LBNL-49275

Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois[1]

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October 2001

[1] This work was supported by the U. S. Environmental Protection Agency under the Urban Heat Island Pilot Project (UHIPP) through the U. S. Department of Energy under contract DE-AC03-76SF00098.

Acknowledgements

This work was supported by the U. S. Environmental Protection Agency under the Urban Heat Island Pilot Project (UHIPP) through the U. S. Department of Energy under contract DE-AC03-76SF00098. We acknowledge the support and guidance from Edgar Mercado, Eva Wong, and Jeanne Briskin of the EPA.

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Abstract

Urban fabric data are needed in order to estimate the impact of light-colored surfaces (roofs and pavements) and urban vegetation (trees, grass, shrubs) on the meteorology and air quality of a city, and to design effective implementation programs. In this report, we discuss the result of a semi-automatic Monte-Carlo statistical approach used to develop data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color orthophotography. The digital aerial photographs for metropolitan Chicago covered a total of about 36 km^2 (14 mi^2). At 0.3m resolution, there were approximately 3.9×10^8 pixels of data.

Four major land-use types were examined: commercial, industrial, residential, and transportation/communication. On average, for the areas studied, at ground level vegetation covers about 29% of the area (ranging 4–80%); roofs cover about 25% (ranging 8–41%), and paved surfaces about 33% (ranging 12–59%). For the most part, trees shade streets, parking lots, grass, and sidewalks. In commercial areas, paved surfaces cover 50–60% of the area. In residential areas, on average, paved surfaces cover about 27% of the area.

Land-use/land-cover (LULC) data from the United States Geological Survey was used to extrapolate these results from neighborhood scales to metropolitan Chicago. In an area of roughly 2500 km^2, defining most of metropolitan Chicago, over 53% is residential. The total roof area is about 680 km^2, and the total paved surfaces (roads, parking areas, sidewalks) are about 880 km^2. The total vegetated area is about 680 km^2.

Executive Summary

The Heat Island Reduction Initiative (HIRI) is a joint program sponsored by the U.S. Environmental Protection Agency (EPA) and the Department of Energy (DOE) to encourage the use of strategies designed to reduce demand for cooling-energy use and prevent smog formation. As part of the initiative, the Urban Heat Island Pilot Project (UHIPP) was launched to quantify the potential impacts of heat island reduction strategies in terms of energy savings, economic benefits, and air-quality improvements. EPA selected five metropolitan areas of Sacramento, CA, Salt Lake City, UT, Chicago, IL, Houston, TX, and Baton Rouge, LA for the UHIPP study. Since the inception of the project, LBNL has conducted detailed studies to investigate the impact of mitigation technologies on heating and cooling energy use in these pilot cities. In addition, LBNL has collected urban surface characteristic data and conducted meteorology and urban smog simulations for the four pilot cities.

One of the components of UHIPP research activities is to analyze the fabric of the pilot cities by accurately characterizing various surface components. This is important since the fabric of the city is directly relevant to the design and implementation of heat-island reduction strategies. Of particular importance is the characterization of the area fraction of various surface types as well as vegetative cover. Accurate characterization of the urban fabric would allow the design of implementation programs with a better assessment of the cost and benefits of program components. In addition, the results of such detailed analysis will be used in simulating the impact of heat-island reduction strategies on local meteorology and air quality.

In this report, a method is discussed for developing high-quality data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography. This method was initially applied to obtain data for Sacramento CA. Here we apply the method to obtain data for the fabric of metropolitan Chicago, IL.

The imagery for metropolitan Chicago covered a total of about 36 km^2 (14 mi^2). **Picture EX.1** depicts a sample photograph in metropolitan Chicago. At 0.3-m resolution, there were approximately 3.9 x 10^8 pixels of data. We devised a semi-automatic method to sample the data and visually identify the surface-type for each pixel. The method involves four steps:

1. visually inspecting aerial photographs and preparing of a list of various surface-types identifiable in the photos;
2. grouping surface categories into major types;
3. randomly sampling a subset of data for each region (through a Monte-Carlo sampling approach), and visual inspection of each sample and the assignment of a surface classification to it (these surface classifications are summarized in Table EX.1); and
4. extrapolating the results to the entire metropolitan Chicago using the United States Geological Survey (USGS) land-use/land-cover (LULC) data as a basis.

The classification in Table EX.1 may include more detail than necessary (even more details can be seen in the photos though, for example, mailboxes, small benches, etc., that are, of course, irrelevant to this task). A distinction was made between Category 1, "Unidentified," and Category

30, “Other Feature.” Those surfaces classified as “Unidentified” could not be accurately defined, while those in the “Other Feature” category could be, but were not relevant to this study. This distinction was necessary to avoid assigning these known features incorrectly.

Table EX.1. Visually identifiable features of interest in the metropolitan Chicago (based on aerial photographs).

Category	Description	Category	Description
1	Unidentified	16	Swimming Pool
2	Tree Covering Roof	17	Auto Covering Road
3	Tree Covering Road	18	Private Paved Surfaces
4	Tree Covering Sidewalk	19	Parking Deck
5	Tree Covering Parking	20	Alley
6	Tree Covering Grass	21	Water
7	Tree Covering Dry/Barren Land	22	Grass on Roof
8	Tree Covering Other	23	Train Tracks
9	Tree Covering Alley	24	Auto Covering Parking
10	Roof	25	Recreational Surface
11	Road	26	Residential Driveway
12	Sidewalk	27	Awning
13	Parking Area	28	N/A
14	Grass	29	N/A
15	Dry/Barren Land	30	Other Feature (not of interest)

The various tree categories (Categories 2–9) were later grouped under one category (designated as “Trees”). For meteorological modeling purposes, one tree category is sufficient to determine the fraction of vegetation in the urban area. However, for implementation purposes, one would like to “see” what lies beneath the canopy of trees. Thus in this case the areas beneath the trees are simply totaled and the tree canopy ignored, assuming trunk area is negligible. As shown in **Table EX.2**, categories of related surface-types were grouped in representative types for an “above-the-canopy” perspective. The grouping was done in order to aggregate similar surfaces that may also have similar albedos.[1] For instance, the “Sidewalk” surface-type is the total of the “Residential Driveway” and “Sidewalk” categories since in the areas analyzed, these categories both appeared to be light-colored concrete. “Parking Area” is the total of parking lots and decks, “Grass” is the total of ground-level grass and roof grass, and the category “Miscellaneous” is the total of sporadic surface-types such as swimming pools, water, alleys, autos, private surfaces, and train tracks. For characterization of the surfaces “under-the-canopy,” the primary criterion for grouping was the function or use of the surface-type. For instance, the under-the-canopy “Roof” category include: “Tree Covering Roof” (Cat. 2), “Roof” (Cat. 10), “Parking Deck” (Cat. 19), “Grass on Roof” (Cat. 22), and “Awning” (Cat. 27). Table EX.2 also shows the assignment of various categories (identi-

[1] When sunlight hits an opaque surface, some of the energy is reflected (this fraction is called albedo = â) and the rest is absorbed (the absorbed fraction is 1-â). Low-a surfaces of course become much hotter than high-a surfaces.

fied in Table EX.1) to surface-types under the canopy. Under-the-canopy characterization also includes a new general category, "Private Paved Surfaces," to distinguish between public surfaces and those surfaces owned privately. The "Tree Cover" category was eliminated, since at the ground level there is no tree canopy.

Table EX.2. Major surface-types

Surface-Type	Categories Included*	Surface-Type	Categories Included
Above-the-Canopy View			
Roof	10, 27	Tree Cover	2–9
Road	11	Grass	14
Parking Area	13, 19	Barren Land	15
Sidewalk & Driveway	12, 26	Miscellaneous	16–18, 20, 21, 23–25, 30
Under-the-Canopy View			
Roof	2, 10, 19, 22, 27	Private Paved Surfaces	18, 26
Road	3, 9, 11, 17, 20	Grass	6, 14
Parking Area	5, 13, 24	Barren Land	7, 15
Sidewalk	4, 12	Miscellaneous	8, 16, 21, 23, 25, 30

* Surface-type categories are defined in Table EX.1.

Results from this analysis suggest several possible land-use and surface-type classification schemes for the metropolitan Chicago area. In this study, the major land-use types examined were commercial, industrial, residential, and transportation/communication. Fifteen different areas were selected for this analysis. For each of these areas, up to 28 different surface-types were identified and their fractional areas computed. The results are shown in **Figures EX.1** (above-the-canopy view of the city) and **EX.2** (under the tree canopy). In the commercial section of suburban Chicago, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 18% of the area, whereas roofs cover 15–25% and paved surfaces (roads, parking areas, and sidewalks) cover 50–54%. The under-the-canopy fabric consists of 53–59% paved surfaces, 15–25% roofs, and 14–18% grass. In the industrial areas, above the canopy, vegetation covers 4–17% of the area, whereas roofs cover 29–41%, and paved surfaces 29–31%. Residential areas exhibit a wide range of percentages among their various surface-types (See **Figure EX.3** and **EX.4**). On the average for residential areas, above the canopy, vegetation covers about 45% of the area (ranging from 24% to 80%), roofs cover about 27% (ranging from 8% to 37%), and paved surfaces about 26% (ranging from 12% to 35%).

In order to extrapolate these results from neighborhood to regional scales, e.g., regional metropolitan Chicago, land-use/land-cover (LULC) data from the United States Geological Survey (USGS) was used as a basis for mapping the area distributions. In this method, the metropolitan

Chicago LULCs were mapped onto those of the USGS and the total areas of surface-types were calculated for the entire region of interest. Of the total domain area of approximately 18,500 km^2, about 2,500 km^2 is categorized as urban area of which approximately 53% is residential (see **Figure EX.5a**). The total roof area as seen above the canopy comprises about 26% of the urban area (about 600 km^2); total paved surfaces (roads, parking areas, sidewalks) are 33% (about 750 km^2); and total vegetated area covers about 33% (750 km^2) (see **Figure EX.5b**). The actual total roof area as seen under the canopy comprises about 27% of the urban area (about 680 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) are 35% (about 880 km^2), and total vegetated area (only grass and bushes) cover about 27% (680 km^2) (see **Figure EX.5c**).

Metropolitan Chicago is fairly green, but the potential for additional urban vegetation may be large. In the commercial and industrial areas, existing trees shade about 0–5% of the grass area and 0–10% of all paved surface areas. In some residential areas, trees shade up to 12% of grass and up to 15% of the paved surfaces. The fraction of roof areas shaded by trees is less than 1%. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, they would add up to about 14% in additional tree cover for the entire city (the validity of these assumptions need to be checked in a detailed study). An additional tree cover of 14% amounts to about 350 km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50 m^2, these calculations suggest potential for 7 million additional trees in metropolitan Chicago. As climate and air-quality simulations have indicated, 7 million additional trees may have a significant impact on cooling metropolitan Chicago and improving ozone air quality.

The potential for increasing the albedo of metropolitan Chicago is also large. Impermeable surfaces (roofs and pavements) amount to 61% of the total area of metropolitan Chicago. Unfortunately, the aerial orthophotos for Chicago cannot be used to accurately estimate the albedo of the surfaces. For illustration purposes, if we assume that the albedo of the residential roofs can increase by 0.2, commercial roofs by 0.3, roads and parking areas by 0.15, and sidewalks by 0.1, the albedo of the urban areas in Chicago can then be increased by about 0.16. Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

These results are based on a limited analysis for one city. In metropolitan Chicago there is a significant variation in the fabric of the neighborhoods selected for this analysis. Although an attempt has been made to select neighborhoods that represent the variation in the overall communities, these results should not be extrapolated to other cities and regions. Many cities are unique in terms of land-use patterns and constructions (e.g. most urban homes in the west coast are single story as opposed to two-story houses in the east). It is recommended that a similar analysis for several other cities in different regions of the country be performed in order to expand our understanding of the fabric of the city.

Picture EX.1. Aerial photo of a commercial area in metropolitan Chicago.

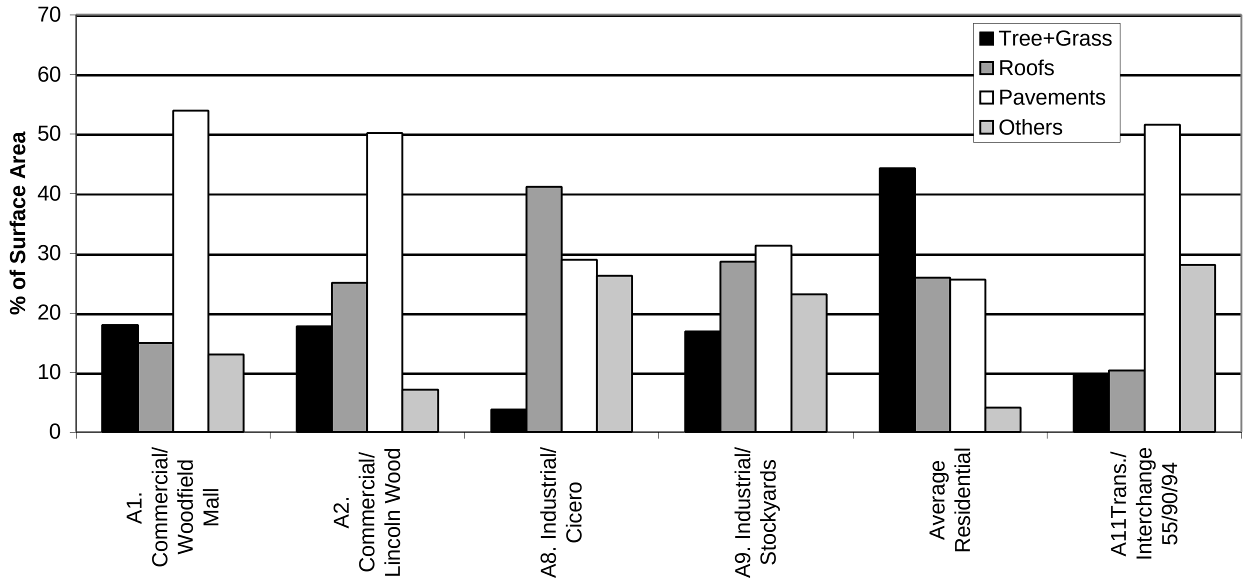

Figure EX.1. Above-the-canopy fabric of metropolitan Chicago, IL.

