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Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah†

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DISCLAIMER

Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah[‡]

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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 Salt Lake City covered a total of about 34 km^2 (13 mi^2). At 0.50-m resolution, there were approximately 1.4×10^8 pixels of data.

Four major land-use types were examined: 1) commercial, 2) industrial, 3) educational, and 4) residential. On average, for the areas studied, vegetation covers about 46% of the area (ranging 44–51%), roofs cover about 21% (ranging 15–24%), and paved surfaces about 26% (ranging 21–28%). For the most part, trees shade streets, parking lots, grass, and sidewalks. In most non-residential areas, paved surfaces cover 46–66% of the area. In residential areas, on average, paved surfaces cover about 32% of the area.

Land-use/land-cover (LU/LC) data from the United States Geological Survey were used to extrapolate these results from neighborhood scales to metropolitan Salt Lake City. In an area of roughly 560 km^2, defining most of metropolitan Salt Lake City, over 60% is residential. The total roof area is about 110 km^2, and the total paved surface area (roads, parking areas, sidewalks) covers about 170 km^2. The total vegetated area covers about 230 km^2.

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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 and Jeanne Briskin of the EPA. We thank Ronnen Levinson for contributing editorial suggestions and assisting with graphics.

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 and slow down smog formation. 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. Sacramento, California; Salt Lake City, Utah; and Baton Rouge, Louisiana were initially selected for the UHIPP. 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 characteristic data and conducted meteorology and air-quality simulations for the three pilot cities.

One of the components of UHIPP research activities is the analysis of 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 fractions 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 costs 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 orthophotography. This method was initially applied to Sacramento, California. In this study we apply the method to analyze the fabric of Salt Lake City, Utah.

The imagery of Salt Lake City covered a total of about 34 km^2 (13 mi^2). **Picture EX.1** depicts a sample orthophoto of downtown Salt Lake City. At 0.5-m resolution, there were approximately 1.4×10^8 pixels of data in all. We devised a semi-automatic method to sample the data and visually identify the surface-type for each pixel. The method involves four steps:

- visual inspection of aerial orthophotos and preparation of a list of various surface-types identifiable in the photos;
- grouping of surface categories into major types;
- random sampling of 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
- extrapolation of the results to the entire Salt Lake City regional area, using the United States Geological Survey (USGS) land-use/land-cover (LU/LC) data as a basis.

The classification in Table EX.1 may include more detail than necessary (actually more details can be seen in the photos, such as mailboxes, small benches, etc., that are, of course, irrelevant to this task). Accordingly, 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 Salt Lake City region (based on aerial orthophotos).

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. 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 railroad 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 includes "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 cate-

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

gories (identified 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	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 EX.1.

Results from this analysis suggest several possible land-use and surface-type classification schemes for the Salt Lake City area. In this study, the following four major land-use types are examined: 1) commercial, 2) industrial, 3) educational, and 4) residential categories. Nine 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 a commercial area of downtown Salt Lake City, a top-down view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 13% of the area, whereas roofs cover 23% and paved surfaces (roads, parking areas, and sidewalks) 56%. The under-the-canopy fabric consists of 65% paved surfaces, 24% roofs, and 3% grass. In an industrial area, vegetation covers 25% of the area, whereas roofs cover 19%, and paved surfaces cover 44%.

Above-the-canopy surface-type percentages in the university campus area were 41% vegetation, 13% roofs, and 29% paved surfaces. In newer commercial areas, vegetation covers 19%, roofs 23%, paved surfaces 55%. Residential areas exhibit a wide range of surface-type percentages. On average, vegetation covers about 46% of the area (ranging from 44% to 51%), roofs cover about 21% (ranging from 15% to 24%), and paved surfaces cover about 26% (ranging from 21% to 28%). The wide range of surface-type percentages in many similar land-use categories demonstrates their site-specific nature. Therefore, it may be especially difficult to account for the variation between similar land-uses in different areas in most traditional land-use/land-cover classification systems.

