5.1 RELATING URBAN THERMAL PATTERNS TO VEGETATION DISTRIBUTION AT VARIOUS SCALES

Anita Walz* and Won Hoi Hwang
Department of Geography, Marshall University, Huntington, West Virginia

1. INTRODUCTION

Urban areas are notorious for being much warmer than their immediate rural surroundings. This urban heat island (UHI; Arnfield, 2003) effect is created in large parts by solid surfaces that provide multiple purposes within the cities, such as pavement for transportation and parking, quick run-off of rainwater to prevent flooding, and sealed roofs to prevent water from penetrating into buildings. These dry, sealed surfaces, however, absorb radiation throughout the day, converting the energy into sensible heat, charging like a battery, and releasing the energy slowly overnight. Typically the darker the surface is, the lower is its albedo, and the more will be absorbed and stored for later release from the same surface. Most road materials, particularly the cheapest, are initially fairly dark, as are resurfacing materials for driveways and parking lots. After the invention of air conditioning, dark roofs also gained in popularity. All of these along with heat sources from traffic, factories and buildings cause the UHI.

Vegetation on the other hand provides a variety of benefits to the urban environment. Particularly trees can sequester a significant amount of carbon, cool the vicinity, remove air pollutants, reduce emissions of volatile organic carbon from gas tanks of cars if they are parked in the shade and remain cooler, and reduce the energy required for the cooling of buildings (e.g. Oke, 1989; Laverne and Lewis, 1996; Scott et al., 1999; Nowak et al., 2002, 2006; Nowak and Crane, 2002; Dwyer et al., 2003; Rosenzweig et al., 2006).

One specific benefit that trees can provide in cities has not obtained much attention: their capacity to intercept sunrays before they reach the ground. While having a small footprint on the ground, trees are not using much space where we need it, instead their canopies spread wide where we don't use the space for ourselves. The absorbed electromagnetic radiation is converted into two other forms of energy that will not cause an immediate rise in temperature. First, transpiration converts the incoming energy into latent heat, stored in the water vapour molecule, until condensation occurs. Water vapour is typically carried away before it condenses, releasing the energy again in form of sensible (thermal) heat. However, this most likely does not happen at ground level in the city. Plants also convert the incoming energy into chemical energy through photosynthesis. Particularly for trees, this energy is typically stored away until the leaves fall or the tree is removed. Either way, the energy is typically transported in its form out of the city and not converted back into sensible heat until decomposition occurs on a compost pile or landfill.

* *Corresponding author address:* Anita Walz, Marshall University, Dept. of Geography, Huntington, WV 25755; e-mail: Hwalz@marshall.edu

This study examines the capacity of vegetation to cool the urban environment. Particular emphasis is placed on the role of trees in shading sealed surfaces. Results of various approaches to map vegetation and examine its relationship with thermal patterns across cities are shown.

2. VEGETATION MAPPING BY REMOTE SENSING

A pilot study during a heat wave in July 2005 showed that pavement surface temperature differences between shaded and sun-exposed pavement remain significant throughout the night (Walz and Hwang, 2007). Although these findings are critical, and this field study allowed for a look under the canopy of trees, this approach had various limitations: a) measuring and mapping of road-side trees to evaluate tree cover over pavement was tedious, hence limited to small areas, b) only vegetation that was in the public right-of-way was accessible, and c) the thermal infrared sensor only yielded point measurements.

In order to solve these issues the next step used high resolution satellite images to obtain aerial coverage of vegetation distribution across the city. The normalized difference vegetation index (NDVI) provides a measure of (active) vegetation cover. It is calculated from the red and near-infrared (NIR) channels and ranges from -1 to +1.

$$NDVI = (NIR - red) / (NIR + red)$$

Values at or above 0.2 indicate a significant proportion of vegetation within the area that is covered by the pixel.

Many readily available high-resolution aerial or satellite images include the near-infrared channel. However, most of these images are used for mapping purposes and are therefore taken during the leaf-off season, so that roads are visible as well. West Virginia has one complete set of these images (1 m resolution). The city of Huntington was photographed in early April (1998), when the grass was already green, but trees were still bare. A second image (Ikonos, 4 m resolution) was ordered and taken in late May (2005), when the canopy was fully developed. The NDVI of both images was reclassified into vegetated and non-vegetated areas. The April NDVI allowed for the distinction between vegetated and dry ground surfaces (still "seeing" through the canopy). When the May-derived NDVI was overlaid with it, canopy that extends over sealed surfaces (roads) could easily be mapped.