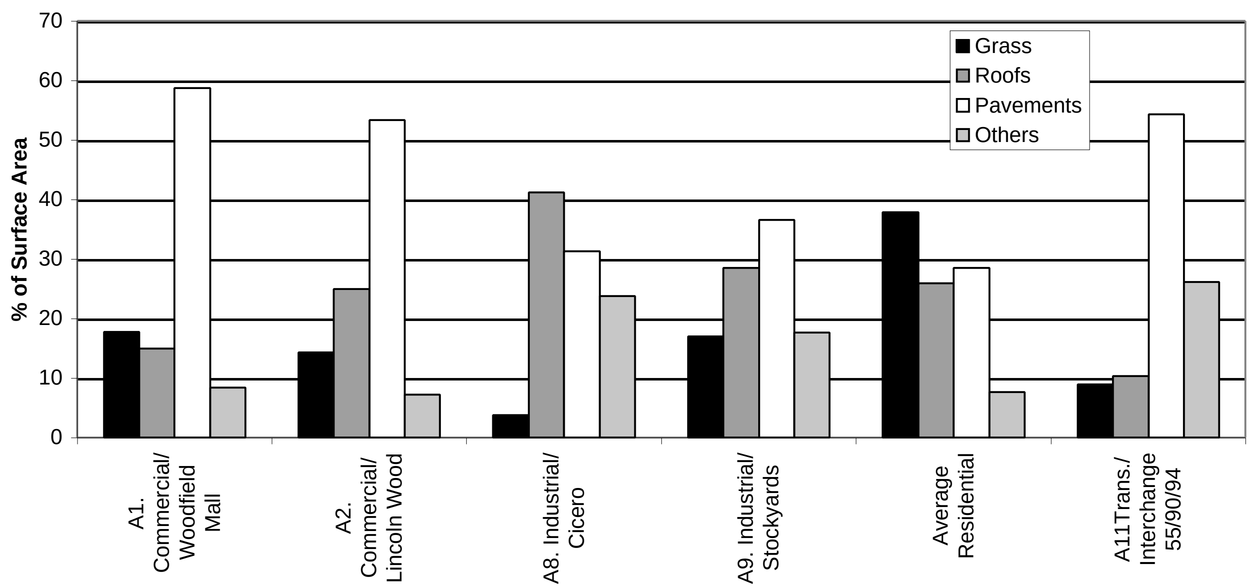

Figure EX.2. Under-the-canopy fabric of metropolitan Chicago, IL.

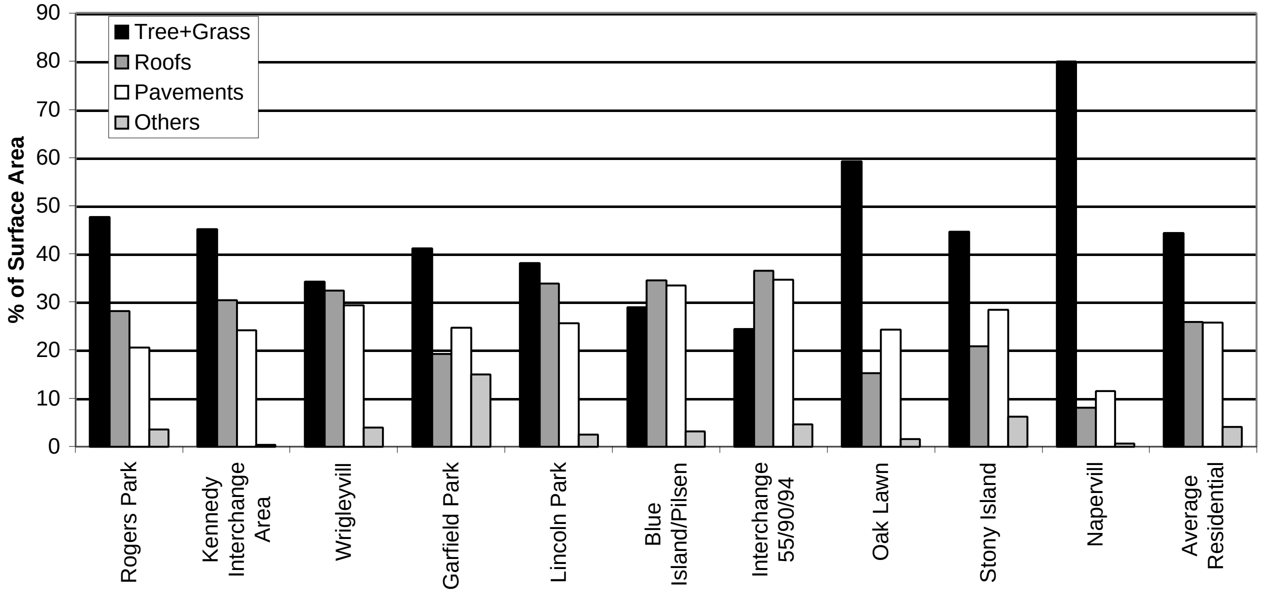

Figure EX.3. Above-the-canopy fabric of residential metropolitan Chicago, IL.

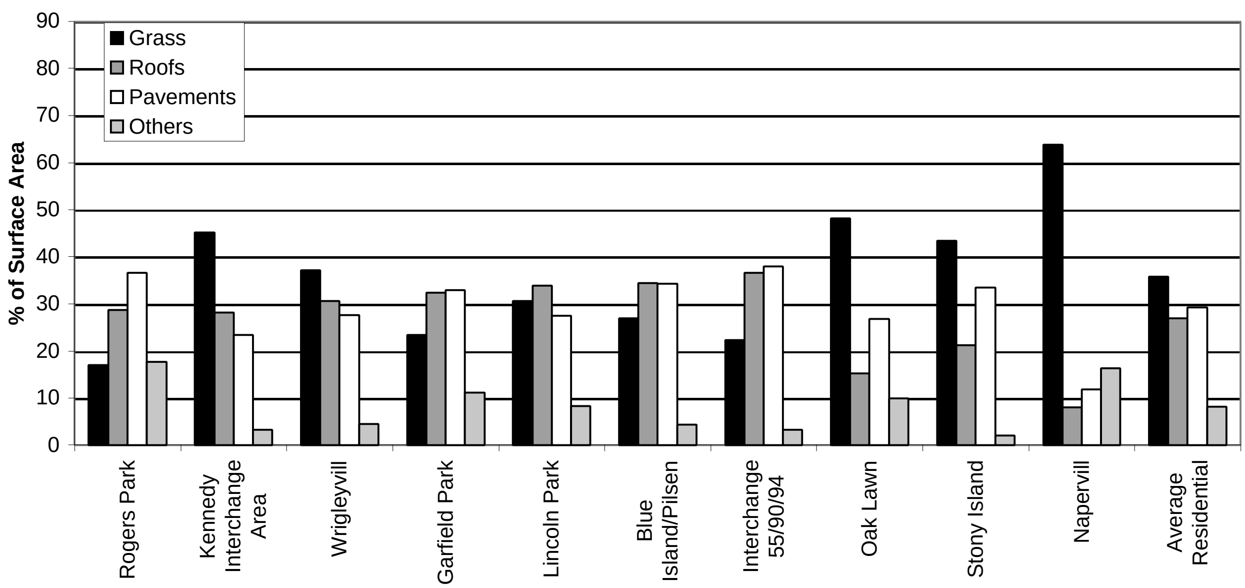

Figure EX.4. Under-the-canopy fabric of residential metropolitan Chicago, IL.

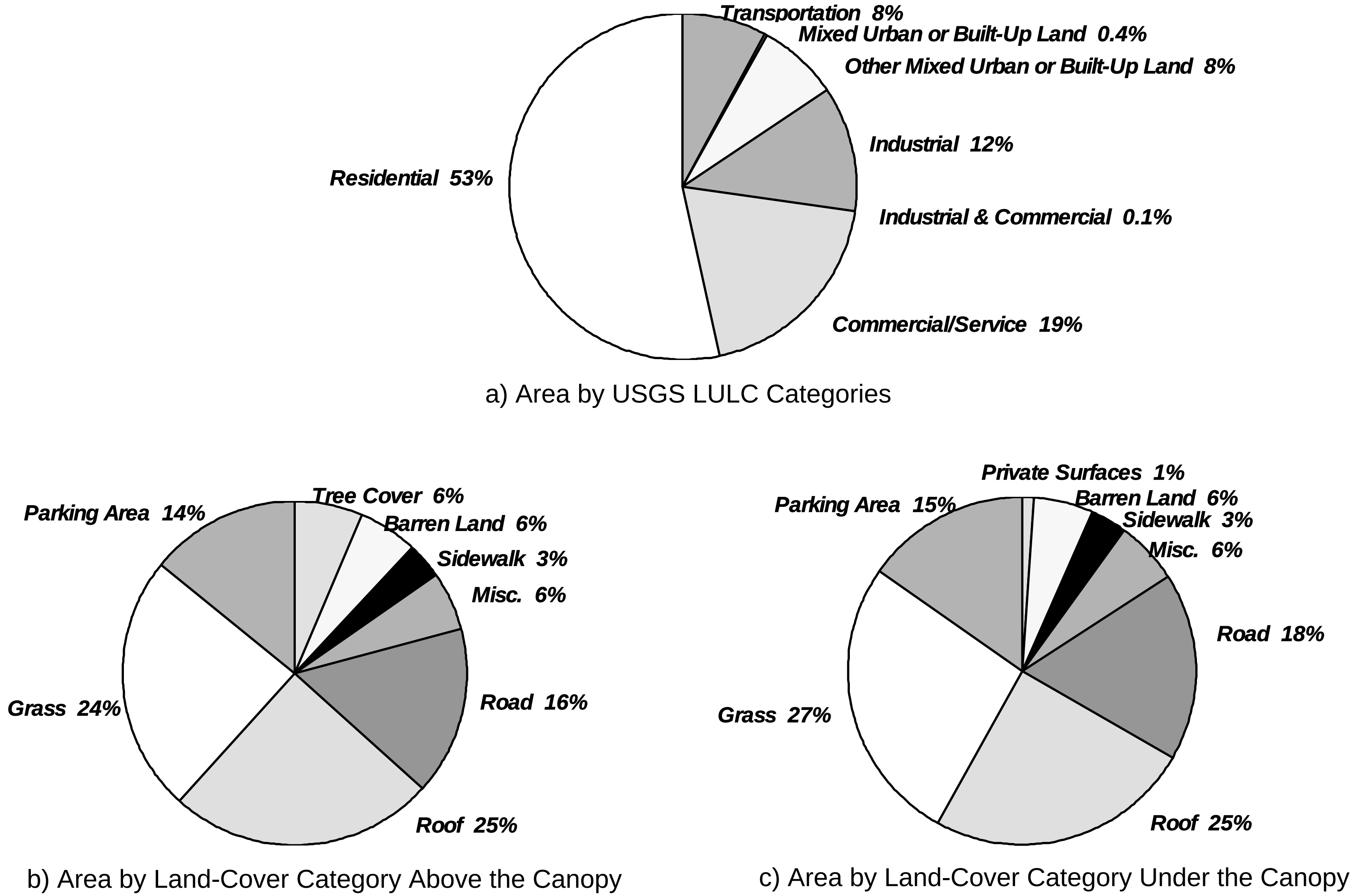

Figure EX.5. Land use/land cover of the entire developed area of metropolitan Chicago, IL

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Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois

1. Introduction

The Heat Island Reduction Initiative (HIRI) is a joint program sponsored by the U. S. Environmental Protection Agency (EPA) and the Department of Energy (DOE) to encourage the use of strategies designed to reduce demand for cooling energy and help slow down smog formation in U. S. cities. As part of the initiative, the Urban Heat Island Pilot Project (UHIPP) was launched to quantify the energy savings, economic benefits, and air-quality improvements achievable by implementation of heat-island reduction strategies. EPA selected five metropolitan areas of Sacramento, CA, Salt Lake City, UT, Chicago, IL, Houston, TX, and Baton Rouge, LA for the UHIPP study. Since the inception of the project, LBNL has conducted detailed studies to investigate the impact of mitigation technologies on heating- and cooling-energy use in the three pilot cities. In addition, LBNL has collected urban surface characteristics data and conducted meteorology and air-quality simulations for the three pilot cities.

One of the components of UHIPP research activities is to analyze the fabric of the pilot cities by accurately characterizing various surface components. This is important since the fabric of the city is directly relevant to the design and implementation of heat-island reduction strategies. Of particular importance is the characterization of the area fraction of various surface-types. These data are required to model and analyze the impact of heat-island mitigation measures in reducing energy consumption and improving air quality. Thus, it is important to characterize the surface as accurately as possible, particularly in terms of surface-type distribution and vegetative fraction. An accurate characterization of the surface will allow a better estimate of the potential for increasing surface albedo[2] (roofs, pavements) and urban vegetation. This would in turn provide more accurate modeling of the impact of heat-island reduction measures on ambient cooling and urban smog air quality.

In two earlier studies, we characterized the fabric of Sacramento, CA and Salt Lake City, UT, using high-resolution aerial digital orthophotos covering selected areas in each city (Akbari *et al.*, 1999 and Akbari and Rose, 2001). Four major land-use types were examined: commercial, industrial, transportation, and residential. Although there are differences between fabrics of these two metropolitan areas, some significant similarities exist. **Table 1** shows the Land Use/Land Cover (LULC) for both metropolitan areas based on USGS data. In Sacramento, of the approximate 800 km^2 of urban area about 49% is residential. In Salt Lake City about 59% of the 620 km^2 urban area is residential. There are a few percentages more of Industrial, Transportation, and Mixed Urban land in Sacramento than Salt Lake City.

