, RStudio, Inc., Boston, MA, USA) to perform these analyses.

Chapter 3. Results.

3.1. Influence of patch origin on global site factor

Mann-Whitney *U* comparisons indicate that forest patch origin has no significant effect on near-ground solar radiation (*U* = 1435, 1667, *P* = 0.52); remnant and regenerated patches had similar global site factor distributions. The median GSF in remnant patches was 0.078 ((*IQR* = 0.054-0.13). In regenerated patches, the median GSF was 0.079 ((*IQR* = 0.061-0.14) (Fig. 3.1). At remnant sites, ten data points (10.6%) were upper outliers (more than 1.5 times the interquartile range greater than the 75th percentile), while at regenerated sites, three data points (9.1%) were outliers, further suggesting that insolation below the canopy is not influenced by patch origin (Fig. 3.1).

3.2. Comparisons of global site factor between forest patches

Across all six sampled forest patches, global site factor ranged from a minimum value of 0.019 to a maximum value of 0.74, with a median GSF of 0.078 (IQR = 0.055-

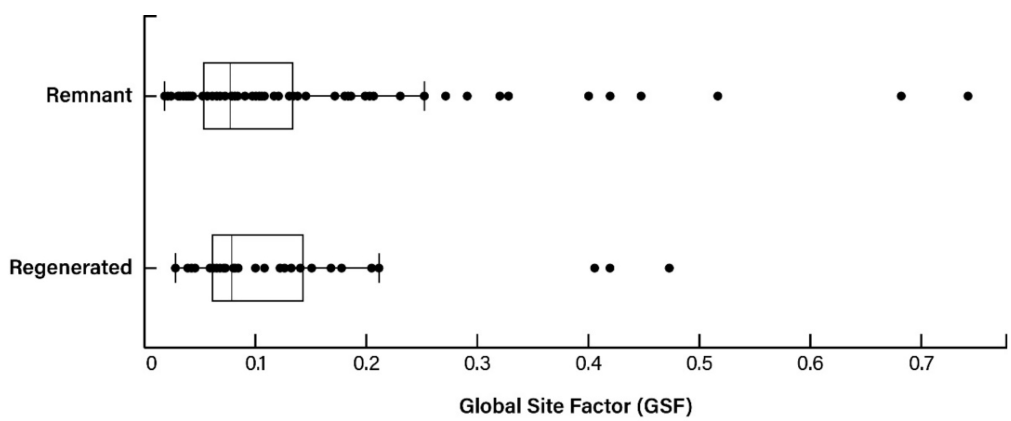

Fig. 3.1. Comparison of global site factor (GSF) distributions between the sampled forest patches, including the median (black line), interquartile range (25%-75%, bound by box), and outliers (values more than 1.5 times the interquartile range greater than the 75th percentile, shown as black dots outside whiskers).

0.13). Analyses of individual patches showed that relative to the other forest patches, near-ground solar radiation was significantly higher at Village Square ($P < 0.05$), which had a median GSF of 0.12 (*IQR* = 0.067-0.35). Additionally, near-ground solar radiation was found to be significantly lower in Forest Glen relative to the other five patches ($P < 0.05$), with Forest Glen having a median GSF of 0.060 (*IQR* = 0.038-0.094). There was no significant difference in solar radiation inputs among the remaining four forest patches, Carroll, Fendal, Herun, and Sinai (Fig. 3.2, Table 3.1).

Across the sampled forest patches, median patch compactness ranged from 0.52 for Village Square to 0.78 for Forest Glen. Linear regression analyses indicate that patch compactness is a significant predictor of solar radiation inputs ($R^2 = 0.79$, $P < 0.02$), with median patch GSF having decreased as compactness increased (Fig. 3.3).

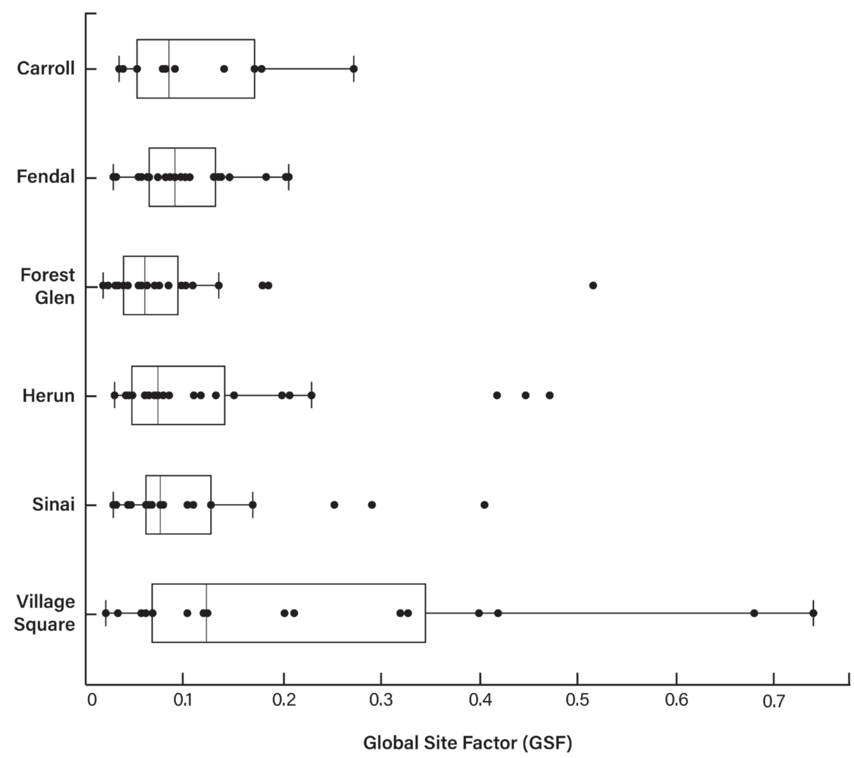

Fig. 3.2. Comparison of global site factor (GSF) distributions between the sampled forest patches, including the median (black line), interquartile range (25%-75%, bound by box), and outliers (values more than 1.5 times the interquartile range greater than the 75th percentile, shown as black dots outside whiskers).

Table 3.1. Summary of global site factor (GSF) values, including the minimum, 25th percentile, median, 75th percentile, and maximum for studied patches and patch groupings: all sites, Carroll, Fendal, Herun, and Sinai (CFHS, grouped), each individual forest patch, remnant sites, and regenerated sites. GSF distributions for Carroll, Herun, Fendal, and Sinai (shown in gray) are reported individually but were studied as a single entity (CFHS) in further analysis.