Figure 1 shows an example of one residential city block with the results of different mapping techniques (manual and images). Especially for the tree canopy there is little discrepancy. This block is also a particularly good example of how much road surface could be protected from the sun by strategically well placed wide-growing trees. Among the 12 residential city blocks of the original pilot study, an average of 61% of the area (front yard, road, and driveways) was sealed. Of these dry surfaces an average of 37% was shaded. A maximum of 53% of shade over sealed surfaces was observed within a block (46% in Figure 1).

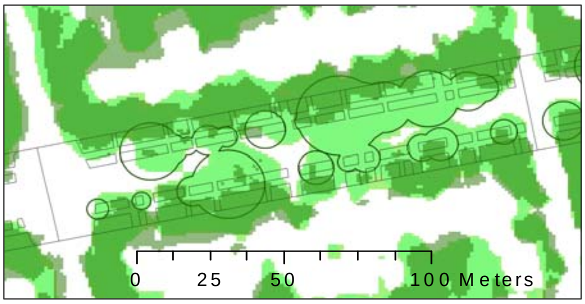

Figure 1. Mapped canopy for a residential city block. Colours show vegetation patterns as derived from NDVI values: dark green – ground vegetation, light green – tree canopy over dry surfaces. The vector layer with circular shapes represents the manual measurement of tree canopies. Roads, sidewalks and driveways are indicated in the background.

3. VEGETATION PATTERNS ACROSS THE CITY

Not all areas across cities have the potential for 50% canopy cover over sealed surfaces. The distribution and proportion of urban vegetation cover is not uniform; instead it depends on the function of the city sector. Typically a gradient in vegetation cover can be observed from almost zero in downtown areas through larger proportions in residential areas to almost complete cover in parks. The degree of fragmentation, e.g. the average size of vegetated patches or sealed patches also varies greatly among functional sectors. High-resolution satellite information is required to detect these fragmented patterns (Lo et al., 1997). In the next step of the study vegetation patterns in various city sectors were characterized.

Large areas representing various functional sectors in Huntington, WV, were digitized: downtown (Dt), other commercial areas (Co), industrial (In), high-, medium-, and low-density residential (Rh, Rm, Rl), campuses (Ca; Marshall and high school), parks and cemeteries (Pk), forest (Fo), and water (Wa). Each sector was represented by at least two areas. For each area the average NDVI value and standard deviation were extracted. Figure 2 shows the sector locations and average NDVI values.