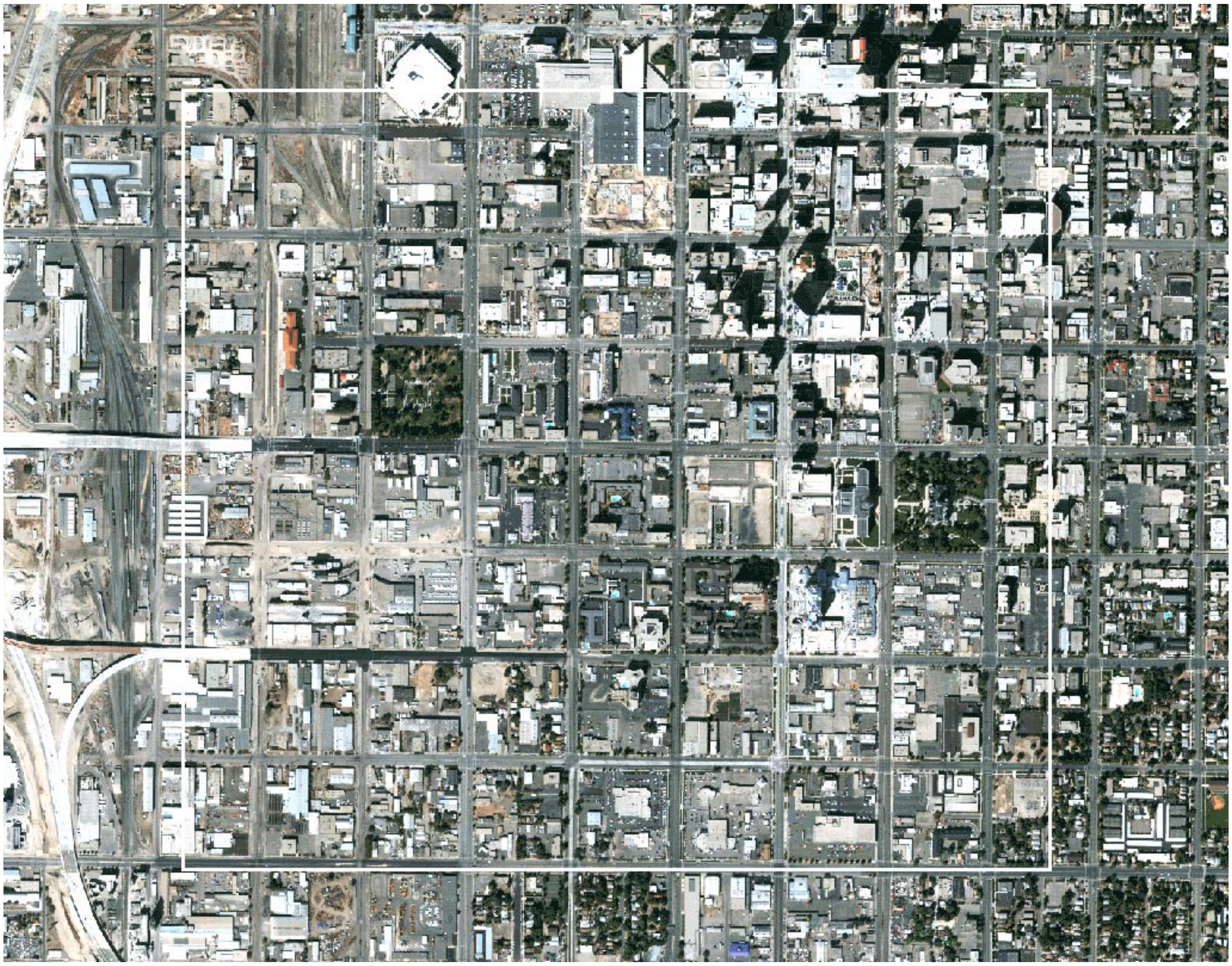
For the most part, trees shade the streets, parking lots, grass, and sidewalks. Under the canopy, the percentage of paved surfaces is significantly higher (see Figure EX.2). In the non-residential areas, paved surfaces cover 36–66% of the area. In residential areas, on the average, paved surfaces cover about 32% of the area. This smaller percentage is primarily due to smaller (generally two-lane) roads in residential areas and a lack of large parking lots.