Patch	*n*	Min.	25th percentile	Median	75th percentile	Max.
All	127	0.019	0.055	0.078	0.13	0.74
CFHS	83	0.028	0.060	0.080	0.13	0.47
Forest Glen	27	0.019	0.038	0.060	0.094	0.52
Village Square	17	0.020	0.067	0.12	0.35	0.74
Carroll	10	0.035	0.053	0.086	0.17	0.27
Fendal	27	0.029	0.065	0.091	0.13	0.21
Herun	28	0.029	0.046	0.073	0.14	0.47
Sinai	18	0.028	0.062	0.076	0.13	0.41
Remnant	94	0.019	0.054	0.078	0.13	0.74
Regenerated	33	0.029	0.061	0.079	0.14	0.47

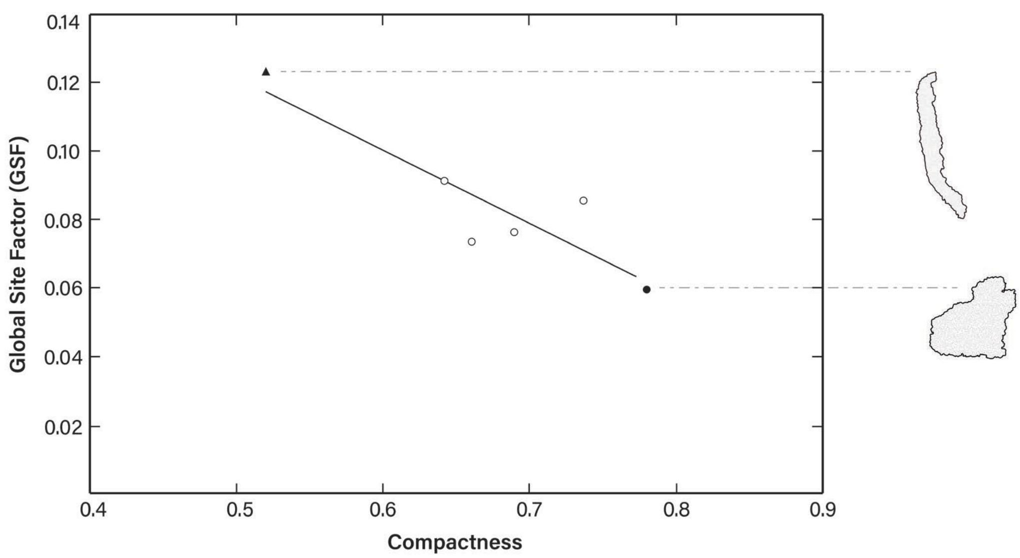

Fig. 3.3. The relationship between near-ground solar radiation, measured as median global site factor, and patch compactness in six forest patches – Village Square (triangle), Forest Glen (closed circle), and Carroll, Fendal, Herun, and Sinai (open circles) – in Baltimore, MD (y = -0.21x + 0.23, R2 = 0.79, P = 0.018). At right, the shape of Village Square, the least compact patch (top), and Forest Glen, the most compact patch (bottom).

3.3. Relationships among topography, forest characteristics, and global site factor

Multiple regression analyses of log-transformed global site factor on aspect, slope, distance to patch edge, and vine invasion showed a significant influence of distance to patch edge and vine invasion on GSF across all forest patches, with the presence and magnitude of these effects varying among sites. In the analyses of GSF on aspect, slope, and distance to patch edge, the adjusted R^2 values ranged from 0.0041 in CFHS to 0.24 in Village Square. When Shumaker vine invasion scores were included in the model, R^2 values ranged between 0.001 in CFHS and 0.72 in Village Square (Table 3.2). Across all sampled patches, the percentage of variance explained by the four predictor variables – aspect, slope, distance to edge, and vine invasion – was just 3.9%. At Forest Glen and Village Square, however, these variables were more predictive of GSF, explaining 11% and 72% of the variance in each model, respectively.

Our analyses indicate that aspect had no significant effect on near-ground solar radiation at any of the studied forest patches (all sites: P = 0.96; CFHS: P = 0.37;

Table 3.2. Summary statistics for multiple regression analyses of global site factor (GSF) on aspect, slope, and distance to patch edge (top) and on aspect, slope, distance to patch edge, and vine invasion (bottom). Because no Shumaker score was determined at 23 sampling sites, a regression model for sites with a Shumaker score was run separately. Results for Carroll, Herun, Fendal, and Sinai (shown in gray) are reported individually but only results from collective analysis of CFHS are discussed.

Patch	n	R^2	P values			
			Aspect	Slope	Distance to edge	Vine invasion
All	127	0.0061	0.96	0.45	**0.049**	
CFHS	83	0.0041	0.37	0.23	0.46	
Forest Glen	27	0.028	0.51	0.15	0.44	
Village Square	17	0.24	0.43	0.49	**0.029**	
Carroll	10	0.21	0.80	0.22	0.30	
Fendal	27	0.0053	0.35	0.19	0.20	
Herun	28	0.048	0.91	0.61	0.14	
Sinai	18	0.045	0.16	0.86	0.71	
All	104	0.039	0.74	0.14	0.29	**0.016**
CFHS	81	0.001	0.83	0.22	0.44	0.16
Forest Glen	16	0.11	0.76	0.40	0.30	**0.016**
Village Square	8	0.72	0.61	0.35	0.06	**0.045**
Carroll	10	0.067	0.81	0.27	0.59	0.89
Fendal	26	0.027	0.57	0.16	0.18	0.52
Herun	27	0.0074	0.73	0.51	0.25	0.43
Sinai	18	0.055	0.40	0.36	0.79	0.14

Forest Glen: $P = 0.51$; Village Square: $P = 0.43$) (Fig. 3.4a). Similarly, on both north and south aspects, slope angle did not significantly influence below-canopy solar radiation inputs (all sites: $P = 0.45$; CFHS: $P = 0.23$; Forest Glen: $P = 0.15$; Village Square: $P = 0.49$) (Fig. 3.4b).