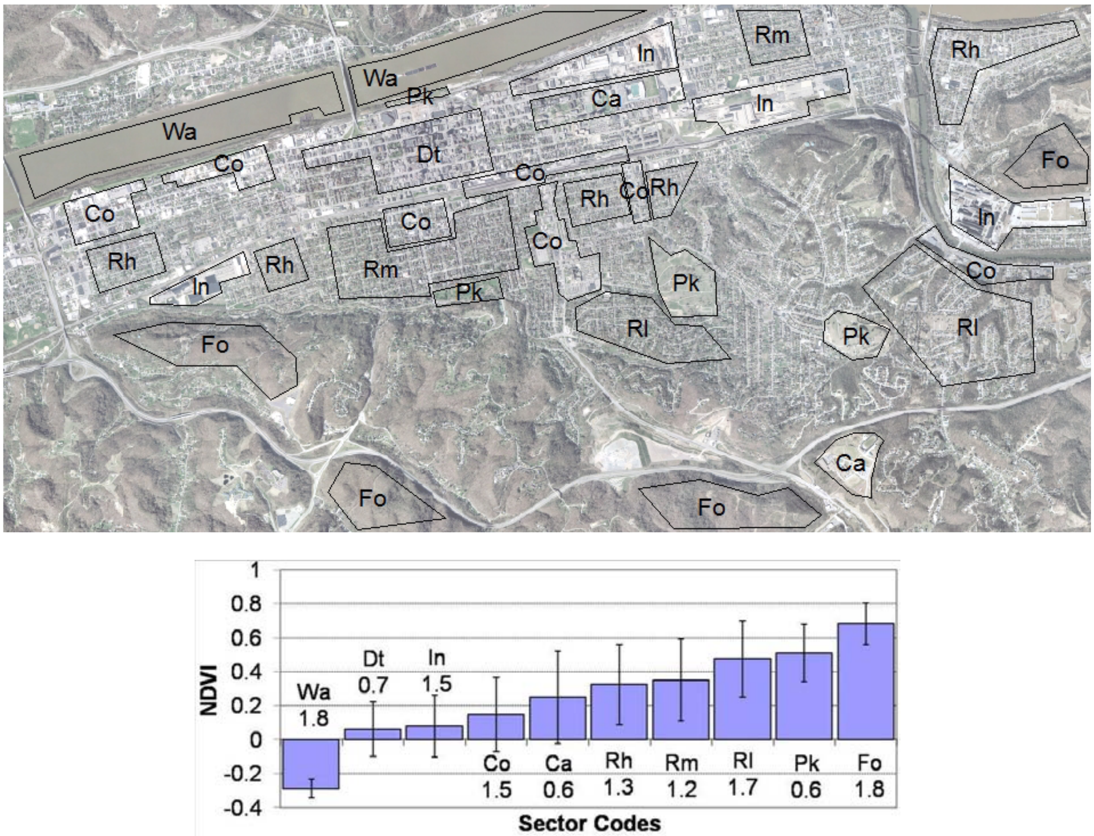

Figure 2. Distribution of various functional sectors in Huntington, WV (top) and average NDVI values within the sectors (bottom). The vertical bars indicate the standard deviation for each sector, the number under the sector type gives the total area that was measured in km^2. Sector types were: Ca – campuses (Marshall University and high school), Co – commercial, Dt – downtown commercial, Fo – forest, In – industrial, Pk – park, Rh, Rm, and Rl – high-, medium-, and low-density residential respectively, Wa – water.

4. INFLUENCE OF IMAGE RESOLUTION

Huntington, WV used to have the title "City of Trees". However, due to budget restraints, the city is now in the process of removing mature large trees completely. This seems to be more economical in the long run because the trees will not have to be trimmed again, and leaf pick-up crews will have smaller quantities to deal with. It also appears that local companies charge more for tree maintenance than for removal. In 2006 a major operation started where more than 800 trees were slated for removal. It is also no longer allowed for home owners to plant large-growing varieties along the street.

Because of these new rules tree cover has been changing rapidly over the last four years. The vegetation map that was derived from a 2005 image is becoming less accurate with every tree that disappears. NDVI also changes across the year (Hwang, 2007). High-resolution images are very expensive to obtain, and it is not feasible to update the map from new images. There is another readily available option: non-commercial satellite images such as Landsat Thematic Mapper (TM). The drawback is that these images are much coarser (TM: 30 m). Although these coarse data sets do not pick up fragmentation details, they do provide thermal infrared data which are not available at a higher resolution at all.

It is critical to understand the influence of resolution on the data. Hence, the comparability of various images and resolutions was tested. The Ikonos image (4 m) was resampled to match the resolution of TM images (30 m). NDVI values were extracted for each area of all sectors from the 30 m resolution Ikonos, a TM image that was taken only 3 days after the Ikonos, a July TM image for the same year (2005) and a July TM image for 2007. Paired t-tests were conducted to check for significant changes between the images. Table 1 shows the outcome of the comparisons that were made.

Table 1. Paired T-tests comparing average NDVI values between images of various resolutions and dates. Reported are the mean difference between NDVI values and the p-value of the test.

Comparison*	Mean NDVI Difference	p-value
Ik: 4 m to 30 m	-0.001	0.3067
Ik 30 m to TM May '05	0.016	0.1041
TM '05: May to Jul	-0.047	<0.0001
TM July: '05 to '07	0.031	<0.0001

* Images used: Ik – Ikonos from May 2005 at 4 m and 30 m resolution, TM – Thematic Mapper images from May 2005, July 2005, and July 2007.

The tests revealed that average NDVI values were reliable when the resolution is changed, or when images were acquired close to each other in time (non-significant p-values for first two comparisons). On the other hand, changing the Month or year significantly affects the outcome of NDVI values. Due to these results the NDVI for the following thermal analysis was derived from the same TM image as the thermal infrared (TIR) data.

5. THERMAL PATTERNS AND VEGETATION

The surface temperature was estimated from the thermal infrared channel for one day during the heat wave (July 2005). Values of the TIR channel (Band 6) were converted to radiance as follows:

$$R = G\,(TIR) + B$$

Where *R* is the radiance, *TIR* the value of Band 6, *G* is the gain, and *B* the offset as found in the images documentation. The surface temperature was then calculated as follows:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{R} + 1\right)}$$

Where *T* is the surface temperature in ^{o}K, K_1 is 607.76, and K_2 is 1260.56 for TM. Temperature estimates were then extracted for each area within the sectors and correlation with NDVI values was measured.

Figure 3 shows the relationship between estimated surface temperatures and NDVI values. Each image pixel was plotted. There are clearly two lobes visible.