The percentage of the total roof areas, as seen from above the canopy, in both metropolitan areas is about 19% (see **Table 2**). Under the canopy, there is about 2% more roof area in Sacramento than in Salt Lake City. There is about 12% more vegetation in Salt Lake City than in Sacra-

[2] When sunlight hits a surface, some of the energy is reflected (this fraction is called albedo = â) and the rest is either absorbed or transmitted. Low-â surfaces can become much hotter than high-â surfaces.

mento, consequently there are about 8% less paved surfaces and 4% less “Other” land use in Salt Lake City.

Under the canopy, the percentage of the total roof area is about 2% higher in Sacramento than Salt Lake City. There is about 13% more vegetation in Salt Lake City, there is 8% less pavement, and there is 6% less “Other” land use than in Sacramento. In the residential areas of Salt Lake City, there is 4% more roof area, 6% more vegetation, 1% more pavements, and 11% less of “Other” land uses than in Sacramento.

Table 1. USGS land use/land cover (LULC) percentages for two cities: Sacramento, CA and Salt Lake City, UT.

	Sacramento	**Salt Lake City**
Total Metropolitan Area (km^2)	809	624
LULC (%)		
Residential	49.3	59.1
Commercial/Service	17.1	15.0
Industrial	7.2	4.9
Transportation/Communication	11.4	9.8
Industrial and Commercial	0.3	0.0
Mixed Urban or Built-up Land	5.2	1.9
Other Mixed Urban or Built-up Land	9.5	9.4

Table 2. Comparison of the fabric of Salt Lake City, UT and Sacramento, CA.

City	**Vegetation**	**Roofs**	**Pavements**	**Other**
Above-the-canopy				
Metropolitan Salt Lake City	40.9	19.0	30.3	9.7
Metropolitan Sacramento	28.6	18.7	38.5	14.3
Residential Salt Lake City	46.6	19.7	25.3	8.5
Residential Sacramento	39.2	19.4	25.6	15.8
Under-the-canopy				
Metropolitan Salt Lake City	33.3	21.9	36.4	8.5
Metropolitan Sacramento	20.3	19.7	44.5	15.4
Residential Salt Lake City	38.6	23.9	31.6	6.0
Residential Sacramento	32.8	19.8	30.6	16.8

Other researchers involved in the analysis of urban climate have tried to estimate the composition of various urban areas. One such work is the analysis of the urban fabric in Sacramento, CA by Myrup and Morgan (1972). They applied the strategy of examining the city data in progressively smaller integral segments of macro-scale (representative areas of Sacramento), meso-scale (individual communities), micro-scale (land-use ordinance zones), and basic-scale (city blocks). The data they used included USGS photos, parks and recreation plans, city engineering roadways, and detailed aerial photos. Their analysis covered 195 km^2 (76 mi^2) of urban areas. The percentages of the land-use areas were calculated as follows: residential 35.5%, commercial 7.2%, industrial 13.5%, streets and freeways 17.0%, institutional 3.2%, and open space and recreational 23.6%. They found the average residential area to be about 22% streets, 23% roofs, 22% other impervious surfaces, and 33% green areas. Overall, for the city, they found 14% streets, 22% roofs, 22% other impervious surfaces, 36% green areas, and 3% water surfaces. They defined "other impervious surfaces" to include highway shoulder strips, airport runways, and parking lots. Streets included curbs and sidewalks.

In this report, we apply the urban fabric analysis to metropolitan Chicago, IL. We discuss our effort in analysis of digital aerial photography and present results of the analysis for several representative areas in metropolitan Chicago. Results from the analysis of representative areas are used to estimate the fabric of greater Chicago (for use in meteorological and air-quality modeling).

2. Custom Remote-Sensed Data for Metropolitan Chicago

In the studies for Sacramento and Salt Lake City, initially, a variety of available data sources were considered in analyzing the fabric of the UHIPP cities. Some of these data were obtained from NASA remote sensing platforms, others from satellite or high-altitude aircraft, and a third group from high-resolution cameras flown at low altitudes. A full discussion of the various data sources considered for this application can be found in the report detailing the results of a similar study in Sacramento, California (Akbari *et al.*, 1999).

Of all approaches tested, high-resolution aerial photography has the highest potential for accurately producing estimates of surface areas for various land covers and uses in a region. To obtain this custom high-resolution data for metropolitan Chicago, aerial photographs were taken at a resolution of 0.3m by Emerge (Andover, MA and Greeley, CO) for Northwestern University (Gray and Finster, 2000, Burnette, 2002). Topographical and GPS data are then used in the process of orthorectification. Thus, errors are minimized that are created by the terrain, and by the angle between the camera and surface.

Using high-resolution aerial photography for Sacramento and Salt Lake City, it was possible to identify clearly the materials and surfaces that make up the fabric of an area. Although the metropolitan Chicago imagery is at the same resolution as the Sacramento and Salt Lake City imagery, there is a significant difference in the quality of the images produced. The metropolitan Chicago imagery has a lower quality than Sacramento and Salt Lake imagery. The apparent difference in data quality can be attributed to a combination of factors. First, the Chicago photographs were collected during high winds. The primary affect of this is that the plane could not collect the data with the camera in a position parallel to ground level. This tilt resulted in higher data distortion, especially at the edges of frames (each selected area is composed of several small independently acquired frames). Another significant factor was that the data was collected on November 27, 1998 when the sun was relatively low in the sky. For both the Sacramento and Salt Lake City collections, the bulk of the data were collected in September when the sun was higher in the sky. Another consideration is the fact that Chicago is a located north of both Sacramento and Salt Lake City, thus exacerbating this effect. If a longer period of data collection were allowed it would have been possible to collect data under less windy conditions, or if the data were collected at a different time of year the resulting imagery would have been of significantly higher quality (Burnette, 2002). The entire area of the imagery acquired during these flights was 36 km2 (14 mi2). Out of the total area about 22 km2 were selected for detailed analysis.

We received the custom orthophoto data from Northwestern University (Gray and Finster, 2000). Under a contract from EPA, Northwestern University had acquired high-resolution digital aerial photographs (0.3m by 0.3m) from the company, Emerge of MA and CO. These color orthophotos are apparently available for over 580 km^2 (225 mi^2) of metropolitan Chicago. The data we received include 14 distinct square-mile sectors selected to represent overall land use in the metropolitan Chicago area. **Figure 1** shows the locations of the selected areas; **Table 3** provides a summary of land-use descriptions. The sampled areas included high-, medium-, and low-density residential, urban and suburban commercial, and southern and western industrial. Also, many of the selected areas displayed mixed land uses.

Table 3. Selected areas for land use analysis of metropolitan Chicago

Gray and Finster Sector No.	LBNL Area Key	Location Description	Land-Use Categories
1	A13	Stony Island – Burnside	Residential, Commercial
2	A9	Stockyards – International Amphitheater	Industrial
3	A11	Interchange 55/90/94	Transportation
4	A4	Kennedy Interchange 90/94	Residential, Commercial Transportation,
5	A8	Cicero	Residential, Industrial
6	A2	Lincolnwood	Residential, Commercial
5	A1	Schaumburg – Woodfield Mall	Commercial
8	A6	Garfield Park	Residential, Recreational
9	A7	Lincoln Park	Residential, Recreational
10	A3	Rogers Park	Residential, Recreational
11	A5	Wrigleyville	Residential, Commercial
12	A12	Oak Lawn	Residential
13	A10	Blue Island–Pilsen	Residential, Industrial
14	A14	Naperville	Residential

Gray and Finster (2000) analyzed the data manually by:

1. Selecting two to four uniform subsections within each land-use category for each square-mile area,
2. Assigning a single color to each surface cover type (using Adobe Photoshop 4.0),
3. Calculating the overall percentages of vegetative, roofs, and paved surfaces for each land-use category in each sector (see **Table 4** for the results of their analysis).

Table 4. Calculated percentages for vegetation cover, roof area, and paved surfaces. The numbers in parentheses indicate the range. (Source: Gray and Finster, 2000)

Category	Vegetative Cover	Roof Area	Paved Surfaces	Number of Samples
Residential—Urban (Medium/High Density)	45% (33–55%)	34% (26–51%)	20% (15–18%)	12
Residential—Near suburban (Medium/Low Density)	50% (42–58%)	27% (21–36%)	23% (21–25%)	4
Residential – Far suburban (Low Density)	71% (65–76%)	13% (12–13%)	17% (12–22%)	2
Recreational	67% (56–90%)	7% (12–13%)	22% (17–27%)	4
Transportation	31.7% (23.6–40.8%)	0.0%	68.3% (59.2–76.5%)	3
Commercial—Urban	16% (12–21%)	33% (22–47%)	51% (32–62%)	3
Commercial—Suburban	12% (10–17%)	26% (18–35%)	62% (52–73%)	4
Industrial	10% (2–21%)	42% (35–50%)	48% (44 –51%)	3

Some of the digital data had significant data quality problems. In a few areas as much 30% of the total pixels were not identifiable.

3. Method of Analysis for Custom Color Orthophotos

The digital data obtained for metropolitan Chicago, covering a total of about 36 km^2 (14 mi^2), at 0.3-m resolution, includes approximately 3.9 x 10^8 pixels. Because of the large volume of data, reviewing all of data visually and in detail is very difficult and time-consuming. Hence, a semi-automated method was deemed necessary to classify the data. The method has four steps:

1. visually inspecting aerial photographs and preparing of a list of various surface-types identifiable in the photos;
2. grouping surface categories into major components;
3. randomly sampling a subset of data for each region (through a Monte-Carlo sampling approach), and visual inspection of each sample and the assignment of a surface classification to it; and finally
4. extrapolating the results to the entire metropolitan Chicago, using USGS LULC as a basis.

3.1 Identification of Surface-Types

Each area photographed is visually inspected using ERDAS Imagine software. The purpose of this visual exercise is to identify qualitatively all surface-types and land-covers that can be seen at the resolution of the data (in this case, 0.3 m). For metropolitan Chicago, the surface-types that were visually identified and used in the analysis are shown in **Table 5**.

Although more details can be seen in the photos, the categories identified in Table 5 covered most surfaces of interest. In general, the "Other Feature" category was a very small fraction (less than 1%) of the selected random samples. Also, a distinction was made between category 1, "Unidentified," and category 30, "Other Feature": those surfaces classified as "Unidentified" could not be accurately identified, while those in the "Other Feature" category could, but identification was not relevant to this study. This distinction was necessary to avoid assigning the known features incorrectly.

3.2 Grouping the Surface-Types

The grouping of surface-types is done differently for "above-the-canopy" and "under-the-canopy" categories. The criterion for grouping above-the-canopy categories was primarily based on requirements for meteorological modeling. Thus surface types made from similar materials were grouped together since they have similar characteristics. However, the under-the-canopy categories were grouped based on requirements for implementation of heat-island reduction measures; the under-the-canopy categories show the actual and functional land-use categories as they are built. Hence, there is a difference in the definition of the categories for above-the-canopy and under-the-canopy under the same category type.

The above- and under-the-canopy groupings are summarized in **Table 6**. For characterization of the surfaces under the canopy, the primarily criteria for grouping was the function or use of the surface-type. For implementation purposes, one would like to "see" what lies beneath the canopy of trees. Hence, in order to calculate areas of various surfaces under the canopy, the areas beneath the trees are totaled. In these calculations it is assumed that the areas occupied by tree trunks are negligible. Also, a "Private Paved Surfaces" category was added to distinguish between those surfaces owned privately and those owned publicly. Obviously, this grouping can be rearranged depending on specific needs.

Table 5. Visually identifiable features of interest in the metropolitan Chicago (based on aerial photographs).

Category	Description	Category	Description
1	Unidentified	16	Swimming Pool
2	Tree Covering Roof	17	Auto Covering Road
3	Tree Covering Road	18	Private Paved Surfaces
4	Tree Covering Sidewalk	19	Parking Deck
5	Tree Covering Parking	20	Alley
6	Tree Covering Grass	21	Water
7	Tree Covering Dry/Barren Land	22	Grass on Roof
8	Tree Covering Other	23	Train Tracks
9	Tree Covering Alley	24	Auto Covering Parking
10	Roof	25	Recreational Surface
11	Road	26	Residential Driveway
12	Sidewalk	27	Awning
13	Parking Area	28	N/A
14	Grass	29	N/A
15	Dry/Barren Land	30	Other Feature (not of interest)

3.3 Identification of Random Samples

Once the surface-types have been identified, as in Table 5, the next task is to determine the fractional areas covered by each type respectively. We used the Monte-Carlo statistical technique for this purpose. The method is a simple process of randomly selecting pixels and visually identifying their surface-types and their percentages. The results are summarized as percentages for various surface types. Initially, when the number of sample points is small, there is a large fluctuation in the percentage of various surface areas. As the number of sample points increases, these fluctuations decreases and the percentages approach asymptotic values. The process is stopped when the fluctuations in the percentages of each and all surface-types is less than an acceptable value (here less than 1%).

To locate the sample points randomly in a given region, ERDAS Imagine's capability to generate random numbers was used to create some 400–600 points for each scene (ERDAS, 1997) (this is the range of points at which the fluctuations in the area percentages stabilize). A scene in this case ranged from 0.5–3 km^2 in area. Note that the scene area and number of sample points should be selected in a coordinated fashion so that a reasonable distribution of random points is achieved. That is, the scene area should be selected so that a large number of surfaces are included and so that the randomly selected points are distributed at reasonable density.