A significant negative relationship between global site factor and distance to patch edge was identified across all sampled sites ($P = 0.049$) (Fig. 3.5a) and at Village Square ($P = 0.029$) (Fig. 3.5b). However, this relationship was not observed at CFHS ($P = 0.46$) or at Forest Glen ($P = 0.44$), and the low R^2 values for all models

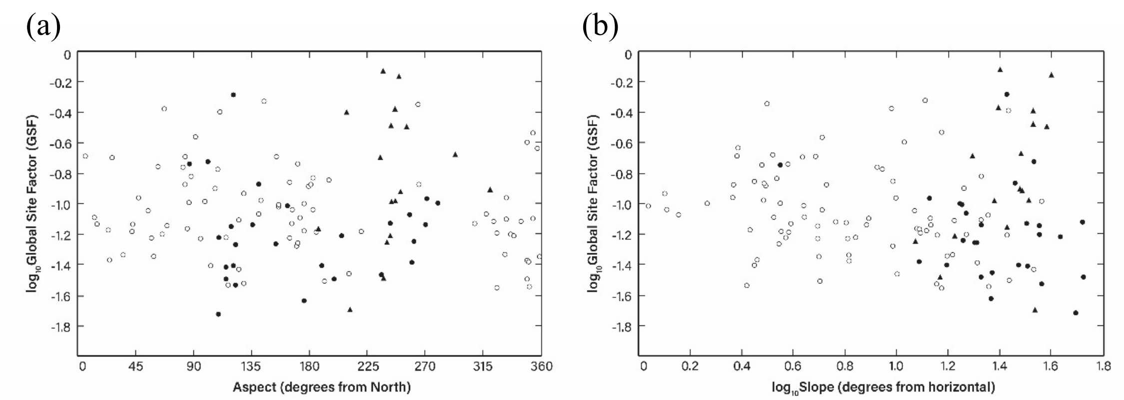

Fig. 3.4. The relationships between near-ground solar radiation, measured as global site factor, and (a) aspect and (b) slope in six forest patches – Village Square (triangles), Forest Glen (closed circles), and Carroll, Fendal, Herun, and Sinai (open circles) – in Baltimore, MD.

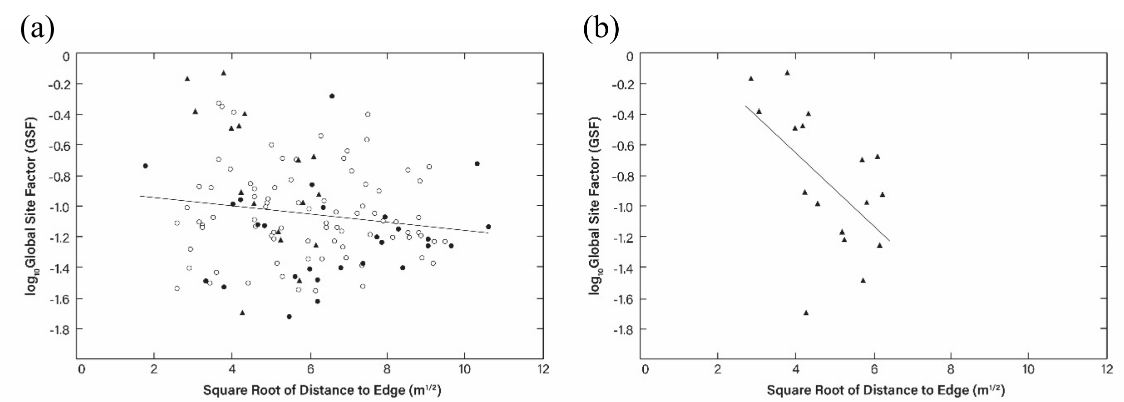

Fig. 3.5. The relationships between global site factor and distance to patch edge in (a) six of Baltimore's forest patches – Village Square (triangles), Forest Glen (closed circles), and Carroll, Fendal, Herun, and Sinai (open circles) ($P = 0.049$) and in (b) Village Square ($P = 0.029$).

(all sites: R^2 = 0.0061; CFHS: R^2 = 0.0041; Forest Glen: R^2 = 0.028; Village Square: R^2 = 0.24) suggest that at most sites, distance to edge was a slight, but not strong predictor of below-canopy solar radiation.

At sampling sites where a Shumaker Vine Invasion Index was recorded (n = 104), vine invasion was identified as a significant predictor of global site factor across all sampled sites (P = 0.016), at Forest Glen (P = 0.016), and at Village Square (P = 0.045). Increased presence of non-native vines generally corresponded with an increase in near-ground solar radiation. However, the Shumaker score was not a significant predictor of GSF at CFHS (P = 0.16) (Fig. 3.6), and along with topographic characteristics and distance to patch edge, vine invasion explained relatively little of the variance in global site factor observed at CFHS and across all patches.