In order to extrapolate these results from neighborhood to regional scales, e.g., greater Salt Lake City, land-use/land-cover (LU/LC) data from the United States Geological Survey (USGS) were used as the basis for mapping the area distributions. In this method, the Salt Lake City LU/LCs were mapped onto those of the USGS and the total areas of various surface-types were calculated for the entire region of interest. For an area of roughly 560 km^2, including most of metropolitan Salt Lake City, about 65% is residential (see **Figure EX.3a**). The total roof area, as seen above the canopy, comprises about 19% of the urban area (about 106 km^2), total paved surfaces (roads, parking areas, sidewalks) 30% (about 170 km^2), and total vegetated area about 41% (230 km^2) (see **Figure EX.3b**). The actual total roof area, as seen under the canopy, comprises about 22% of the urban area (about 120 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) 36% (about 200 km^2), and total vegetated area (only grass and bushes) is about 33% (180 km^2) (see **Figure EX.3c**).

Salt Lake City is a fairly green city, but the potential for additional urban vegetation is large. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, and 30% of parking areas, they would add up to about an additional 13% tree cover for the entire city. An additional tree cover of 13% is about 70 km^2 of the urban area. Assuming that an average mature tree can have a horizontal cross-section of about 50 m^2, these calculations suggest a potential for an additional 1.4 million trees in Salt Lake City. As climate and air-quality simulations have indicated, 1.4 million additional trees can have a significant effect on cooling Salt Lake City and improving ozone air quality.

The potential for increasing the albedo of Salt Lake City is also large. Impermeable surfaces (roofs and pavements, as seen above the canopy) amount to 49% of the total area of Salt Lake City. For illustration purposes, if we assume that the albedo of the residential roofs can increase by 0.1, commercial roofs by 0.2, roads and parking areas by 0.15, and sidewalks by 0.1, the albedo of the urban areas in Salt Lake City can then be increased by about 0.07. Like urban vegetation, increasing albedo would reduce the ambient temperature and in turn reduce ozone concentration in the city.

In Salt Lake City there is a significant variation in the fabric of the neighborhoods selected for this analysis. Although an attempt was made to select neighborhoods that represent the variation in land-use/land-cover, 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 orthophoto of a commercial area in downtown Salt Lake City.

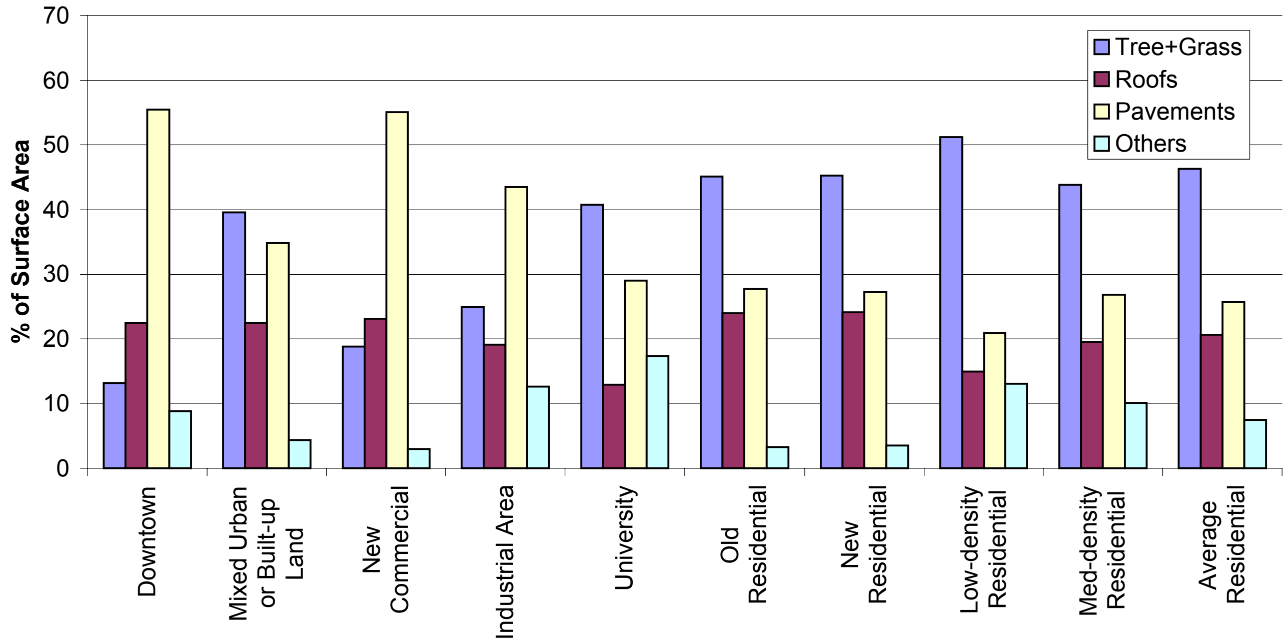


Figure EX.1 Above-the-canopy fabric of Salt Lake City, Utah.