Table 6. Major surface-types

Surface-Type	Categories included*	Surface-Type	Categories Included
Above-the-canopy view			
Roof	10, 27	Tree Cover	2–9
Road	11	Grass	6, 14
Parking Area	13, 19	Barren Land	15
Sidewalk & Driveway	12, 26	Miscellaneous	16–18, 20, 21, 23–25, 30
Under-the-canopy view			
Roof	2, 10, 19, 22, 27	Private Paved Surfaces	18, 26
Road	3, 9, 11, 17, 20	Grass	6, 14
Parking Area	5, 13, 24	Barren Land	7, 15
Sidewalk	4, 12	Miscellaneous	8, 16, 21, 23, 25, 30

* Surface-type categories are defined in Table 1.

Once these points have been generated, they are recalled, and each is visually inspected and assigned to one of the surface-types listed in Table 6. Given the fine resolution of these images, one can usually identify the surface-type, although variations in quality of this data present challenges to visual identification. When selected surfaces are unclear, continuity and context are used to identify particular surfaces when possible. Those surfaces that are impossible to identify are entered in the "Unidentified" category.

In the Monte-Carlo approach, as the sample size is increased the standard errors of the estimates of percentages for each land-cover area are expected to decrease. We performed a statistical exercise to evaluate the impact of sample size on standard error of estimate. In this exercise, we calculated the standard deviation of the observations progressively for all observations (samples 1–400), the last 300 observations (samples 101–400), the last 200 observations (samples 201–400), and the last 100 observations (samples 301–400). **Table 7** shows the results of this analysis, both above and under the canopy, for downtown Chicago. It can be clearly observed that the standard deviations decrease progressively as the sample size is increased, indicating convergence towards the population means. Based on this analysis, the estimated 95% confidence interval is less than 10% of the percentage for almost all surface-types.

3.4 Extrapolation of Data for Climate Simulation

For meteorological and air-quality modeling, the characteristics of the surface in different regions must be investigated. Because of the difficulty of carrying out thorough measurement of the entire area (modeling domain), it is necessary to extrapolate the small-scale data to larger regions of interest.

We used Land-Use/Land-Cover (LULC) data from the United States Geological Survey (USGS) to extrapolate to the entire metropolitan Chicago area the limited data obtained from the analysis of aerial photos. LULC data classify the surface at a 200-meter resolution into many different urban and non-urban categories. LULC classifications for urban areas include: residential, commercial/service, industrial, transportation/communications, industrial/commercial, mixed urban or built-up land, and other mixed urban and build-up land. The following steps were taken in order to extrapolate the data from aerial photographs to metropolitan Chicago:

1. We first grouped aerial photographs into LULC categories (i.e., residential, commercial/services, industrial, etc).
2. We then calculated the average characteristics (fabric) for each category.
3. We assigned the observed land-use categories (OLUC) from the analysis of the aerial photographs to those of the LULC data set.
4. Finally, the 200-meter resolution data were averaged to obtain data at 2,000-meter resolution used in meteorological and air-quality modeling.

4. Results for Metropolitan Chicago, IL

The areas selected for these flights were chosen to be representative of the primary urbanized land-uses in metropolitan Chicago. A variety of resources was used in the selection process. The selection of these areas was performed by Dr. Kimberly Gray and Ms. Mary Finster of Northwestern University (Gary and Finster, 2000). They selected scene areas based on their knowledge of the area (Gray and Finster, 2000, pp. 91–94). Hence, a combination of commercial, industrial, and residential areas was selected. Since the majority of the Chicago metropolitan area is used for residential development, an accurate assessment was necessary of the range and coverage of surfaces in residential neighborhoods. All of the areas are shown in **Figure 1** (all areas), in their exact geographic position. They are shown on a relatively small scale so that their positional accuracy is maintained.

Table 7. The impact of sample size on estimates of area percentages of land-use categories for downtown Chicago. The entries show the "sample mean" in percentage of area; the numbers in parentheses are standard deviations from the mean. Note that the above-the-canopy percentages show the "bird's-eye" view of the surfaces; under-the-canopy percentages are the actual land-use types.

Sample Size Surface Type	Above the Canopy				Under the Canopy			
	1–400	**101–400**	**201–400**	**301–400**	**1–400**	**101–400**	**201–400**	**301–400**
Roof	14.6 (2.9)	14.5 (0.5)	14.5 (0.4)	14.3 (0.3)	14.6 (3.0)	14.5 (0.5)	14.6 (0.4)	14.3 (0.3)
Road	11.2 (2.2)	11.3 (0.6)	11.2 (0.4)	11.5 (0.3)	11.8 (2.5)	11.8 (0.7)	11.6 (0.4)	11.9 (0.3)
Parking Area	42.6 (4.3)	41.9 (2.0)	40.7 (1.0)	40.0 (0.3)	46.2 (4.3)	45.6 (1.5)	44.7 (0.7)	44.2 (0.23)
Sidewalk	1.6 (1.3)	2.2 (1.0)	2.8 (0.3)	2.7 (0.1)	1.6 (1.3)	2.2 (1.0)	2.8 (0.3)	2.7 (0.1)
Grass	16.2 (1.8)	16.3 (0.5)	16.5 (0.4)	16.7 (0.3)	16.5 (1.9)	16.7 (0.4)	16.9 (0.3)	17.0 (0.3)
Barren Land	7.2 (1.4)	7.5 (0.5)	7.6 (0.5)	8.0 (0.3)	7.3 (1.4)	7.5 (0.5)	7.6 (0.5)	8.1 (0.3)
Tree Cover	0.3 (0.2)	0.4 (0.2)	0.4 (0.1)	0.4 (0.1)				
Private Surfaces					0.04 (0.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

4.1 Typical Commercial Areas

4.1.a Commercial (A1) (Woodfield Mall)

This rectangular area analyzed in metropolitan Chicago is defined by central Universal Transverse Mercator (UTM)[3] coordinates (413772.6, 4655313.5). It is 1.92 km x 1.57 km, making the total area studied approximately 3.0 km^2. The area analyzed is shown in **Figure 2**. It is typical of a sub-urban mall shopping area and is located about 38 km northwest of downtown Chicago.

As described previously, 400 random points were generated throughout the selected study area. Next, these points were located in the acquired imagery and identified according to their surface type. Initially, the percentages of surface types fluctuate widely, but with the increasing sample size, the accuracy of the percentage of each surface type increases and the percentages stabilize. The results of this analysis are detailed in **Tables 8** and **9**.

From these results it appears that paved surfaces and roofs have the greatest potential to contribute to heat-island reduction in metropolitan Chicago. In fact, over 65% of the entire area is either paved surfaces or roofs. Targeting parking areas to increase albedo would affect 40% of the surface area. Unique to this area is a very high percentage of impermeable surfaces (roofs and parking areas) and a low percentage of tree cover, less than 1%. Therefore, both targeted tree-planting and albedo increase measures are potentially effective in mitigating the heat-island effect in a typical suburban mall development.

4.1.b Commercial (A2) (Lincolnwood)

The second commercial area analyzed in metropolitan Chicago is irregularly shaped and centered on the coordinates (440400.7, 4649841.56), with an area of 0.58 km^2. As shown in **Figure 3**, the area analyzed consists of commercial development alongside the major roads of the area. This area is surrounded by single-family homes.

Similar to the first commercial area, this area also has a high percentage of paved surfaces and a low percentage of tree cover. The percentages of roads and parking areas are 19 and 29, respectively. The roof coverage area is also high at 25%. For each of these suburban commercial areas, tree-planting strategies and increases in albedo of pavements are particularly promising.

4.2 Typical Industrial Areas

4.2.a Industrial Area (A8) (Cicero)

As shown in **Figure 4,** the selected industrial area is situated at center UTM coordinates of (437104.2, 4633906.7). Its area is about 0.66 km x 0.75 km, or 0.49 km^2. It is surrounded by sub-urban, single-family homes.

[3] For a definition of UTM coordinates and how to read them, the reader is referred to http://mac.usgs.gov/mac/isb/pubs/factsheets/fs07701.html#utm.

Strikingly, the roof coverage in this area is 41 %. This is the highest percentage for any surface type in any of the study areas. The surface area of pavements was also high at 29%. In this area it appears that the most effective methods of reducing the heat island would be to target the roof surfaces and pavements for increases in albedo, and to invest in tree-planting.

4.2.b Industrial Area (A9) (Stockyards)

The area of the industrial area is 2.34 km^2. The industrial area has a center coordinate of (445566.1, 4629853.1). Its width and height are approximately 1.65 km x 1.42 km. As shown in **Figure 5**, this area is the largest industrial area analyzed.

This area is similar to Cicero industrial area. The roof coverage is slightly lower at 28%, while the grassy area is a bit higher at 16%. The pavement area is 23%. Thus, as in the previous industrial area, effective methods for heat-island reduction include tree-planting and albedo increases of roofs and pavements.

4.3 Typical Residential Areas

In the Chicago metropolitan area most of the land is used for residential development. Ten residential areas were analyzed ranging in age and housing density .

4.3.a Rogers Park (A3) (Medium/High Density)

The selected residential area is a medium/high density neighborhood north of downtown. It has an area of 2.46 km^2 and is centered on the point (443668.47, 4651290.90). **Figure 6** shows the area selected for analysis. It appears to consist primarily of densely packed single-family homes.

The predominant land cover in this neighborhood is grass at 38%. Roofs cover 28% of the area and pavements 20%. Trees cover only 10% of the area. Interestingly, the total surface area of roofs and pavements in this area is similar to the industrial area, A9. The primary difference between the areas is the much higher percentage of vegetation in this residential area.

4.3.b Kennedy Interchange Area (A4) (Medium/High Density)

The Kennedy Interchange Area is a residential neighborhood located northwest of metropolitan Chicago near the 90/94 interchange. To maximize the study area an irregularly shaped area was selected for analysis, with an area of 0.46 km^2. The selected area extends from (437218.50, 46448.72) at its upper left to (438007.67, 4645224.36) at its lower right, and is shown in **Figure 7**.

This area is similar in its surface coverage to the Rogers Park Area. The only difference between these two areas is the slightly more intensive usage in the Kennedy Interchange area characterized by the higher percentages of roofs and pavements and only a minor reduction (2.5%) in the vegetation level. In each of these areas targeting roofs for albedo increases would be an ideal method for heat-island reduction. Also increasing the vegetation could make a significant positive impact.

4.3.c Wrigleyville (A5) (Medium/High Density)

The rectangular area used for the analysis of this medium/high density residential area is centered on the point (444569.48, 4643596.49), with an area of 2.53 km^2. As shown in **Figure 8**, this area is interspersed with commercial development.

This area has higher percentages of man-made surfaces than the other medium/high density residential areas analyzed. The level of vegetation in this area is 34%. It maintains a higher percentage of tree cover (13%) than the other medium/high density areas. Ideal targets for heat-island reduction strategies in this area would include both roofs and pavements.

4.3.d Garfield Park (A6) (Medium/High Density)

The Garfield Park area is west of downtown Chicago. The analyzed area is shown in **Figure 9**. Its area is 1.79 km^2 and it is centered at (441215.38, 4636888.29).

This medium-density area is not as developed as the other similar areas studied. Its coverage of roofs and pavements is only 44%. It also has 41% vegetation. Since the percentage of barren land is 9% in this area, tree planting would be a beneficial and simple way of improve environmental conditions in this neighborhood.

4.3.e Lincoln Park (A7) (Medium/High Density)

The Lincoln Park area is just north of downtown Chicago. The area selected for analysis (**Figure 10**) is centered on (446726.35, 4641024.31) and covers 1.23 km^2 in area.

The urban-fabric percentages of this medium-density area are similar to those of the Wrigleyville area. The sum of the roof and paved coverage is 59% and the vegetative coverage 38%. As in the Wrigleyville area, albedo increases of both roofs and pavements would be the most effective method of heat-island reduction in this area.

4.3.f Blue Island/Pilsen (A10) (Medium/High Density)

The Blue Island/Pilsen area is west of the Interchange 55/90/94 area (A11) discussed below. The irregularly shaped area selected for analysis is contained between (443111.40, 4634359.29) and (444721.80, 4632818.43) at its upper left and lower right corners. As shown in **Figure 11**, this area is 1.70 km^2.

This is one of two high-density areas analyzed. A total of 68% of the coverage of this area is either roofed or paved. Therefore, targeting these surfaces for albedo increase could significantly mitigate the heat island effect.

4.3.g Interchange 55/90/94 (A11) (Medium/High Density)

This residential area is just south of downtown Chicago near the Blue Island/Pilsen area (A10). It is 0.60 km^2 in area and is centered at (446662.74, 4632394.96). This area is shown in **Figure 12**.

Similar to the Blue Island/Pilsen area, this area is also a high-density development. For each of these areas the roof coverage is the highest, followed closely by pavements and then by vegetation. Excluding commercial and industrial areas, this trend occurs only in the high-density residential areas and appears to be a characteristic of them.

4.3.h Oak Lawn (A12 (Low/Medium Density)

This suburban area in metropolitan Chicago is located southwest of downtown in Oak Lawn, IL. The selected area covers 1.32 km^2. As shown in **Figure 13**, it is centered at the UTM coordinate (437939.83, 4618042.24).

This is one of the two low-density areas analyzed. As would be expected in this type of area, the predominant land coverage is vegetative at 59%. The paved and roof areas coverage are 24% and 15%, respectively. Thus, pavement is the surface-type best-suited for albedo increases in this area.

4.3.i Stony Island (A13 (Low/Medium Density)

The Stony Island area covers 1.27 km^2 and is centered at (451895.34, 4620044.81). This area appears to contain recreational areas and schools as typical of a medium-density residential development. **Figure 14** shows the defined study area.

The surface coverage of this area is fairly typical of medium-density residential areas. Roofs cover 21% while pavements cover 29%. The vegetative coverage (trees and grass) in this area is also typical at 45%. Compared to the other medium-density residential areas analyzed, this area has a low tree coverage at only 5%, making attractive both tree planting and albedo-increasing strategies.