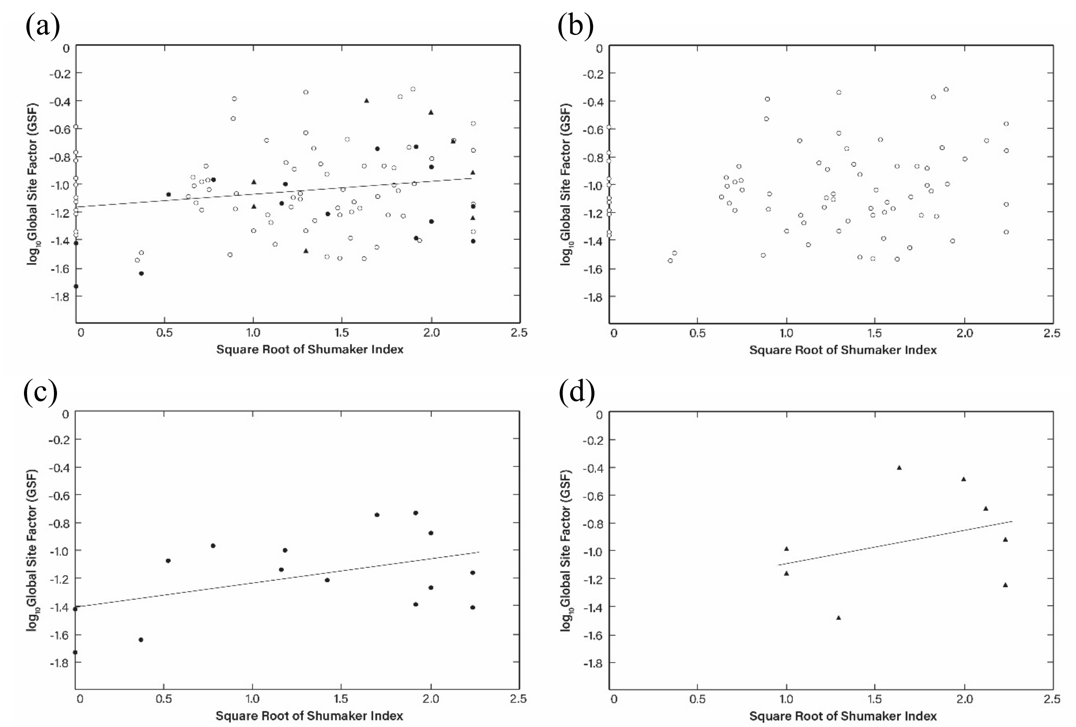

Fig. 3.6. The relationships between global site factor and Shumaker Vine Invasion Index in (a) six of Baltimore's forest patches – Village Square (triangles), Forest Glen (closed circles), and Carroll, Fendal, Herun, and Sinai (open circles) (P = 0.016); (b) Carroll, Fendal, Herun, and Sinai (P = 0.16); (c) Forest Glen (P = 0.016); and (d) Village Square (P = 0.045).

Chapter 4. Discussion.

Analyses of the effects of multiple patch attributes – patch origin, patch shape, slope, aspect, distance to edge, and vine invasion – on near-ground insolation showed that internal patch attributes and landscape characteristics affect energy inputs, although the strength of the observed relationships varied between patches. While patch origin had no significant affect solar radiation inputs (Fig. 3.1), we observed a strong negative relationship between GSF and patch compactness (Fig. 3.2). In terms of within-patch variability, sites that were closer to patch edges and had greater vine presence tended to receive more radiation than less invaded, interior sites (Fig. 3.5, 3.6). However, the relationships among GSF, distance to edge, and vine invasion differed between patches and were statistically significant at only two of the six sampled forest stands.

4.1. Influence of patch origin on global site factor

Our results indicate that during the past 90 years, regenerated forest patches have developed relatively rapidly and today receive below-canopy solar radiation inputs comparable to remnant ones (Fig. 3.1). The similarities in GSF distributions between patch types further suggest that radiation-driven processes and canopy density are also alike, despite an approximately 50-year age difference between patch types and estimates that Northeastern hardwood forests require several hundred years to reach climax conditions (Brubaker, 1981). This parallel between forest stands is likely due to the early establishment of shade intolerant species such as *Liriodendron tulipfera* and the dominance of species such as *Acer rubrum*, *Quercus rubrum*, *Fagus* *grandifolia*, and *Fraximus pennsylvanica* about 100 years after the abandonment of agricultural land (Christensen and Peet, 1981; Goldblum and Beatty, 1999). The trends observed in Baltimore's forest patches align with patterns found by Zipperer (2002), who inventoried remnant and regenerated forest patches in Syracuse, New York. Zipperer (2002) reported nearly equivalent basal areas between remnant and regenerated sites, closed canopies in all disturbed patches, and a high species richness regardless of patch origin. These patterns differ from those observed by Wallace et al. (2017) in a study of below-canopy light conditions in restored, unrestored, and remnant urban forests in New Zealand. Wallace et al. (2017) found that canopy openness and light transmittance was higher in unrestored patches than in old-growth remnants and restored sites. The difference in results between Wallace et al.'s (2017) study and ours may be because the unrestored patches inventoried by Wallace et al. (2017) were disturbed more recently and likely more severely (e.g., from clear-felling and sand mining) than those surveyed in our study. Additionally, remnant sites inventoried for our study were not old-growth forests, but rather were cleared in the mid-nineteenth century, fifty to eighty years prior to the establishment of regenerated sites.

In our study area, the vast majority (85%) of regenerated sites grew over grasslands and agricultural fields that were abandoned during the first half of the twentieth century. While former agricultural sites have long comprised the majority of urban land available for afforestation, an increasing proportion of regenerated forest cover in the Baltimore region occurs on land cleared for urban development rather than agriculture (Zhou et al., 2011). In Baltimore, the population declined by

37% between 1950 and 2019, (Burch and Grove, 1993; US Census Bureau 2019), resulting in 30,000 properties presently vacant throughout the city, 14,000 of which contain no building (Tauzer, 2009; Baltimore Department of Planning, 2016). These vacant properties afford opportunity for urban greening and afforestation (Baltimore Department of Planning). However, because environmental factors that influence forest regeneration (e.g., soil conditions, the species pool, and nutrient availability) can vary greatly between developed and agricultural sites (Prach et al., 2001; Oldfield et al., 2013), the tree canopy of forests regenerated on vacant lots may differ substantially from those regenerated on former agricultural land (Zhou et al., 2011). Future studies of forests regenerated from vacant properties could be conducted to assess the influence of prior urban development on forest regeneration and below-canopy solar radiation.

4.2. Comparisons of global site factor between forest patches

Comparisons of median GSF values among the six urban forest patches suggest that patch compactness has a strong effect on near-ground solar radiation (Fig. 3.3). The negative relationship observed between insolation and compactness is consistent with results from previous studies of microclimate in forest fragments (Saunders et al., 1991; Baldocchi and Collineau, 1994). The influence of compactness on microclimate and ecosystem processes has commonly been attributed to lower edge-to-interior ratios, and thus the minimization of edge effects in compact patches (Harrison and Bruna, 1999). However, we found that in Baltimore’s forest patches, the negative relationship between GSF and compactness was not due solely to the higher proportion of edge at elongated sites. The expected negative relationship between

GSF and distance to patch edge, i.e., a decline in near-ground solar radiation with increasing distance from edge, was present at just one of the six sampled forest patches. Similar trends of patch compactness influencing ecological function despite a lack of edge effects have been reported by Buffa et al. (2018). It is therefore possible that solar radiation is higher in less compact patches due to increased disturbance from adjacent development (e.g., pollutants from the surrounding matrix that saturate a patch and alter ecological processes) affecting radiation inputs throughout the entire patch (Forman, 1990).