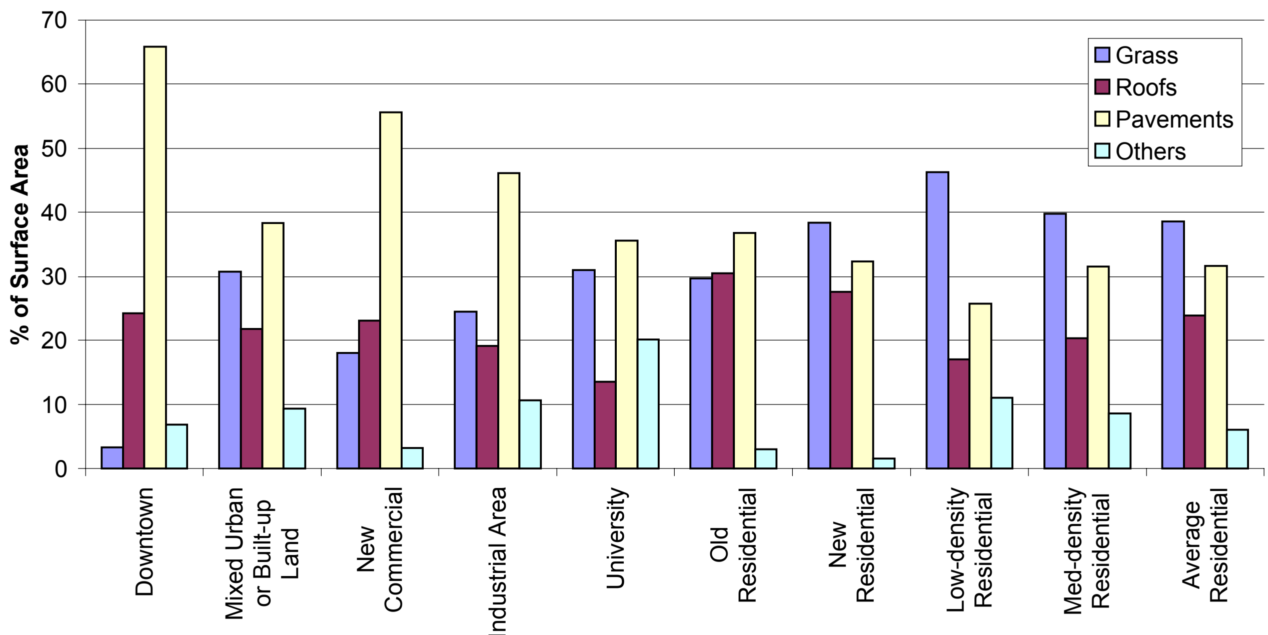


Figure EX.2 Below-the-canopy fabric of Salt Lake City, Utah.