4.3.j Naperville (A14 (Low-Density)

The Naperville area is located further from downtown Chicago than any of the other areas studied. It is a low-density residential area near the town of Naperville, IL. The area analyzed, covering 2.22 km^2, is shown in **Figure 15**. The central coordinate of the selected area is (406086.15, 4624483.68).

Since this is a low-density area it is not surprising that it has a high level of vegetation and correspondingly low levels of man-made materials. The percentage of roofs and pavements is only 20% while vegetation covers 80% of the area. Obviously, tree-planting or albedo-increasing strategies in this area would yield little benefit. It is important, however, to analyze such areas, since they are expanding in their geographic coverage, they have the potential for further detrimental development, and it would be difficult to implement any type of heat-island reduction strategies in them because of their sprawling nature.

4.4 Transportation/Communication

4.4.a Interchange 55/90/94 (A11)

This area is the freeway and adjacent areas of Interchange 55/90/94 surrounded by single-family residential communities (see section 4.3.g). The area used for the fabric analysis is shown in **Figure 16.**

The under-the-canopy fabric of this area is about 65% impermeable surfaces (roofs: 10.4%, roads: 34.4%, and parking area: 19.9%). The vegetation cover is about 10% (trees: 0.8% and grass 9.0%). Miscellaneous land uses constitute about 21% of the area. Since, a significant fraction of the area is impermeable surfaces, increasing the surface reflectance should be the prime focus of heat island reduction. Also, planting trees to shade parking areas, part of roofs, and parts of paved surfaces could be beneficial.

4.5 Summary

The results of this analysis for all land-uses are summarized in **Figure 17** (above-the-canopy view of the city) and **Figure 18** (under the tree canopy). In the commercial section of downtown Chicago, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 18% of the area, whereas roofs cover 15–25% and paved surface (roads, parking areas, and sidewalks) 50–54%. The under-the-canopy fabric consists of 53–59% paved surfaces, 15–25% roofs, and 14–18% grass. In the industrial areas, above the canopy, vegetation covers 4–17% of the area, whereas roofs cover 29–41%, and paved surfaces 27–30%. Residential areas exhibit a wide range of percentages among their various surface-types (See **Figure 19** and **20**). On the average, above the canopy, vegetation covers about 44% of the area (ranging from 24% to 80%), roofs cover about 26% (ranging from 8% to 37%), and paved surfaces about 26% (ranging from 12% to 35%).

5. Extrapolation to Metropolitan Chicago

Table 10 summarizes the assignments of the observed land-use categories (OLUC) in metropolitan Chicago to those of the USGS Land-Use/Land-Cover (LULC) categories. Since our aerial photos were mostly concentrated on urban areas, we have several samples of Residential and Commercial categories and only limited samples for Industrial, Industrial/Commercial, and “Mixed-Urban or Built-up Land.” For “Transportation/Communication,” we were uncertain regarding which categories to map; therefore, it remained unchanged. For “Other Mixed-Urban or Built-up Land,” we have assigned the characteristics of A9.

The average characteristics of various LULC categories are listed in **Table 11**. The USGS/LULC categories presented in Table 11 are summarized in **Figure 21a**. The data clearly indicate that about 53% of the 2500 km^2 analyzed in this study is residential. Commercial service and industrial areas taken together constitute another 31% of the total area.

As shown in Table 11, tree cover in metropolitan Chicago is highest in the Residential land-use category (11), at 11%. It is followed by the Mixed Urban or Built-up Land (16) category at 7%. This is in contrast with Sacramento where the Residential (11) category has a tree coverage of 15% and the Other Mixed Urban or Built-up Land (17) and Mixed Urban or Built-up Land (16) categories each have 27% of their areas covered by trees. The percentage of roof coverage differs by about 15% for all of the land-use categories. In the Residential (11) category, roads covered 17% on average. Also notable is the high percentage of parking area in the Industrial (13) category of metropolitan Chicago. Interestingly, in metropolitan Chicago the percentage of grassy areas is higher for all land-use categories than other cities studied (Sacramento and Salt Lake City). The highest increase in grass coverage is in the Industrial (13) category at 16%. This shows a significant difference in the vegetative coverage of the three cities. **Table 13** and **14** expands the data presented in Tables 1 and 2 to include Chicago.

The areas for each LULC category for the entire simulation domain of 18500 km^2 were then calculated (See **Table 12**). Of the total domain area of approximately 18500km^2, about 2500 km^2 is categorized as urban area, of which approximately 53% is residential. The total roof area as seen above the canopy comprises about 26% of the urban area (about 600 km^2), total paved surfaces (roads, parking areas, sidewalks) comprise 33% (about 750 km2), and total vegetated area about 33% (750 km^2) (see **Figure 21b**). The actual total roof area as seen under the canopy comprises about 27% of the urban area (about 680 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) comprise 35% (about 880 km^2), and total vegetated area (only grass and bushes) about 27% (680 km^2) (see **Figure 21c**).

Table 8. Above-the-canopy view of metropolitan Chicago, IL. Entries are rounded to nearest 0.1. Numbers in parenthesis show the standard deviations of the last 100 samples.

Area	Surface Type (% of total cover)							
	Roof	Road	Parking Area	Sidewalk Driveway	Tree Cover	Grass	Barren Land	Misc.
1. Commercial								
a. A1. Woodfield Mall	15.0 (0.32)	11.4 (0.29)	40.1 (0.27)	2.5 (0.12)	0.5 (0.10)	17.5 (0.29)	7.9 (0.26)	5.1 (0.22)
b. A2. Lincolnwood	25.0 (0.51)	18.5 (0.44)	29.2 (0.56)	2.5 (0.19)	4.8 (0.33)	12.9 (0.27)	3.4 (0.11)	3.7 (0.38)
2. Industrial								
a. A8. Cicero	41.2 (0.44)	7.1 (0.50)	20.3 (0.45)	1.5 (0.07)	0.0 (0.00)	3.8 (0.29)	16.2 (0.34)	10.0 (0.18)
b. A9. Stockyards	28.6 (0.78)	7.0 (0.34)	23.2 (0.49)	1.1 (0.09)	0.5 (0.05)	16.4 (0.46)	16.4 (0.63)	6.7 (0.17)
3. Residential								
a. A3. Rogers Park	28.2 (0.30)	11.7 (0.16)	5.2 (0.23)	3.6 (0.24)	9.8 (0.18)	37.8 (0.36)	2.3 (0.10)	1.3 (0.12)
b. A4 Kennedy Interchange	30.3	16.8	4.2	3.2	11.3	33.9	0.0	0.3
c. A5. Wrigleyville	32.4 (0.47)	20.3 (0.59)	4.2 (0.11)	4.8 (0.30)	13.0 (0.39)	21.2 (0.53)	0.6 (0.11)	3.3 (0.15)
d. A6. Garfield Park	19.2 (0.28)	13.8 (0.21)	3.7 (0.17)	7.1 (0.26)	5.9 (0.15)	35.3 (0.42)	8.5 (0.25)	6.5 (0.42)
e. A7. Lincoln Park	33.8	17.4	3.6	4.6	8.5	29.5	0.0	2.5
f. A10. Blue Island/Pilsen	34.4 (0.85)	22.1 (0.19)	3.7 (0.13)	7.7 (0.39)	3.7 (0.16)	25.2 (0.21)	1.7 (0.08)	1.4 (0.07)
g. A11. Interchange 55/90/94	36.5 (0.29)	24.3 (0.38)	6.2 (0.16)	4.2 (0.15)	3.9 (0.16)	20.5 (0.35)	1.5 (0.12)	3.0 (0.10)
h. A12. Oak Lawn	15.2 (0.36)	19.0 (0.46)	0.3 (0.02)	5.0 (0.14)	16.6 (0.46)	42.6 (0.45)	0.9 (0.07)	0.6 (0.07)
i. A13. Stony Island	20.8 (0.30)	18.2 (0.33)	2.9 (0.12)	7.3 (0.30)	4.7 (0.25)	39.9 (0.53)	0.3 (0.02)	5.9 (0.16)
j. A14. Naperville	8.0 (0.26)	9.2 (0.18)	0.0 (0.00)	2.3 (0.19)	29.5 (0.40)	50.4 (0.48)	0.3 (0.12)	0.3 (0.02)
4. Transportation **A11Trans. Interchng 55/90/94**	10.4 (0.17)	32.5 (0.34)	19.1 (0.45)	0.0	0.8 (0.09)	9.0 (0.30)	4.9 (0.18)	23.2 (0.76)

Table 9. Under-the-canopy view of metropolitan Chicago, IL. Entries are rounded to nearest 0.1. Numbers in parenthesis show the standard deviations of the last 100 samples.

	Surface Type (% of total cover)							
	Roof	**Road**	**Parking Area**	**Sidewalk**	**Private Surface**	**Grass**	**Barren Land**	**Misc.**
1. Commercial								
a. A1. Woodfield Mall	15.0 (0.32)	11.9 (0.26)	44.4 (0.27)	2.5 (0.12)	0.0 (0.00)	17.8 (0.29)	8.1 (0.25)	0.3 (0.02)
b. A2. Lincolnwood	25.0 (0.51)	20.5 (0.34)	30.1 (0.58)	2.0 (0.23)	0.8 (0.06)	14.3 (0.37)	3.4 (0.11)	3.9 (0.15)
2. Industrial								
a. A8. Cicero	41.2 (0.44)	7.1 (0.51)	20.6 (0.46)	1.5 (0.07)	2.1 (0.14)	3.8 (0.28)	16.2 (0.33)	7.6 (0.22)
b. A9. Stockyards	28.6 (0.79)	7.5 (0.53)	24.8 (0.46)	1.1 (0.09)	3.2 (0.15)	17.0 (0.42)	16.4 (0.64)	1.3 (0.09)
3. Residential								
a. A3. Rogers Park	28.2 (0.30)	12.4 (0.17)	5.4 (0.27)	4.7 (0.17)	0.8 (0.07)	45.1 (0.43)	2.8 (0.09)	0.5 (0.05)
b. A4 Kennedy Interchange Area	30.6	20.0	4.2	3.2	0.3	37.1	0.0	4.5
c. A5. Wrigleyville	32.4 (0.47)	23.3 (0.53)	4.2 (0.11)	4.8 (0.30)	0.6 (0.17)	23.3 (0.30)	0.6 (0.12)	10.6 (0.77)
d. A6. Garfield Park	19.2 (0.28)	15.0 (0.29)	3.7 (0.18)	7.1 (0.26)	3.1 (0.27)	38.7 (0.52)	8.5 (0.25)	4.8 (0.23)
e. A7. Lincoln Park	33.8	18.5	4.3	4.6	0.0	30.6	0.0	8.2
f. A10. Blue Island/Pilsen	34.4 (0.85)	22.3 (0.21)	4.0 (0.15)	7.7 (0.39)	0.3 (0.13)	26.9 (0.26)	1.7 (0.08)	2.6 (0.10)
g. A11. Interchange 55/90/94	36.5 (0.29)	26.4 (0.41)	6.8 (0.15)	4.2 (0.15)	0.6 (0.05)	22.3 (0.27)	1.5 (0.12)	1.8 (0.16)
h. A12. Oak Lawn	15.2 (0.36)	20.7 (0.40)	0.3 (0.02)	3.2 (0.13)	2.6 (0.10)	48.1 (0.39)	0.9 (0.07)	9.0 (0.42)
i. A13. Stony Island	21.1 (0.33)	22.9 (0.38)	2.9 (0.12)	4.7 (0.26)	2.9 (0.13)	43.4 (0.44)	0.3 (0.02)	1.8 (0.14)
j. A14. Naperville	8.0 (0.26)	9.5 (0.17)	0.0 (0.00)	2.0 (0.17)	0.3 (0.02)	63.9 (0.58)	0.3 (0.12)	16.0 (0.54)
4. Transportation **A11Trans. Interchange 55/90/94**	10.4 (0.18)	34.4 (0.41)	19.9 (0.29)	0.0	0.0	9.0 (0.31)	4.9 (0.18)	21.3 (0.54)

Metropolitan Chicago is fairly green, but the potential for additional urban vegetation may be large. In the commercial and industrial areas, existing trees shade about 0–5% of the grass area and 0–10% of all paved surface areas. In some residential areas, trees shade up to 12% of grass and up to 15% of the paved surfaces. The fraction of roof areas shaded by trees is less than 1%. The potential may be large for planting additional urban vegetation in metropolitan Chicago. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, this amounts to about an additional 14% tree cover for the entire city (the validity of these assumptions should be checked in a detailed study). An additional tree cover of 14% is about 350 km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50 m^2, these calculations suggest a potential for an additional 7 million trees in metropolitan Chicago. (For a detailed reference for the potential of tree-planting in metropolitan Chicago, the reader is referred to McPherson *et al.*, 1994.) As climate and air-quality simulations have indicated, 7 million additional trees can have a significant impact on cooling Chicago and improving ozone air quality.

The potential for increasing the albedo of metropolitan Chicago is also very large. Impermeable surfaces (roofs and pavements) comprise about 62% of the total area of metropolitan Chicago. Unfortunately, the aerial orthophotos for Chicago cannot be used to accurately estimate the albedo of the surfaces. For illustration proposes, we calculate potentials for changing the albedo of metropolitan Chicago, assuming two different scenarios. One scenario assumes a modest change in the albedo of impermeable surfaces, while the other assumes an aggressive increase in the albedo of all surfaces. These scenarios are summarized in **Table 15**. The resulting change in the albedo of the city is summarized in **Table 16**. Under the low-albedo scenario, the overall residential and commercial albedo is changed by 6.2% and 9.7% respectively; the average albedo of the city is increased by 7.4%. For the high-albedo scenario, the overall albedo of residential and commercial areas change by 13.9% and 18.9%, and the average albedo of the city is increased by 15.7%. Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

These examples are used for illustration purposes only. For climate and air-quality simulations where both albedo and vegetation are changed, the overall changes in albedo and vegetation differ from these calculations.