Increased insolation can influence a range of biophysical and ecohydrological processes essential to the structure and function of forest communities (Baldocchi and Collineau, 1994; Zou et al., 2007). Specifically, light availability and the corresponding solar energy inputs drive plant establishment and understory development (Wallace et al., 2017; Spies, 1998). In forested areas with higher levels of solar radiation, the presence of sky gaps where light was previously limiting can enhance the growth of invasive herbaceous plants (Saunders et al., 1991; McQueen et al., 2006). Such changes in forest community structure alter resource availability and may thus affect fauna as well. For example, Whelan and Maina (2005) found that in deciduous oak forests in Illinois, USA, bark-foraging birds were less present in areas with greater solar radiation inputs, likely due to the higher metabolic costs of foraging in hotter, drier habitat. Species responses to solar radiation were also observed by Skelly et al. (2005), who found that amphibian distribution in northeastern forested wetlands was related to GSF, with some species such as marbled salamander (*Ambystoma opacum*) preferring shaded environments and others such as gray treefrog (*Hyla versicolor*) and spring peeper (*Pseudacris crucifer*) favoring environments with open canopies and more incoming radiation.

Interactions between canopy cover and light availability affect soil temperature and soil evaporation rates (Zou et al., 2007). In low-light environments, soil temperatures tend to be lower due to shading from the canopy and the accumulation of leaf litter (Breshears et al., 1998). By contrast, high soil temperatures below canopy gaps drive rates of soil evaporation, which in turn decreases soil water availability (Breshears et al., 1998; Loik et al., 2004). While the presence of canopy gaps has the potential to increase soil moisture due to a decline in interception of precipitation by the canopy (Minckler, 1973), the variation in soil temperature resulting from sky gaps may cause substantial fluxes in the amount of water available to plants (Wallace et al., 2017). Soil water availability alters species composition, leaf production, plant growth, soil microorganism activity, litter decomposition, and nutrient cycling in forest ecosystems (Pastor and Post, 1986; Parker, 1989). For instance, herbaceous species cover and tree germination rates are both positively correlated with soil moisture and negatively correlated with soil temperature (Floyd, 1983; Gálhidy et al., 2006). In a study of eastern deciduous hardwood forests, Brzostek et al. (2014) found that most tree species responded negatively to increased water stress, and that even small declines in soil water availability could reduce net ecosystem production by more than 15%. Because near-ground solar radiation impacts plant community structure and other ecological processes, land management strategies that aim to enhance ecosystem functions and services in urban forest patches may benefit from prioritizing the conservation of compact patches with lower solar radiation inputs.

4.3. Relationships among topography, forest characteristics, and global site factor

Our results reveal that near-ground solar radiation in urban forest patches is driven by multiple factors that vary in influence across sites. The low R^2 values for the full dataset suggest that while distance to edge and vine invasion are significant variables, other forest stand characteristics are more important drivers of GSF (Table 3.2). However, the R^2 values of 0.11 at Forest Glen and 0.72 at Village Square indicate that the studied variables, namely distance to edge and vine invasion, can have a quite strong effect on solar radiation inputs to urban forest patches. The inconsistent relationships between GSF and topography, distance to edge, and vine invasion across sites may be caused by other components of the heterogeneous urban matrix (Cadenasso et al., 2007; Band et al., 2005). For example, factors uniquely modified by urbanization such as patch connectivity (Stenhouse, 2004; Pirnat and Hladnik, 2016), soil properties (Pavao-Zuckerman, 2008), species interactions (Faeth et al., 2005), and biodiversity (Schwartz et al., 2002; Müller et al., 2018; Soanes et al., 2019) shape vegetation dynamics and forest patch conditions (Johnson et al., 2020). Urban and ecological variables interact in a range of ways at sites throughout the city (Zhou et al., 2017), which in turn may affect the magnitude of microclimatic responses at different forest patches. The influence of each of the variables we studied – aspect, slope, distance to edge, and vine invasion – on near-ground solar radiation, as well as potential causes of variability between sites, are discussed below.

4.3.1. Aspect and Slope

Microtopography and vegetation interact with one another in a complex manner that can impact solar radiation and microclimatic patterns in forested areas (Zou et al., 2007; Geiger et al., 2009). Generally, variations in ground-level insolation across space are attributed to changes in slope and aspect (Chung and Yun, 2004), with steeper, south-facing slopes receiving more radiation (Dobrowski, 2011; Frey et al., 2016). In this study, however, we found that aspect and slope did not affect near-ground solar radiation (Table 3.2, Fig. 3.4). This was likely due to the overwhelming influence of the density and variability of the forest canopy diminishing the effects of microtopography. While the interactions between solar radiation and topography may have been muted due to the inclusion of diffuse radiation in the calculations of solar radiation inputs (Rosenberg et al., 1983), a similar lack of relationship between below-canopy direct radiation and topography further reinforces the conclusion that under high and variable canopy cover conditions, the influence of topography on near-ground solar radiation is negligible (Fig. 4.1).

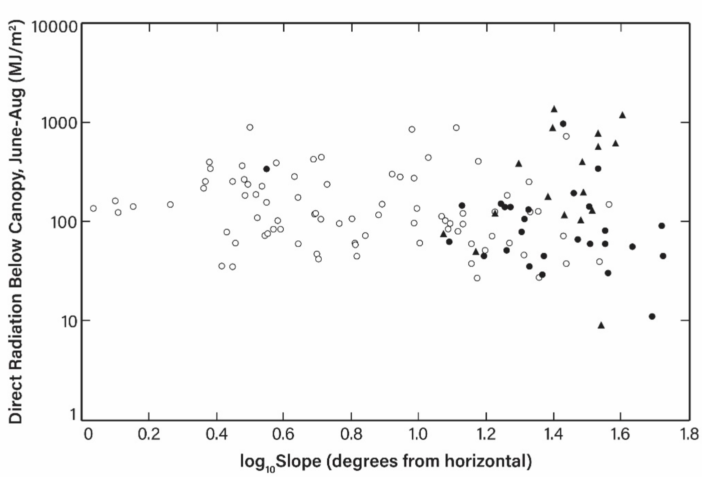

Fig. 4.1. Direct solar radiation inputs below the canopy from June to August, plotted against log-transformed slope in six forest patches – Village Square (triangles), Forest Glen (closed circles), and Carroll, Fendal, Herun, and Sinai (open circles) – in Baltimore, MD.