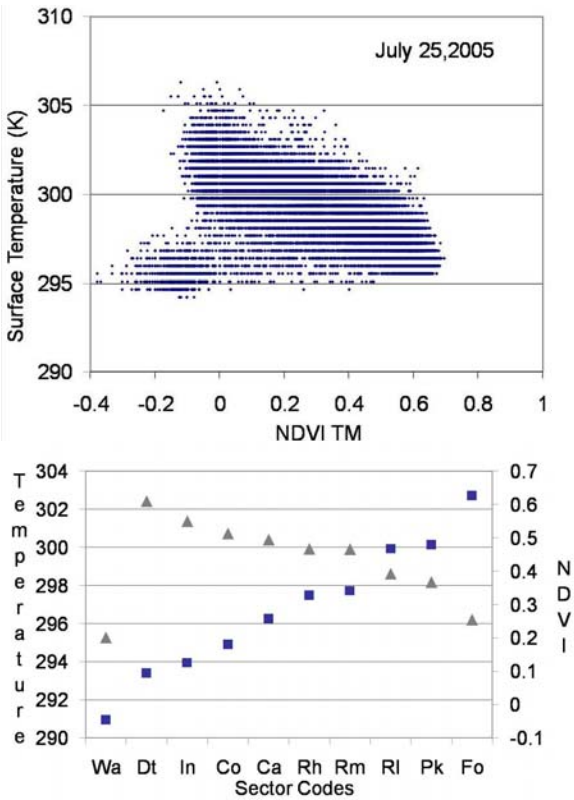

Figure 3. Relationship between surface temperature and NDVI across the city. Top: all pixels of the scene (entire city); the lower left lobe is caused by water. Otherwise the temperature declines gradually as the NDVI (and the vegetation cover) increases. Bottom: average temperatures (gray triangles) and NDVI (blue squares) by sector. Source: Landsat TM.

The main trend is a clear decline in temperature as the NDVI increases. This portion is attributable to terrestrial surfaces. The smaller lobe in the lower left corner is caused by the Ohio river’s cool water surface. Water has an extremely low NDVI.

The correlation between NDVI values from the aggregated high resolution and the TM images were strong (R2 = -0.46) despite the interference of the “water lobe”. Not surprisingly a highly significant inverse relationship exists between vegetation proportion and surface temperature. Even the coarse resolution allowed for the detection of hotspots that are caused by as little as a quarter of a city block of sealed surfaces (e.g. schools) in otherwise vegetated residential neighbourhoods (Walz and Hwang, 2007). A single block of high vegetation cover in the middle of an otherwise highly sealed area, such as the Court House block in downtown Huntington or Marshall University campus, caused a clear depression in surface temperatures. The Ohio River with low NDVI but also low temperatures was an exception that can easily be explained by the fact that the river surface is not sealed and dry but provides an unlimited amount of water for evaporation. Figure 4 shows the maps of NDVI and surface temperature as extracted from the July 2005 TM image. TIR data are originally collected with a 90 m resolution, hence are coarser than what the cell size indicates when TM data are distributed. This is the reason why the temperature image does not have as fine a resolution as the NDVI image. Otherwise vegetation patterns clearly follow temperature patterns.