6. Discussion

This report focuses on the characterization of the fabric of a region in terms of surface-type makeup. The data obtained from the metropolitan Chicago (and the other two UHIPP cities of Sacramento and Salt Lake City) over flights suggest that it is possible to characterize the fabric of a region of interest accurately and cost-effectively. However, depending on the purpose of the application and the funds available, a separate decision must be made for each UHIPP city or region as to the most appropriate combination of data, i.e., a combination of aerial orthophotographs, USGS/LULC, and satellite/aircraft data such as ATLAS or AVHRR.

Based on the studies performed for metropolitan Chicago and Sacramento, it is estimated that in cities the size of metropolitan Chicago and Sacramento (i.e., 800 to 2,500 km^2) between 20 and 50 km^2 of aerial orthophotography would suffice. At a rate of \$140–200 per km^2, the total cost of the overflight and data would amount to about $7,000–10,000. For small data selections the per km^2 price is not applicable because of flight costs (a minimum price is set).

The companies that perform this type of data collection are flexible in dealing with and designing flight paths and selecting flight times. This allows for better planning of the flight track and its timing, to minimize shadows and focus on areas of interest, e.g., specific land-uses or land-covers. This process is recommended for any city interested in implementing heat-island reduction strategies or in modeling their meteorological and air-quality.

Apart from human error in analyzing the data (minimized to the extent possible by repeating the analysis and developing standard analytical processes and protocols), two other sources of error are possible in determining the fabric of a city. First, error introduced by use of the Monte-Carlo approach is typically less than 1% (for a 95% confidence interval). This error can be controlled by studying the relationship of sample size and standard error of estimate for each aerial frame studied. Second, errors may be introduced by integrating the fabric data obtained from aerial orthophotos into USGS LULC categories. We performed an analysis of this source of error using imagery from one of the areas acquired in the Salt Lake City flight (Akbari and Rose, 2001). In addition to these two sources of error, potential errors relating to the accuracy of USGS LULC data are not addressed in this report. Finally, USGS data are older than aerial orthophotos, possibly introducing discrepancies between the two data sources: USGS data and aerial orthophotos.

Table 10. USGS/LULC description for urban area and related observed land-use categories (OLUC).

USGS/LULC	Description	OLUC Included
11	Residential	A3–A6, A10–A14
12	Commercial/Service	A1, A2
13	Industrial	A8, A9
14	Transportation/Communications	A11Trans
15	Industrial and Commercial	A2, A9
16	Mixed Urban or Built-up Land	A2, A4, A6, A7
17	Other Mixed Urban or Built-up Land	A9

Table 11. Calculated surface-area percentages by USGS/LULC categories.

USGS/LULC	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.
11	10.7	25.9	17.3	5.0	3.4	1.6	33.6	2.5
12	2.7	20.0	15.0	2.5	34.7	5.7	15.2	4.4
13	0.3	34.9	7.1	1.3	21.8	16.3	10.1	8.4
14	0.8	10.4	32.5	0.0	19.1	4.9	9.0	23.2
15	2.7	26.8	12.8	1.8	26.2	9.9	14.7	5.2
16	7.3	24.8	16.4	4.3	12.4	4.0	27.4	3.5
17	0.5	28.6	7	1.1	23.2	16.4	16.4	6.7

Table 12. Total surface areas (km^2) in metropolitan Chicago (by category).

USGS/ LULC	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.	Total
11	144.1	348.9	232.9	67.1	45.8	21.7	453.3	33.8	1348
12	12.9	97.0	72.5	12.1	168.1	27.4	73.7	21.3	485
13	0.7	101.6	20.5	3.8	63.3	47.4	29.4	24.3	291
14	1.5	20.1	62.7	0.0	36.9	9.5	17.4	44.8	193
15	0.1	0.8	0.4	0.1	0.8	0.3	0.4	0.2	3
16	0.7	2.2	1.5	0.4	1.1	0.4	2.5	0.3	9
17	1.0	54.9	13.4	2.1	44.5	31.5	31.5	12.9	192
Total Urban Area									
	160.9	625.4	404.0	85.6	360.5	138.1	608.2	137.6	2521
Total Urban and Non-Urban Area Simulated									**18538**

Table 13. USGS land use/land cover (LULC) percentages for three cities: Sacramento, CA, Salt Lake City, UT, and Chicago IL.

	Sacramento	Salt Lake City	Chicago
Total Metropolitan Area (km^2)	809	624	2521
LULC (%)			
Residential	49.3	59.1	53.5
Commercial/Service	17.1	15.0	19.2
Industrial	7.2	4.9	11.5
Transportation/Communication	11.4	9.8	7.7
Industrial and Commercial	0.3	0.0	0.1
Mixed Urban or Built-up Land	5.2	1.9	0.4
Other Mixed Urban or Built-up Land	9.5	9.4	7.6

Table 14. Comparison of the fabric of Salt Lake City, UT, Sacramento, CA and Chicago, IL.

City	Vegetation	Roofs	Pavements	Other
Above-the-canopy				
Metropolitan Salt Lake City	40.9	19.0	30.3	9.7
Metropolitan Sacramento	28.6	18.7	38.5	14.3
Metropolitan Chicago	30.5	24.8	33.7	11.0
Residential Salt Lake City	46.6	19.7	25.3	8.5
Residential Sacramento	39.2	19.4	25.6	15.8
Residential Chicago	44.3	25.9	25.7	4.1
Under-the-canopy				
Metropolitan Salt Lake City	33.3	21.9	36.4	8.5
Metropolitan Sacramento	20.3	19.7	44.5	15.4
Metropolitan Chicago	26.7	24.8	37.1	11.4
Residential Salt Lake City	38.6	23.9	31.6	6.0
Residential Sacramento	32.8	19.8	30.6	16.8
Residential Chicago	35.8	26.9	29.2	8.1

Table 15. Two albedo modification scenarios.

Surface-Type	High-Albedo Change	Low-Albedo Change
Residential Roofs	0.3	0.1
Commercial Roofs	0.4	0.2
Roads	0.25	0.15
Parking Areas	0.25	0.15
Sidewalks	0.2	0.1

Table 16. Net change in the albedo of metropolitan Chicago for high- and low-albedo scenarios.

Area	High-Albedo Scenario	Low-Albedo Scenario
Residential	0.139	0.062
Commercial/Service	0.189	0.097
Industrial	0.179	0.079
Transportation/Communications	0.160	0.088
Industrial and Commercial	0.181	0.087
Mixed Urban or Built-up Land	0.155	0.072
Other Mixed Urban or Built-up Land	0.164	0.075
Average over the Entire Area	0.157	0.074

7. Conclusions

To estimate the impact of light-colored surfaces (roofs and pavements) and urban vegetation (trees, grass, shrubs) on the meteorology and air quality of a city, it is essential to accurately characterize various urban surfaces. Of particular importance is the characterization of the area fraction of various surface-types and the vegetative fraction. In this report, a method is discussed for developing data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography. We devised a semi-automatic Monte-Carlo method to sample the data and visually identify the surface-type for each pixel. The color aerial photographs for metropolitan Chicago covered a total of about 36 km^2 (14 mi^2). At 0.3m resolution, there were approximately $4x10^8$ pixels of data available for analysis.

Results from this analysis suggest several possible land-use and surface-type classifications for the metropolitan Chicago area. We examined four major land-use types: commercial, industrial, residential, and transportation/communication. For each of these land-uses, up to 30 different surface-types were identified and their fractional areas computed. Results were tabulated in various parts of this report. In addition, a method was devised to extrapolate these results from neighborhood to metropolitan scales. The method relies on using land-use/land-cover data from the USGS to map area distributions.

In the commercial section of downtown Chicago, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 18% of the area, whereas roofs cover 15–25% and paved surface (roads, parking areas, and sidewalks) 50–54%. The under-the-canopy fabric consists of 53–59% paved surfaces, 15–25% roofs, and 14–18% grass. In the industrial areas, above the canopy, vegetation covers 4–17% of the area, whereas roofs cover 29–41%, and paved surfaces 27–30%. Residential areas exhibit a wide range of percentages among their various surface-types. On the average, above the canopy, vegetation covers about 44% of the area (ranging from 24% to 80%), roofs cover about 26% (ranging from 8% to 37%), and paved surfaces about 26% (ranging from 12% to 35%).

Land-use/land-cover (LULC) data from the USGS was used to extrapolate these results from neighborhood scales to metropolitan Chicago. For 2,500 km^2, defining most of metropolitan Chicago, about 53% is residential. The total roof area as seen above the canopy comprises about 26% of the urban area (about 600 km^2) total paved surfaces (roads, parking areas, sidewalks) comprise 33% (about 750 km^2), and total vegetated area about 33% (750 km^2). The actual total roof area as seen under the canopy comprises about 27% of the urban area (about 680 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) 35% (about 880 km^2), and total vegetated area (only grass and bushes) about 27% (680 km^2).

The potential is large for additional urban vegetation in metropolitan Chicago. In the commercial and industrial areas, existing trees shade about 0–5% of the grass area and 0–10% of all paved surface areas. In some residential areas, trees shade up to 12% of grass and up to 15% of the paved surfaces. The fraction of roof areas shaded by trees is less than 1%. The potential may be large for planting additional urban vegetation in metropolitan Chicago. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, 30% of parking areas, they would add up to about 14% in additional tree cover for the entire city. An additional tree cover of 14% amounts to about 350 km^2 of the urban area. Assuming that an average tree can have a horizontal cross-section of about 50 m^2, these calculations suggest potential for 7 million additional trees in metropolitan Chicago. As climate and air-quality simulations have indicated, 7 million additional trees can have a significant impact on cooling Chicago and improving ozone air quality.

The potential is also very large for increasing the albedo for metropolitan Chicago. Impermeable surfaces (roofs and pavements) comprise about 61% of the total area of metropolitan Chicago. Unfortunately, the aerial orthophotos for Chicago cannot be used to accurately estimate the albedo of the surfaces. For illustration proposes, if we assume that the albedo of the residential roofs can increase by 0.2, commercial roofs by 0.3, roads and parking areas by 0.15, and sidewalks by 0.1, the albedo of metropolitan Chicago can then be increased by about 0.16. Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

In metropolitan Chicago, the fabric of the neighborhoods selected for this analysis varied significantly. Although an attempt has been made to select neighborhoods that represent many different variations in the overall communities, these results should not be extrapolated to other cities and regions. Many cities are unique in terms of land-use patterns and constructions (e.g. most urban homes on the West Coast are single-story as opposed to two-story houses in the east). It is recommended that a similar analysis be performed for several other cities in different regions of the country in order to expand our understanding of the fabric of the city. The next step should be to expand this effort and obtain data for other UHIPP cities, such as Houston and Baton Rouge, and to compare the results of this analysis with those obtained in the previous studies of Sacramento, California and Salt Lake City, Utah.

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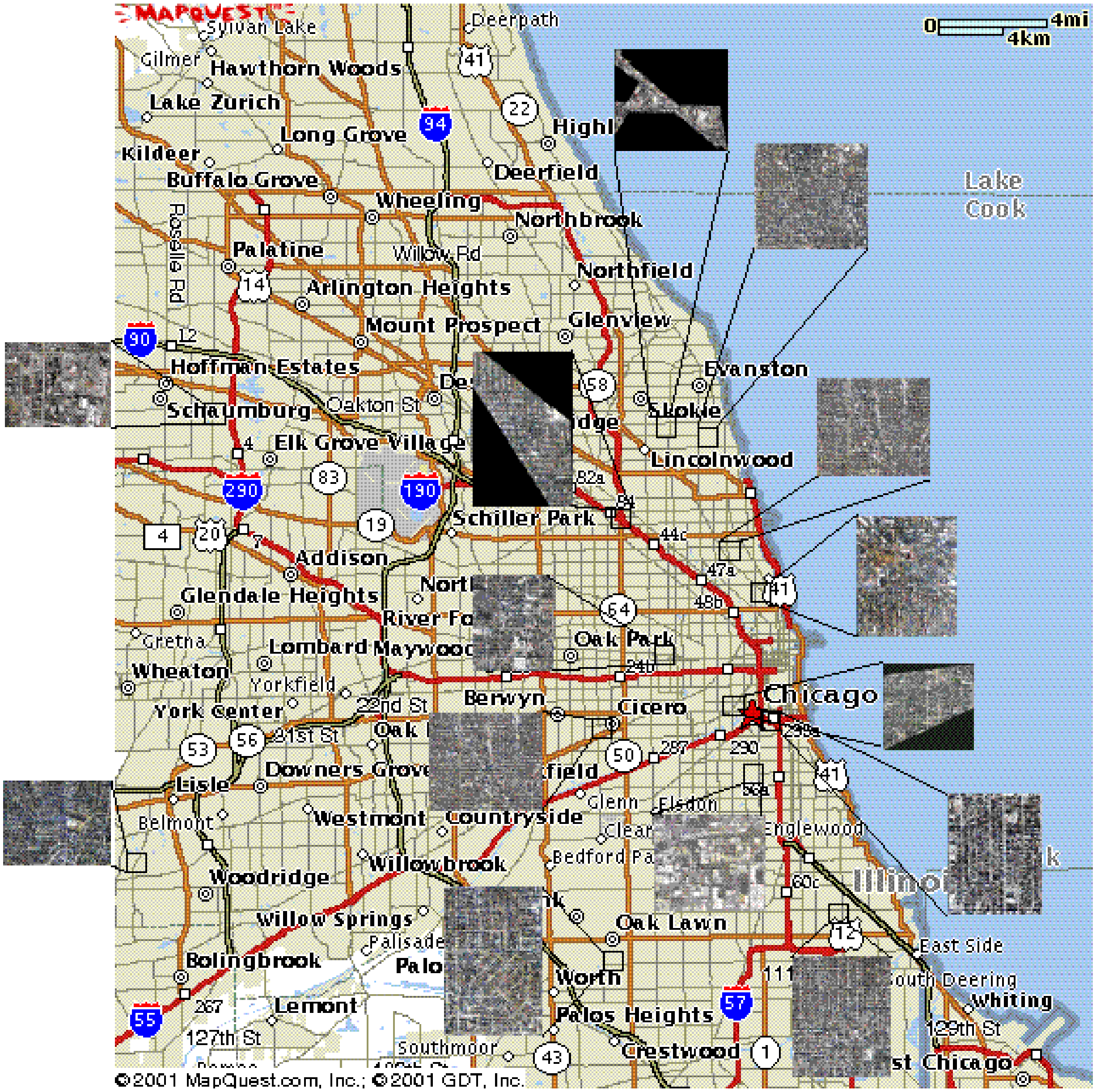

Figure 1. Digital aerial photographs taken for analysis in the Chicago metropolitan area overlaid on a map.