Our findings that topography did not influence solar radiation inputs below the forest canopy are supported by observations made by Zou et al. (2007) in a study modeling the response of solar radiation inputs to changes in aspect, slope, and tree cover. Zou et al. (2007) determined that during the summer and under high canopy cover, all influence of slope and aspect on near-ground radiation transmittance was obscured by the heavy tree canopy. In the urban hardwood forests we studied, where the canopy tended to be dense and median global site factor was between 50 and 75% lower than the site factor analyzed by Zou et al. (2007), the effects of topography on below-canopy radiation were likely even more muted. These trends differ from those observed by Jucker et al. (2018), who found that understory microclimate in Borneo's tropical forests was affected by topography, due in part to the capacity of slope and aspect to shape canopy structure. In their study, canopy height and correlated variables such as temperature and vapor pressure deficit responded to changes in elevation, aspect, and the curvature of the terrain. Topographic effects on vegetation structure were also reported by Swetnam et al. (2017), who saw that forested sites with low slope angles and northernly aspects had greater biomass accumulation. Given that there was no significant relationship between topography and GSF at the sites we sampled, we conjecture that slope and aspect did not affect the structure or density of the tree canopy either. It is probable that in landscapes like those in Baltimore, which are less topographically diverse, there is a weaker vegetation response to slope and aspect than occurs in areas with more variable topography. The ability of vegetation to establish under a variety of topographic conditions present in mid-Atlantic cities suggests that planning for effective urban forest stands may not be constrained by topography and slope orientation.

4.3.2. Distance to patch edge

The trend that near-ground solar radiation increased with proximity to the patch edge across all sampling sites aligns with a widely accepted understanding of forest patch edges as regions characterized by higher light transmittance and higher temperatures (Fig. 3.5a) (Godefroid and Koedam, 2003; Jose et al., 1996). When forest edges are created, they are opened to wind and solar radiation. This often results in edge effects, unique microclimatic processes that arise from edge creation (Camargo and Kapos, 1995; Matlack and Litvaitis, 1999). Edge creation can cause an increase in tree mortality, further contributing to greater radiation exposure at patch edges (Williams-Linera, 1990; Harper et al., 2005). Disturbance and high-light conditions at patch edges have also been found to prompt the growth of invasive vines, which can lead to a positive feedback between the presence of vines and increased insolation (Lovejoy et al., 1986; Panetta and Hopkins, 1991). However, at our sampled patches, no significant relationship between vine invasion and distance to edge was observed (Fig. 4.2). Rather other microclimatic, structural, and disturbance factors likely drove the increase in below-canopy solar radiation near patch edges.

While a negative relationship between GSF and distance to patch edge was quite strong at Village Square and present overall, near-ground solar radiation at most of the studied patches was not affected by a site's proximity to the edge (Fig. 3.5). Though unexpected, a number of other studies have reported similar results (Buffa et al., 2018; Camargo and Kapos, 1995). Camargo and Kapos (1995) attributed the

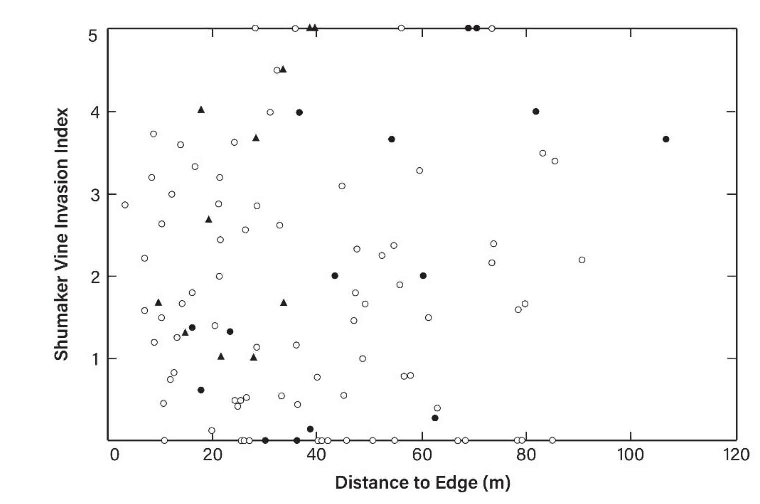

Fig. 4.2. Relationship between vine invasion, reported using the Shumaker Vine Invasion Index, and distance to patch edge in six forest patches – Village Square (triangles), Forest Glen (closed circles), and Carroll, Fendal, Herun, and Sinai (open circles) – in Baltimore, MD.

complex patterns of soil moisture (as opposed to a gradient from forest edge to interior) seen in Amazonian forests to changes in vegetation structure in the time after edge creation. Similar changes to vegetation at forest edges over time have likewise been observed by Ranney et al. (1981) and Matlack (1994) in temperate deciduous forests in Wisconsin, USA and Pennsylvania and Delaware, USA, respectively. When a forest edge is first created, the canopy at the edge is typically unaltered. Soon after, the openness of the edge to wind and solar radiation can spur shifts in edge microclimate and species composition. Over time, high branch and leaf production by existing trees, as well as the new growth of denser vegetation can "seal" the edge and protect the forest inside (Camargo and Kapos, 1995; Ranney et al., 1981). Such processes limit the transmission of solar radiation into a forest fragment and can explain the similarities in GSF distribution we observed from the edge to the interior of most of the sampled patches. Kapos et al. (1993) also found that with time, canopy gaps that formed near the edge after the initial disturbance tended to propagate towards the patch interior. The occurrence of canopy gaps throughout forest fragments in the decades after edge creation is consistent with our findings of low canopy, high radiation conditions at both the edge and interior of the studied patches.

The varying responses of the patches to edge creation suggest that land uses adjacent to each patch may impact forest response and near-ground solar radiation (Hersperger and Forman, 2003; Laurance et al., 2001). For example, at Village Square, which is adjacent to a six-lane highway, edge influence was far more prevalent than at the other sampled patches, many of which were adjacent to open lawns, golf courses, or residential streets. This may have been because the high level of disturbance from large roads can exacerbate common responses to edge creation such as tree damage, loss of canopy cover, and habitat degradation (Forman et al., 1997; Harper et al., 2005; Gascon et al., 2000). In addition to transportation corridors, the range of land uses present in urban areas may affect forest edge conditions. For instance, natural edges created by tributaries and human-generated edges both border forest patches throughout Baltimore. Trees at natural edges tend to have variation in crown structure and degree of damage, whereas at human-generated edges, the abrupt boundaries are more uniform, and the large clearings adjacent to forest patches can cause greater wind turbulence and increased harm to trees (Matlack and Litvaitis, 1999). Moreover, contrasts between forest patches and their adjacent land uses may further impact the magnitude of edge effects, particularly as related to energy flows and microclimate (Li et al., 2018; Harper et al., 2005). Different land adjacencies likely influence ecological processes and the extent of ecosystem degradation in urban forest patches (Hobbs, 2000; Naveh, 2001). This is of particular relevance in heterogeneous urban areas, where land uses change greatly over short distances (Cadenasso et al., 2007). Indeed, in Baltimore each forest patch was adjacent to at least two distinct land covers (Fig. 4.3). Despite the importance of adjacent land use to forest edge conditions (Moran, 1984; Hersperger and Forman, 2003), few studies of ecological function at urban forest edges have differentiated between adjacent land uses. Future research focused on implications of urban edge heterogeneity would provide insight into causes of divergent microclimatic responses across forest patches and could inform strategic, targeted approaches to patch management.