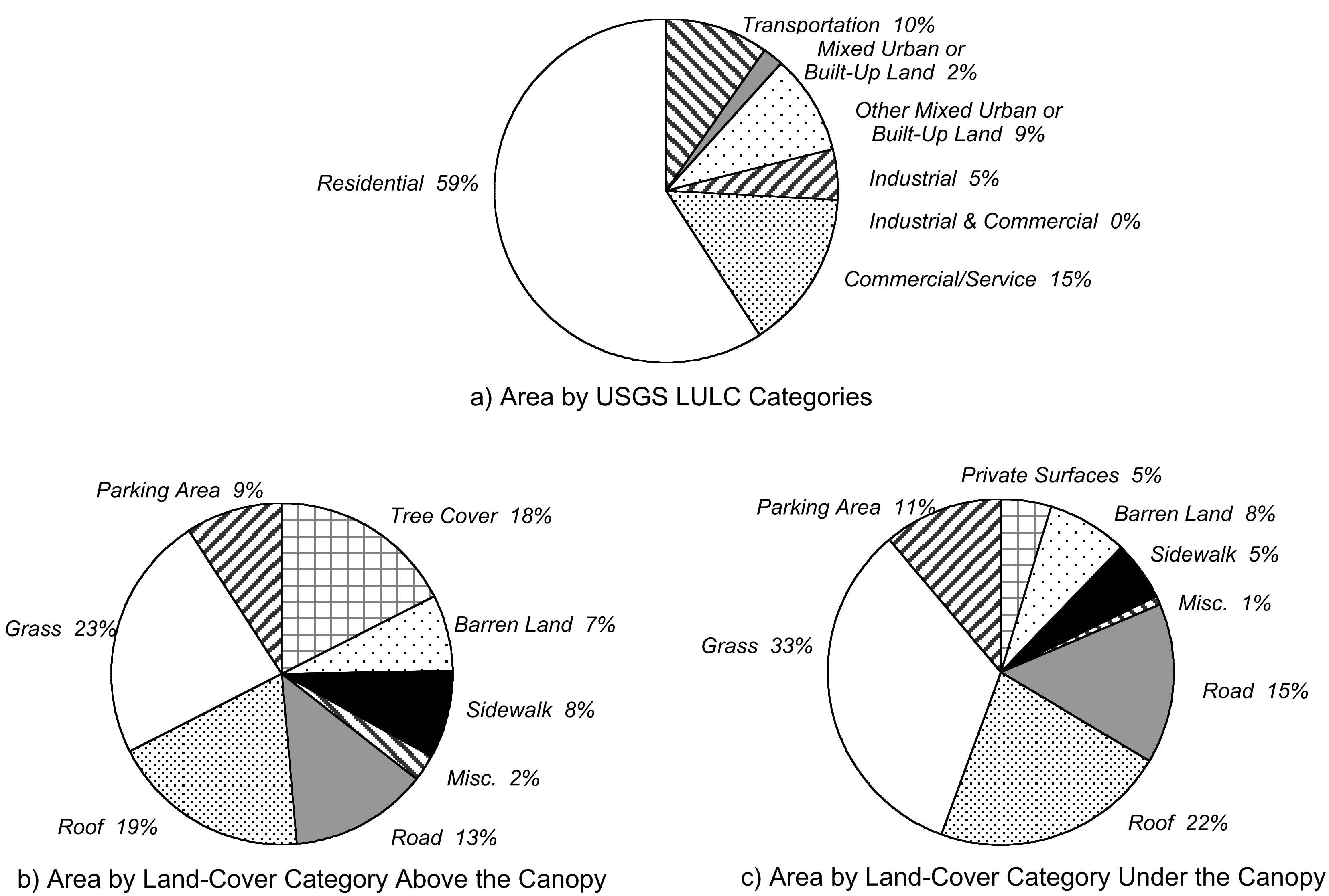


Figure EX.3 Land-use/land-cover of the entire developed area of Salt Lake City, Utah.

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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. Sacramento, California; Salt Lake City, Utah; and Baton Rouge, Louisiana were initially selected for the UHIPP. 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[§] (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 an earlier effort, we characterized the fabric of Sacramento, California using aerial digital orthophotography covering about 65 km^2 (25 mi^2) of metropolitan area (Akbari *et al*. 1999). Five major land-use types were examined: 1) downtown and city center, 2) industrial, 3) offices, 4) commercial, and 5) residential. In downtown Sacramento, a top-down view (above the canopy) shows that vegetation covers 30% of the area, whereas roofs cover 23% and paved surfaces (roads, parking areas, and sidewalks) 41%. Under-the-canopy fabric consists of 52% paved surfaces, 26% roofs, and 12% grass. In the industrial areas, vegetation covers 8–14% of the area, whereas roofs cover 19–23%, and paved surfaces cover 29–44%. The surface-type percentages in the office area were 21% trees, 16% roofs, and 49% paved surfaces. In commercial areas, vegetation covers 5–20%, roofs 19–20%, paved surfaces 44–68% (about 25–54% are parking areas). Residential areas exhibit a wide range of percentages of surface-types. On average, vegetation covers about 36% of the area (ranging 32–49%), roofs cover about 20% (ranging 12–25%), and paved surfaces about 28% (ranging 21–34%). For the most part, trees shade streets, parking lots, grass, and sidewalks. Under the canopy the percentage of paved surfaces is significantly higher. In most non-residential areas, paved surfaces cover 50–70% of the area. In residential areas, on average, paved surfaces cover about 35% of the area.