Figure 2. Aerial photo of Woodfield Mall commercial area, metropolitan Chicago.

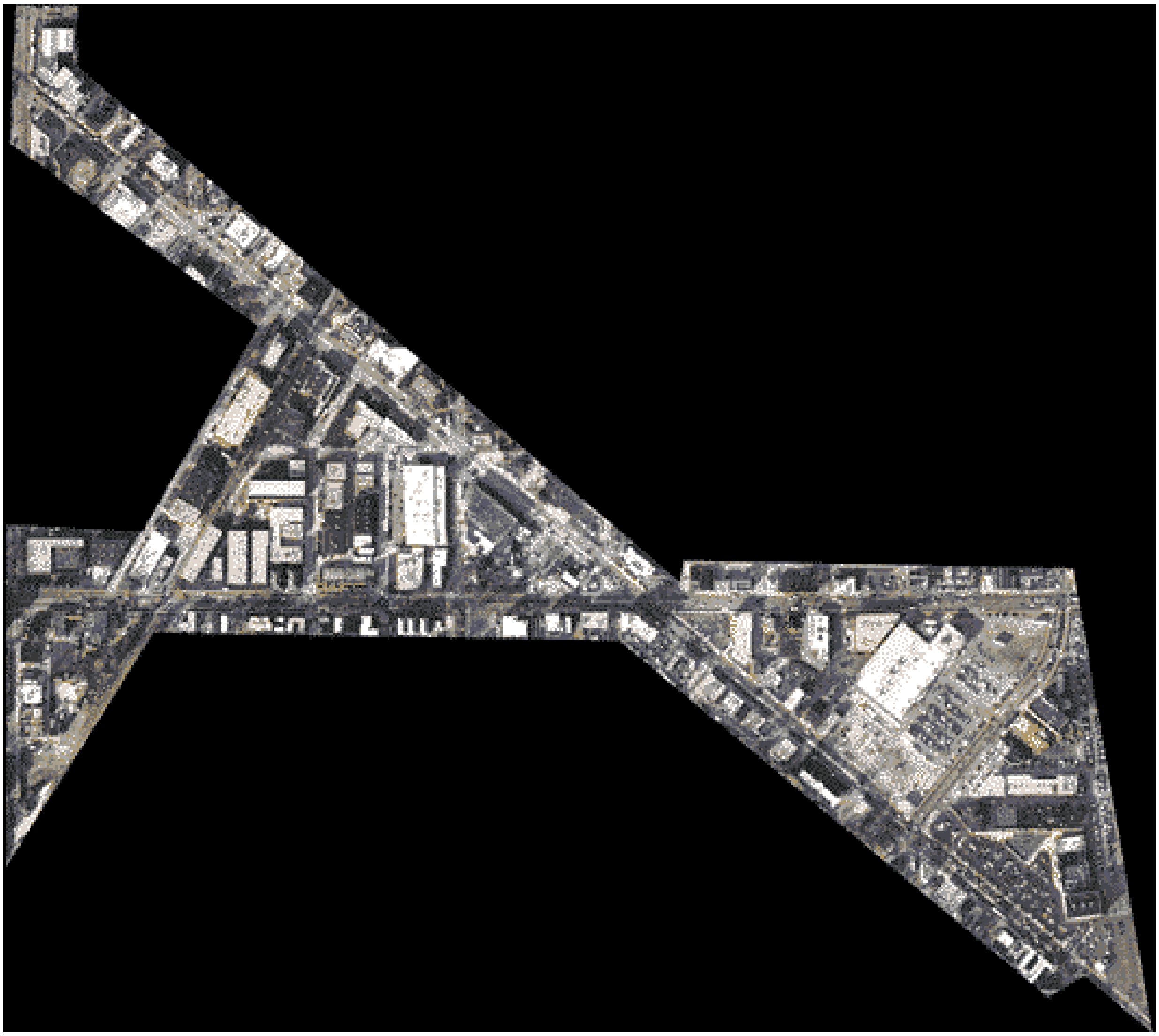

Figure 3. Aerial photo of Lincoln Wood commercial area, metropolitan Chicago.

Figure 4. Aerial photo of Cicero industrial area, metropolitan Chicago.

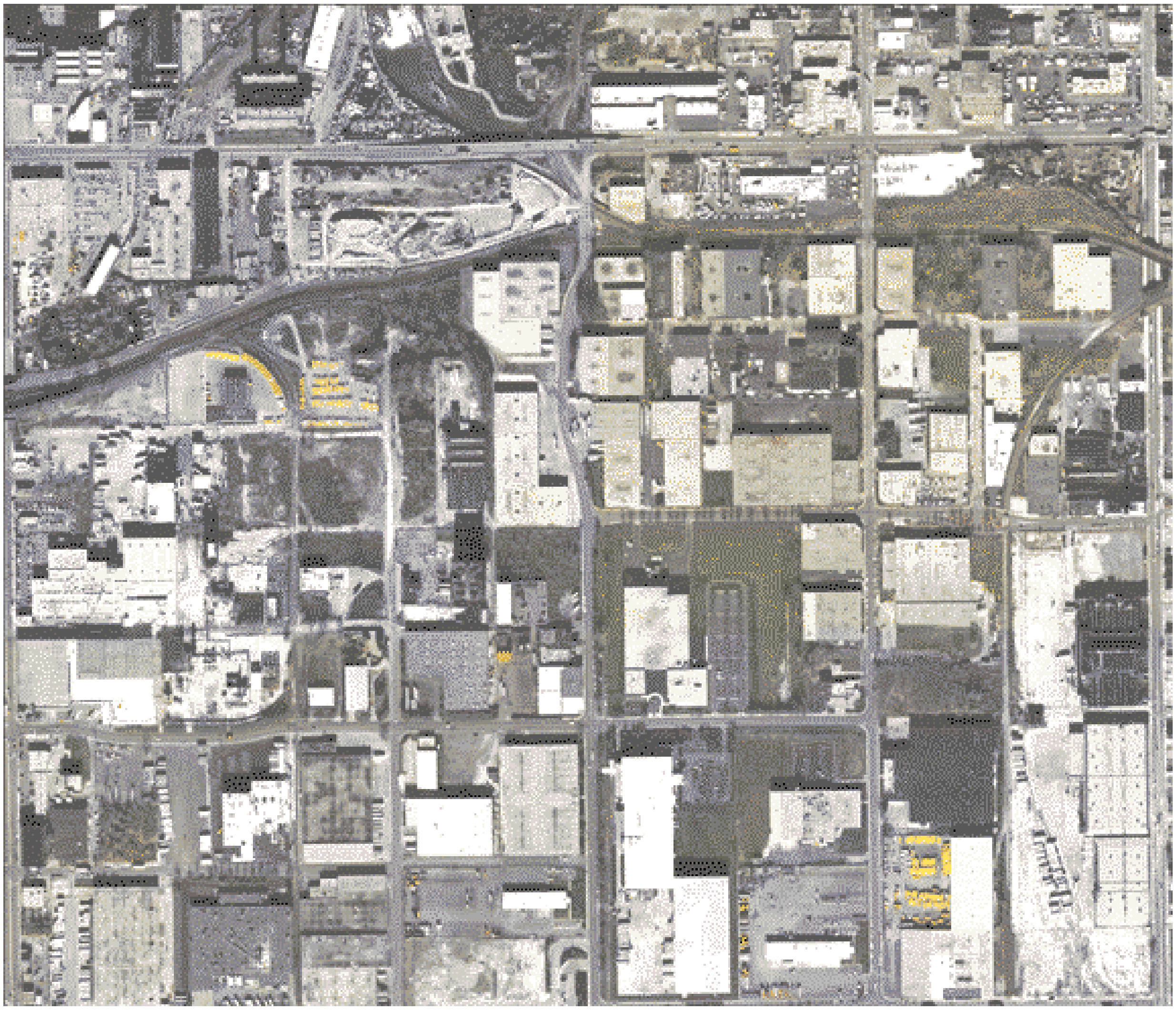

Figure 5. Aerial photo of Stockyards industrial area, metropolitan Chicago.

Figure 6. Aerial photo of Rogers Park residential area, metropolitan Chicago.

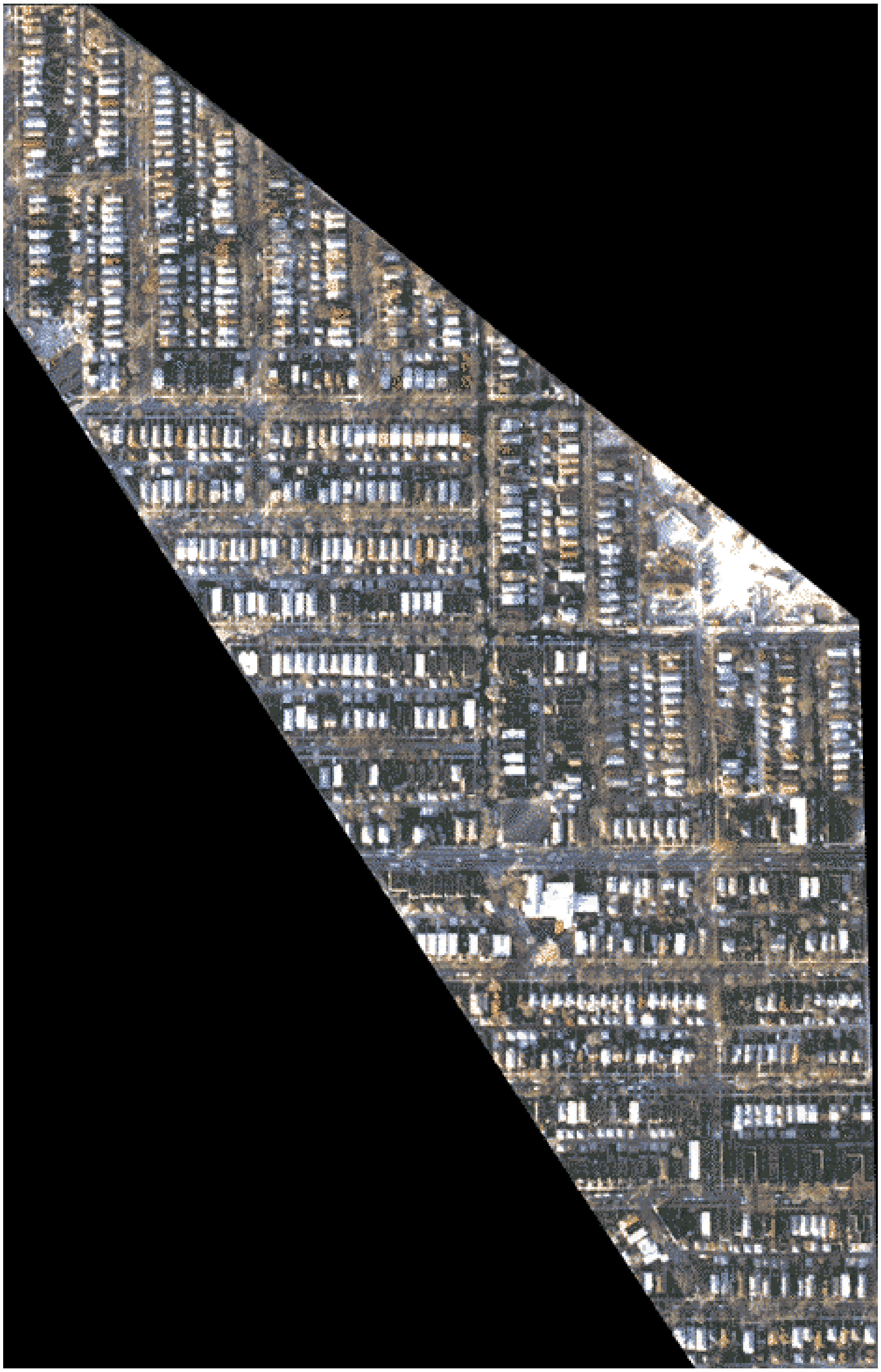

Figure 7. Aerial photo of Kennedy Interchange residential area, metropolitan Chicago.

Figure 8. Aerial photo of Wrigleyville residential area, metropolitan Chicago.

Figure 9. Aerial photo of Garfield residential area, metropolitan Chicago.

Figure 10. Aerial photo of Lincoln Park residential area, metropolitan Chicago.

Figure 11. Aerial photo of Blue Island/Pilsen residential area, metropolitan Chicago.

Figure 12. Aerial photo of Interchange 55/90/94 residential area, metropolitan Chicago.

Figure 13. Aerial photo of Oak Lawn residential area, metropolitan Chicago.

Figure 14. Aerial photo of Stony Island residential area, metropolitan Chicago.

Figure 15. Aerial photo of Naperville residential area, metropolitan Chicago.

Figure 16. Aerial photo of Interchange 55/90/94 transportation/communication area, metropolitan Chicago.