4.3.3. Vine invasion

The positive relationship between GSF and Shumaker Index observed at two of the six sampled patches indicates that while a greater presence of invasive vines can correlate with increased near-ground solar radiation, the interactions between vine

Fig. 4.3. Edge conditions at Herun (left, top and bottom) and Village Square (right). A diverse array of land uses, including lawn areas, streams, trails, and highways, are adjacent to forest patches throughout Baltimore.

presence and tree canopy are variable and complex (Fig. 3.6). The vine species most common in Baltimore's forest patches – *Hedera helix*, *Lonicera japonica*, *Ampelopsis brevipedunculata*, and *Celastrus orbiculatus* – each affect host trees differently (Strelau et al., 2018; Larson et al., 2007; Emerine, 2011; McKenzie-Gopsill and MacDonald, 2021). *C. orbiculatus*, for example, is widely known to rapidly dominate existing vegetation, engulfing trees and weakening the canopy (Dreyer, 1994; McNab and Meeker, 1987; Fike and Niering, 1999). In Village Square, where *C. orbiculatus* appeared to dominate, the strong, positive relationship between vine invasion and insolation was likely due to the suppression of canopy growth and damage to weakened trees. On the other hand, at patches such as Fendal, where *H. helix* was most prevalent, no significant relationship between invasion and GSF was observed (Fig. 4.4). Although some have found that the presence *H. helix* inhibits forest regeneration and causes canopy gaps to form (Thomas, 1980; Larocque, 1999), others argue that *H. helix* does not damage healthy trees (Metcalfe, 2005; Gianoli et al.,

Fig. 4.4. *C. orbiculatus* engulfing trees in Village Square (left); *H. helix* growing on tree stems in a closed canopy forest in Fendal (right).

2010; Strelau et al., 2018). Our results correspond with the latter findings, with vine presence having minimal influence on near-ground solar radiation at most sites invaded by *H. helix*. Given the varying canopy responses to different vine species, it is possible that the lack of relationships between invasion and GSF are a function not only of vine presence but also species composition.

Important to this analysis is that GSF was determined using hemispherical photographs, whereas vines were inventoried using prism sampling. As such, there was overlap in the trees accounted for in the determination of each variable, but the sampled plots were not identical. The difference between sampling regimes may have affected the strength of the relationships reported at each patch. Despite this challenge, our work still indicates that vine invasion affects near-ground solar radiation. To better understand patterns of invasion and microclimate in urban forest patches, future work should seek to prioritize consistency between sampling methods and account for the influence of species composition.

Chapter 5. Conclusion.

In this study, we related solar radiation inputs to multiple urban forest patch characteristics across six forest stands in Baltimore, MD. Overall, we found that near-ground solar radiation is highly heterogeneous, and the strength of the insolation response to patch attributes varies between sites. In particular, we identified that solar radiation inputs tend to be higher closer to patch edges, at sites with a greater presence of invasive vines, and in elongated patches. By contrast, patch origin, slope, and aspect did not have a significant influence on near-ground solar radiation. Although the observed trends were not consistent across all sampled forest patches, our findings highlight opportunities for planning and management regimes that consider patch heterogeneity and patterns of insolation. Our results also suggest directions for future research that may better explain the inconsistencies we found and that investigate other mechanisms driving variability in radiation beneath urban forest patch canopies.

5.1. Implications for urban forest patch management

By absorbing solar radiation and converting solar energy to latent heat (Federer, 1976; Grimmond and Oke, 1991), urban trees moderate urban summer temperatures and thereby improve living conditions in cities, a primary objective of urban forest management plans (Ordóñez and Duinker, 2013). However, most management strategies focus on increasing tree canopy coverage (Kenney et al., 2011), a measure that does not account for finer-scale variation in canopy density, solar radiation transmittance, and ecosystem service delivery (Greene and Millward, 2017). Our study of localized solar radiation within forest patches highlights the need for urban forest management strategies that consider the heterogeneity of near-ground solar radiation and address it through the implementation of plans that target areas with high radiation inputs. Specifically, our results suggest that sites close to patch edges and heavily invaded sites are critical areas for management. Tree planting efforts and the removal of vines at such sites may help increase canopy density and decrease solar radiation inputs in urban forest patches (Webster et al., 2006). Additionally, prioritizing the conservation of compact patches, where solar radiation inputs are lower, while increasing restoration efforts in elongated patches may improve urban tree canopy quality and strengthen the ability of the urban forest to deliver ecosystem services.

5.2. Further questions

Although we found that several patch attributes and ecological factors influence solar radiation inputs in urban forest patches, our study and its results raise additional questions that remain to be explored. As previously mentioned, the strong relationship between GSF and edge proximity observed only at Village Square, a patch adjacent to a large highway, suggests that the adjacent land use and level of disturbance at the patch edge may impact forest response to edge creation. Future research that considers the influence of multiple land uses abutting and within forest patches (e.g., streams, trails, playing fields, roads) will be important for clarifying relationships between urban edge conditions and below-canopy radiation inputs. Additionally, because solar radiation near patch boundaries and the strength of edge effects may be influenced by the aspect of the forest edge (Chen et al., 1993; Aragón et al., 2015), the sampling design of future studies on solar radiation in urban forest patches should account for the potential influences of edge orientation.

A main premise for studies of solar radiation and other microclimate variables is that these factors govern many essential ecosystem functions (Reifsnyder et al., 1971; Hutchison and Matt, 1977; Baldocchi et al., 1984). To understand how insolation influences ecosystem function and service provision in urban areas, future studies in Baltimore's forest patches could be conducted that relate the solar radiation data from this study to air and ground temperature, soil moisture, nutrient cycling, species dynamics, and other characteristics important for land management.