Akbari *et al.* (1999) also used the land-use/land-cover (LU/LC) data from the United States Geological Survey to extrapolate these results from neighborhood scales to metropolitan Sacramento. In an area of roughly 800 km^2, defining most of metropolitan Sacramento, about half is

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residential. The total roof area is about 150 km^2, and the total paved surface area (roads, parking areas, side walks) is about 310 km^2. The total vegetated area is about 230 km^2.

Other researchers involved in the analysis of urban climate have tried to estimate the surface-type composition of various urban areas. One such work is the analysis of the urban fabric in Sacramento, California by Myrup and Morgan (1972). They applied the strategy of examining the land-use 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 Salt Lake City, Utah. We present our effort in data collection and analysis of digital aerial photography and present results of the analysis for several representative areas in Salt Lake City. Results from the analysis of representative areas are used to estimate the fabric of greater Salt Lake City (for use in meteorological and air-quality modeling).

2 Custom Remote-Sensed Data for 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 orthophotography has the highest potential for accurately producing estimates of surface areas for various land-covers and land-uses in a region. To obtain this custom high-resolution data, a custom color digital camera is flown at low-altitude aboard an aircraft equipped with a GPS (Global Positioning System) and a computer for acquiring and storing data from both the camera and the GPS. The data collected by the GPS system along with topographical data are used in the process of orthorectification. Thus, errors created by the terrain and angle between the camera and surface are minimized.

Using digital, remote-sensed data at a 0.5-m pixel size (for the Sacramento study the resolution was at 0.3 m), it is possible to identify clearly the materials and surfaces that make up the fabric of an area. In the imagery, the red, green, blue, and near infrared bands of data can be utilized in a visual classification scheme. For the data acquisition in Salt Lake City, the Digital Airborne Imagery System (DAIS-1) was used. The bands of the DAIS-1 sensor are similar to those of the IKONOS satellite system and of Landsat Thematic Mapper 4/5 data (Jensen 1996). The wavelengths represented by each of the four bands of the DAIS sensor are 450–530 nm (Blue), 520–610 nm (Green), 640–720 nm (Red), and 770–880 nm (NIR) (Hutchins 1999).

Even though three of the bands (red, green, and blue) are in the visible spectrum and one band is in the near infrared region, data for the entire solar and thermal radiative range is not captured. However, its similarity to the bands of the IKONOS and Landsat sensor affords the opportunity of combining these data types to aid in extrapolations to larger scales, to examine a larger range of wavelengths, or to conduct a multi-temporal study.

An advantage of custom aerial data acquisition is that flights can be scheduled as desired. Accordingly, the orthophotos can be taken at solar noon, thus minimizing the inaccuracies introduced by shadows. In addition, the high resolution allows for the calibration of the digital values in each of the bands with laboratory-measured reference panels that can be placed under the flight path in the field. Such laboratory-calibrated reference panels can be used to calibrate each of the bands of the orthophoto, therefore making it possible to estimate the reflectance of any surface in the orthophoto over the wavelengths covered by the sensor of the camera. Another method of calibrating the bands of the orthophoto is to take field albedo measurements in corresponding wavelengths of features in the orthophoto that remain stable in their reflective properties, such as roads or roofs.

The Salt Lake City data was acquired with a DAIS sensor on-board a specially modified Cessna 421c twin engine plane. The majority of the imagery was acquired on September 26, 1999 under sunny, cloud-free conditions between approximately 2 and 4 pm mountain time (not exactly solar noon). A second flight was required since there were some small gaps (areas where no data was taken) in some of the imagery (A2, A6, and A7) acquired in September. This second flight occurred on November 11, 1999 under similar conditions. For each of these flights, the aircraft took off from Salt Lake City Airport 2 and flew at an altitude of approximately 2,470 m (8,100 ft) (Hutchins 1999). The total area of the imagery acquired during these flights was 34 km^2 (13 mi^2). An area about 15 km^2 was selected for detailed analysis. All data were taken at a 0.5-m resolution.

3 Method of Analysis for Custom Color Digital Orthophotos

The digital data obtained for Salt Lake City covered a total of about 34 km^2 (13 mi^2). At 0.5-m resolution, this was equivalent to approximately 1.4×10^8 pixels of data. Because of the large volume of data collected, it was impossible to review all of it visually in detail. Hence, we used a semi-automatic system to sample the data and visually identify the surface-type for each pixel. The method has four steps:

1) visual inspection of aerial orthophotos and preparation of a list of various surface-types identifiable in the photos;
2) grouping of surface categories into major components;
3) random sampling of 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
4) extrapolating the results to the Salt Lake City region, using USGS LU/LC as a basis.