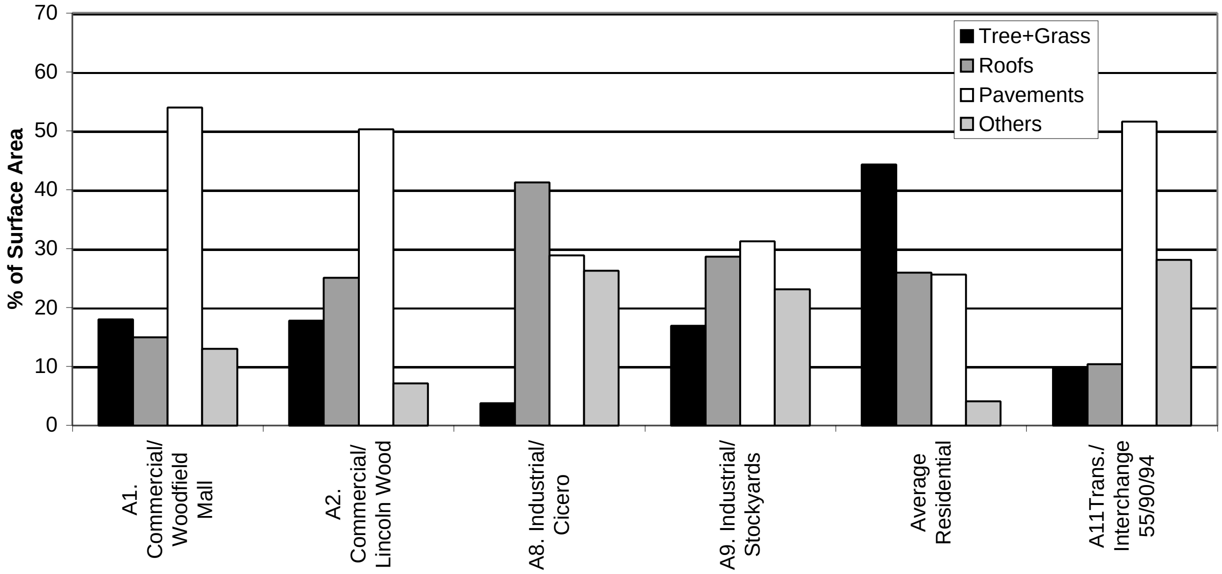

Figure 17. Above-the-canopy fabric of metropolitan Chicago, IL.

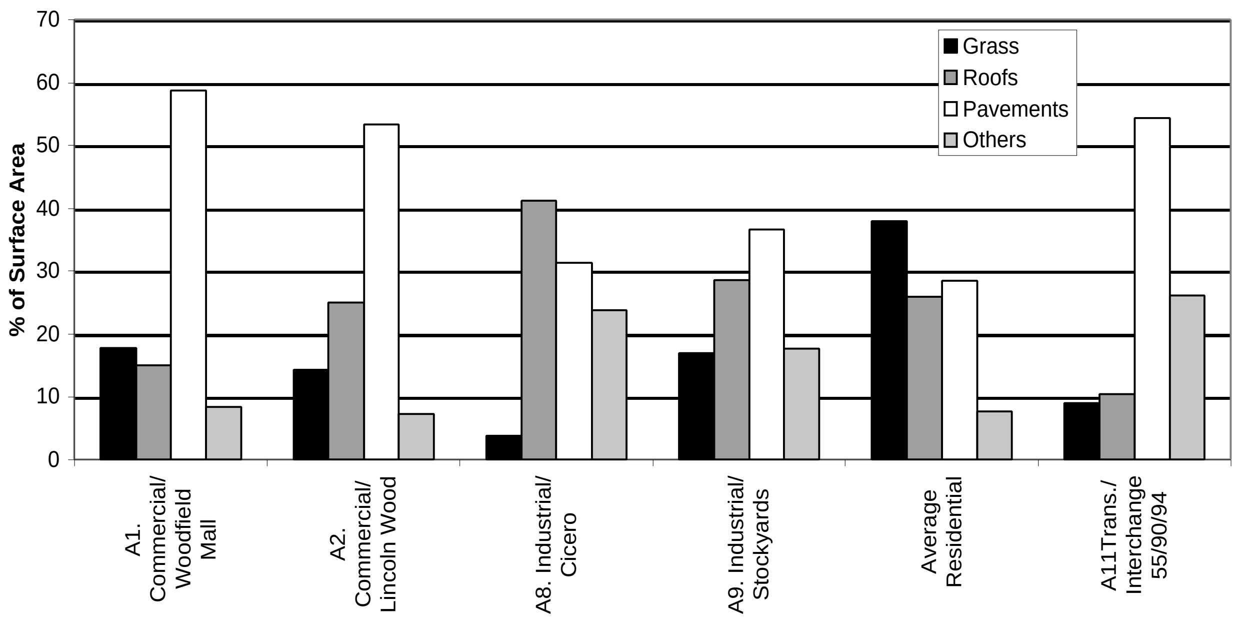

Figure 18. Under-the-canopy fabric of metropolitan Chicago, IL.

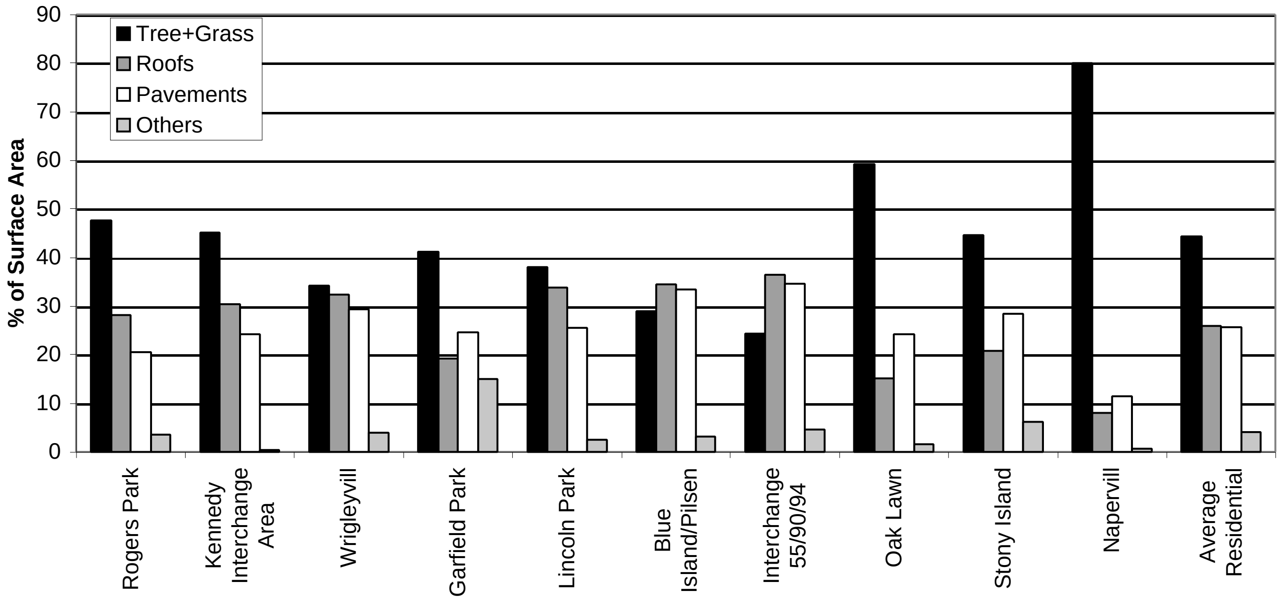

Figure 19. Above-the-canopy fabric of residential metropolitan Chicago, IL.

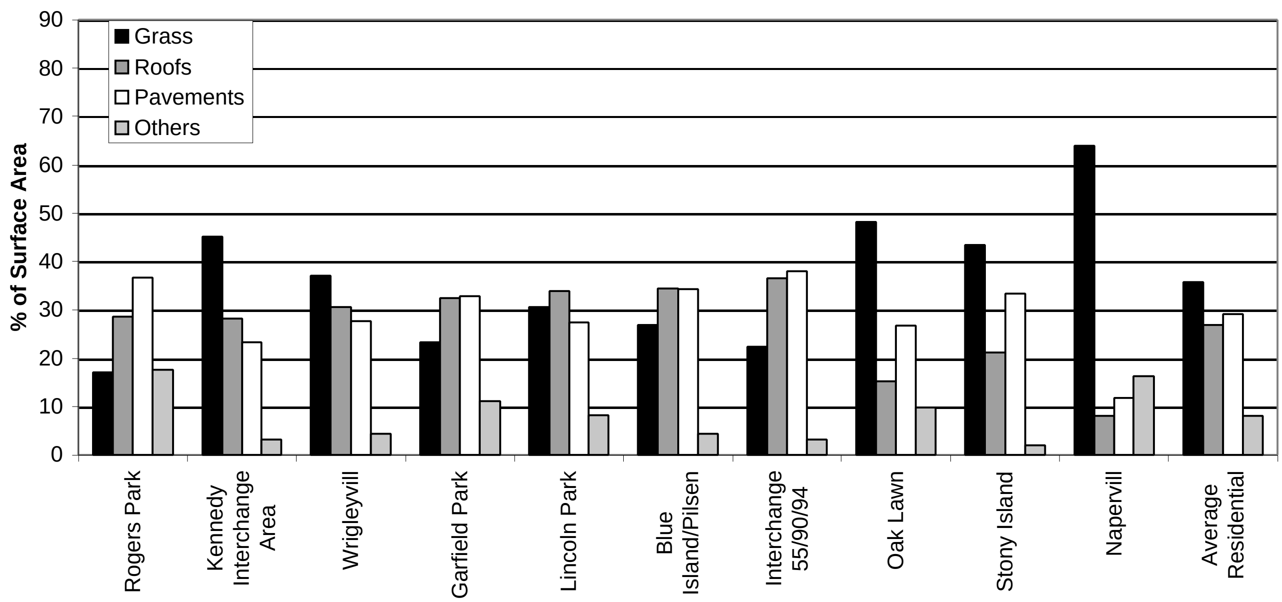

Figure 20. Under-the-canopy fabric of residential metropolitan Chicago, IL.

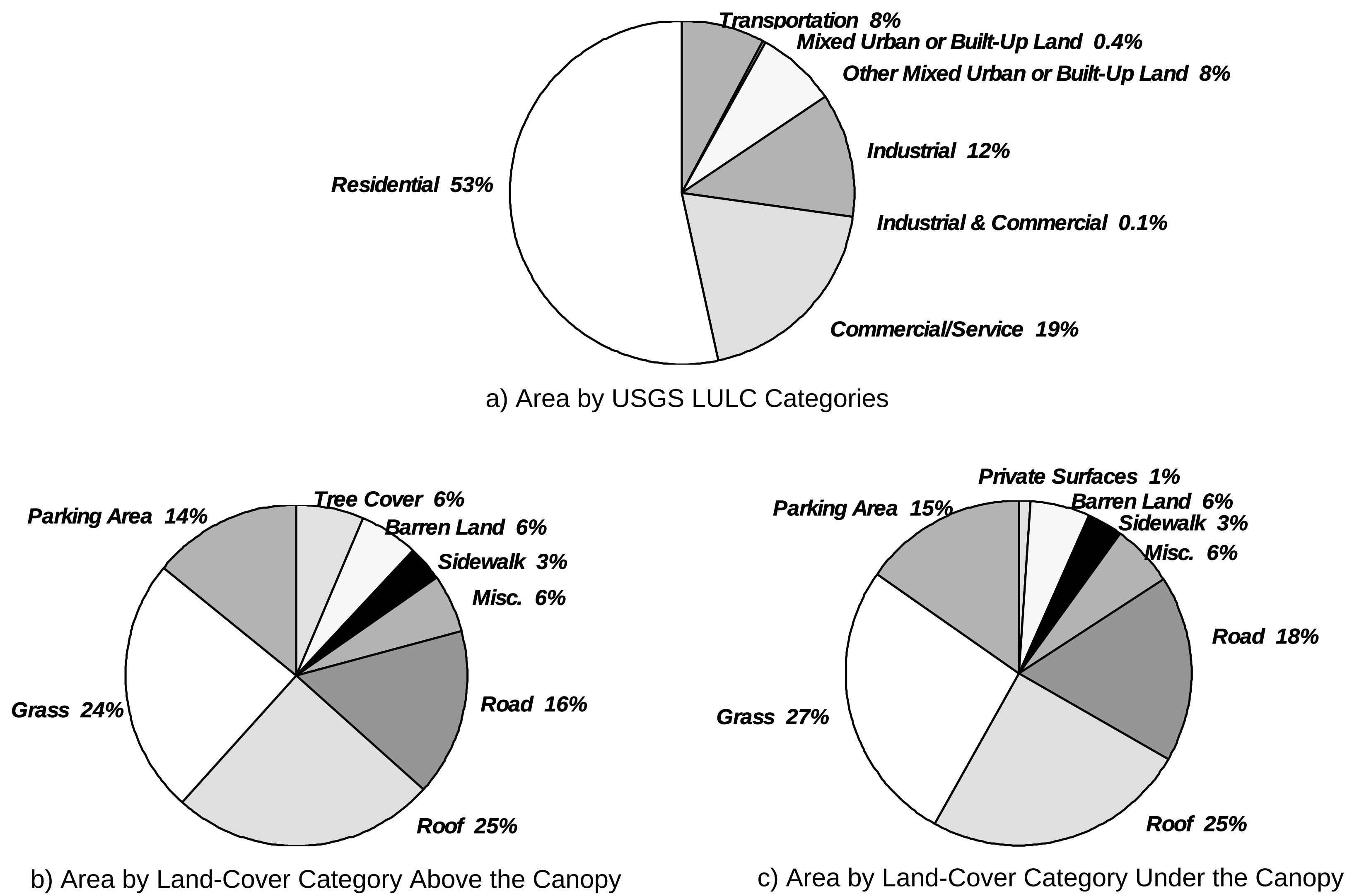

Figure 21. Land use/land cover of the entire developed area of metropolitan Chicago, IL.