Finally, while hemispherical photography is a commonly used technique that typically estimates near-ground solar radiation with accuracy (Mailly, 2017), several studies have reported differences between radiation inputs assessed from hemispherical canopy photographs and those determined by direct field measurements. For example, Roxburgh and Kelly (1995) found that under dense canopies, photograph analyses underestimated near-ground solar radiation because light transmission through leaves was not accounted for. As most of our sampling sites were heavily shaded, it would be useful to calibrate our estimates against direct measurements of solar radiation.

Appendix A

For calculating Global Site Factor (GSF), we first define its components:

DifAb – the diffuse radiation above the canopy for a given sky sector, corrected for surface orientation, calculated as:

$$DifAb = S_{out} * DFP * SH * \cos(Aln\theta, \alpha),$$

where S_{out} is the external solar flux, *DFP* is the diffuse proportion of total radiation, *SH* is the total time the sun is above the horizon in June, July, and August, and $Aln\theta,\alpha$ is the angle of incidence between the centroid of the sky sector and the intercepting surface;

DifBe – the diffuse radiation below the canopy for a given sky sector, corrected for surface orientation, calculated as:

$$DifBe = DifAb * SkyGap,$$

where *SkyGap* is the gap fraction for a given sky sector, calculated as:

$$SkyGap = \frac{P_{vis}}{P_{tot}},$$

where P_{vis} is the number of visible sky pixels in the sector and P_{tot} is the total number of pixels in the sector;

DirAb – the direct radiation above the canopy for a given sky sector, corrected for surface orientation, calculated as:

$$DirAb = S_{dir} * SV * \cos(Bln\theta, \alpha),$$

where S_{dir} is the direct radiation flux, *SV* is the proportion of each Sunmap sector included in the calculation, and $Bln\theta,\alpha$ is the angle of incidence between the solar position and the intercepting surface;

DirBe – the direct radiation below the canopy for a given sky sector, corrected for surface orientation.

$$DirBe = DirAb * SunGap,$$

where *SunGap* is the gap fraction for a given sunmap sky sector, calculated as:

$$SunGap = \frac{P_{vis}}{P_{tot}} \quad ,$$

where P_{vis} is the number of visible sky pixels in the sector and P_{tot} is the total number of pixels in the sector.

Global Site Factor (GSF) is then calculated as:

$$GSF = \frac{DifBe + DirBe}{DifAb + DirAb} \quad .$$

Appendix B

Summary of aspect, slope, distance to edge, and vine invasion values, including the minimum, 25th percentile, median, 75th percentile, and maximum for studied patches and patch groupings: all sites, Carroll, Fendal, Herun, and Sinai (CFHS, grouped), and each individual forest patch. Summary statistics for Carroll, Herun, Fendal, and Sinai (shown in gray) are reported individually but were studies as a single entity in multiple regression analyses.

Patch	*n*	*Aspect (degrees from North)*				
		Min.	25th percentile	Median	75th percentile	Max.
All	127	6.00	109.94	171.93	250.13	358.65
CFHS	83	6.00	86.07	156.74	265.20	358.65
Forest Glen	27	87.29	120.51	154.11	239.22	279.70
Village Square	17	186.92	237.29	243.43	249.66	320.48
Carroll	10	13.21	67.25	108.66	159.40	211.29
Fendal	27	83.37	141.85	166.25	178.26	220.65
Herun	28	6.00	46.47	86.79	276.29	357.44
Sinai	18	42.27	163.49	335.25	349.16	358.65

Patch	*n*	*Slope (degrees from horizontal)*				
		Min.	25th percentile	Median	75th percentile	Max.
All	127	1.09	4.38	12.90	23.31	52.65
CFHS	83	1.09	3.38	6.34	13.23	36.50
Forest Glen	27	3.53	18.29	23.38	34.71	52.65
Village Square	17	11.75	23.89	29.93	33.48	39.54
Carroll	10	3.00	5.92	9.66	11.27	34.16
Fendal	27	1.09	2.76	3.53	4.62	6.94
Herun	28	1.26	3.26	7.03	13.68	26.68
Sinai	18	5.82	11.08	14.56	17.84	36.50

Patch	*n*	*Distance to Edge (meters)*				
		Min.	25th percentile	Median	75th percentile	Max.
All	127	3.19	20.03	35.75	54.73	112.27
CFHS	83	6.81	21.17	35.98	55.21	90.67
Forest Glen	27	3.19	26.78	40.16	65.72	112.27
Village Square	17	8.42	17.91	21.66	33.76	39.72
Carroll	10	6.86	13.89	20.71	49.12	73.36
Fendal	27	6.81	24.71	36.20	55.18	90.67
Herun	28	8.61	15.94	31.86	48.82	79.65
Sinai	18	10.67	29.03	41.38	65.44	84.94

Patch	*n*	*Vine Invasion*				
		Min.	25th percentile	Median	75th percentile	Max.
All	104	0.00	0.49	1.63	3.02	5.00
CFHS	81	0.00	0.44	1.50	2.63	5.00
Forest Glen	16	0.00	0.43	2.00	3.83	5.00
Village Square	8	1.00	1.50	3.33	4.62	5.00
Carroll	10	1.20	1.45	2.33	3.18	5.00
Fendal	26	0.00	0.56	1.85	2.98	4.50
Herun	27	0.00	1.48	2.00	2.81	5.00
Sinai	18	0.00	0.00	0.00	0.13	1.50

Appendix C

Variance inflation factors (VIFs) of aspect, slope, distance to edge, and vine invasion against the other independent variables for the four patch groupings: all sites, CFHS, Forest Glen, and Village Square.

Variable	**Variance Inflation Factor**							
	All Sites		*CFHS*		*Forest Glen*		*Village Square*	
	A, S, and/or DE	VI	A, S, and/or DE	VI	A, S, and/or DE	VI	A, S, and/or DE	VI
Aspect (A)	1.061	1.210	1.065	1.323	1.046	1.049	1.016	1.455
Slope (S)	1.076	1.093	1.096	1.079	1.023	1.663	1.171	1.079
Distance to Edge (DE)	1.000	1.016	1.015	1.014	1.006	1.839	1.159	1.276
Vine Invasion (VI)	1.133		1.264		1.218		1.023	

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