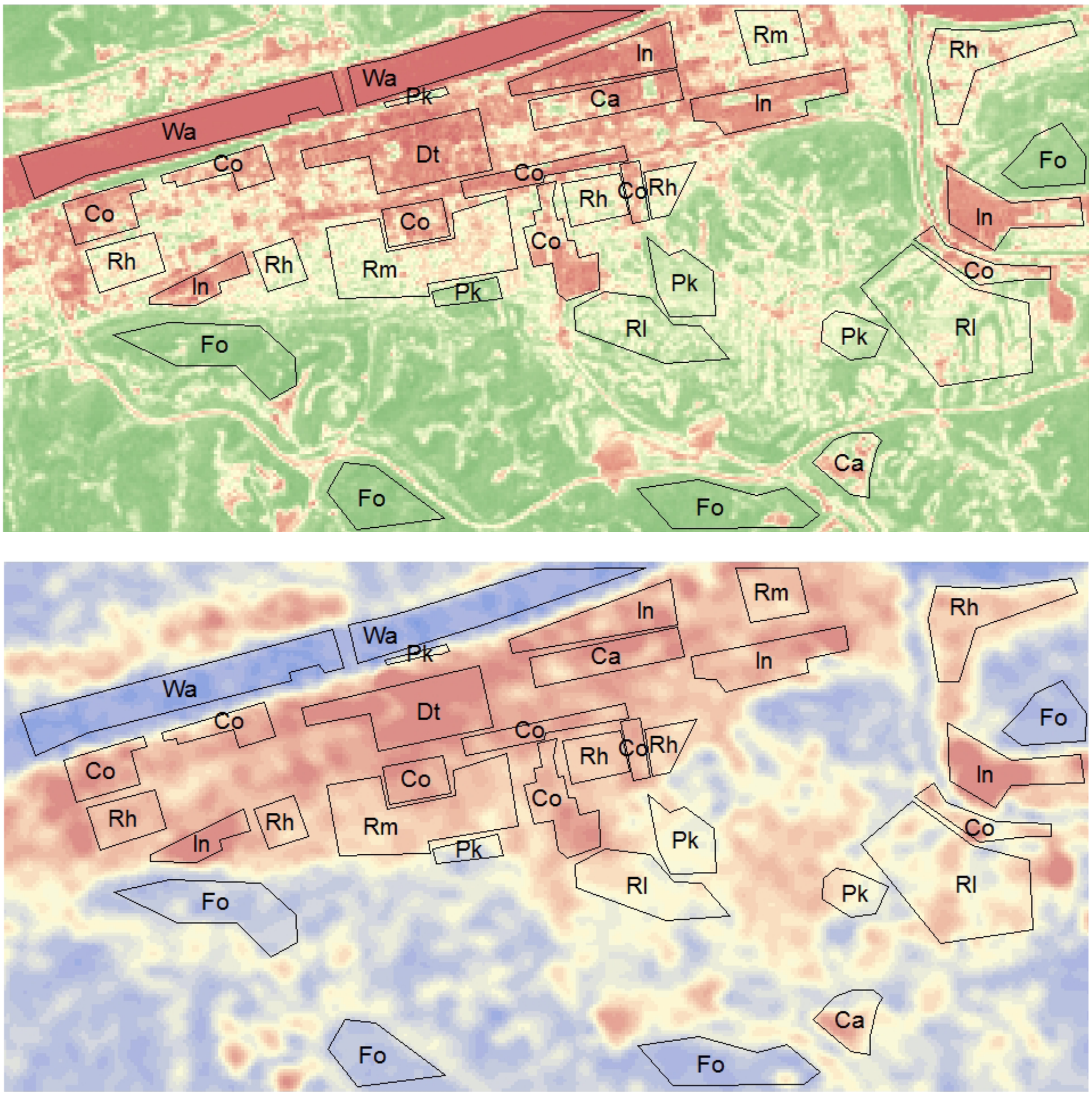

Figure 4. Maps of NDVI where red indicates low and green high vegetation patterns (top), and surface temperature distribution (bottom) where red is warm and blue represents cool. Sector types are outlined and represent: Ca – campuses (Marshall University and high school), Co – commercial, Dt – downtown commercial, Fo – forest, In – industrial, Pk – park, Rh, Rm, and Rl – high-, medium-, and low-density residential respectively, Wa – water.

CONCLUSIONS

Results of this study support a transition to a more park-like design of urban centres wherever possible. It has been known for a while that parks have a cooling effect on cities (Oke, 1989), but even in areas with large proportions of ground-level sealed surfaces, particularly on parking lots and along the side of roads, trees would yield a significant improvement of air temperature and even quality (Scott et al., 1999). On the ground, where human activity occurs, trees' footprints are small. Instead they expand above the zone that is typically used by humans. There the canopy intercepts radiation, preventing it from heating the ground. Trees are the ideal solution for ground-level surfaces, even in areas that are otherwise paved over.

Another option to aid the urban climate has to be mentioned here. Trees are less suitable and manageable in terms of roof shading, particularly for higher structures. For exposed surface materials an adjustment toward increased reflectivity would help ameliorate the UHI, as long as the glare does not interfere with air traffic. For roof tops there are another two highly suitable solutions, both come at an initial cost: roof-top gardens (green roofs) and solar panels. Green roofs are suitable for flat roofs, are known for their insolating capacities, but need structural strengthening because of their weight. Solar panels have just made a major leap in their development. They are now thinner, can simply be rolled out, and can now be produced in an assembly line manner. Prices should drop in the near future. An old argument against solar panels is that they use a huge amount of space, competing with other types of land uses. I argue that we have enough "wasted" space that is perfectly suitable for solar panels: roof tops. If we cover city roofs with solar panels or green roofs and plant trees to shade roads and parking lots, we will come a long way in ameliorating the urban climate.

Huntington, WV has been on a short budget for several decades already. If this city is a model in terms of tree maintenance of what is to come under the current global financial situation, we need to make sure that we treat city trees as capital, not a liability or an unnecessary cost factor.

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