3.1 Identification of Surface-Types

Each aerial orthophoto is visually inspected using the 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, 0.5 m). For Salt Lake City, the surface-types that were visually identified and used in the analysis are shown in **Table 1**.

Although more details can be seen in the photos, the categories identified in Table 1 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, whereas those in the "Other Feature" category could (but this 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 the view "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 physical 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 the above-the-canopy and under-the-canopy views within the same category type.

The above- and under-the-canopy groupings are summarized in **Table 2**. This was done in order to aggregate similar materials that may also have similar characteristics. 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 1 Visually identifiable features of interest in the Salt Lake City region (based on aerial orthophotos).

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)

Table 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	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.

3.3 Identification of Random Samples

Once the surface-types have been identified, as in Table 1, the next task is to determine the fractional areas covered by each type respectively. We used a Monte-Carlo statistical technique for this purpose. The method is a simple process of randomly selecting pixels and visually identifying their surface types and, subsequently, their percentages. The results are summarized as percentages for various surfaces. 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 being examined increases, these fluctuations become smaller and approach asymptotic values. The process is stopped when the fluctuations in the percentages of each and all surface-types is acceptably small (here less than 1%). Experimental analysis of the approach indicated that a random sample size of 400–600 points/pixels was sufficient to identify accurately the fabric of an area of about 5–10 km^2.

To locate the sample points randomly in a given region (i.e., aerial orthophoto), ERDAS Imagine's capability to generate random numbers was used (ERDAS 1997). A random-number generator was used to create some 400–600 points for each scene (this is the range of points at which the area percentages stabilize). A scene in Salt Lake City averaged 5 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 the randomly selected points are distributed at reasonable density.

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 2. Given the fine resolution of these images, one can almost always identify the surface-type. Even areas in the shade can be relatively easily identified from continuity and context. 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 3** shows the results of this analysis for both above and under the canopy for downtown Salt Lake City. It can be clearly observed that the standard deviations get progressively smaller 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 surfaces in the entire modeling domain must be characterized. Because of the difficulty of carrying out the thorough measurement of the entire area (modeling domain), it is necessary to extrapolate the small-scale data to the region of interest.

We used the land-use/land-cover (LU/LC) data from the United States Geological Survey (USGS) to extrapolate the limited data obtained from the analysis of aerial photos to the entire Salt Lake City area. The USGS LU/LC data classify the surface at 200-meter resolution into many different urban and non-urban categories. The LU/LC classification for urban areas includes 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 the Salt Lake City region:

1. We first grouped data from aerial photographs into LU/LC categories (e.g., residential, commercial/services, industrial, etc).
2. We then calculated the average characteristics (fabric) for each category.
3. We assigned the properties of the observed land-use categories (OLUC) from the analysis of the aerial orthophotos to those of the LU/LC data set. For instance, for a residential LU/LC category, we assigned the percentage areas obtained from aerial photos.
4. Finally, the 200-meter resolution data were averaged to obtain data at 2000-meter resolution used in meteorological and air-quality modeling.

Table 3 The impact of sample size on estimates of area percentages of land-use categories for downtown Salt Lake City. The entries show the "sample mean" in percentage of areas; the numbers in parenthesis are standard deviations of the means. 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	22.75 (3.64)	21.81 (1.43)	21.35 (0.93)	21.97 (0.32)	26.40 (4.11)	25.48 (1.74)	24.60 (0.75)	24.99 (0.26)
Road	20.77 (5.10)	22.65 (1.06)	23.13 (0.53)	23.01 (0.64)	28.16 (5.47)	30.25 (1.09)	30.68 (0.64)	30.29 (0.58)
Parking Area	15.48 (5.46)	13.60 (0.56)	12.65 (0.31)	11.58 (0.33)	12.82 (5.87)	11.22 (1.22)	10.64 (0.99)	9.80 (0.21)
Sidewalk	6.52 (5.66)	5.48 (0.56)	5.23 (0.31)	5.32 (0.33)	9.73 (5.38)	8.91 (0.48)	9.09 (0.44)	9.31 (0.45)
Grass	5.80 (1.72)	6.02 (1.29)	6.75 (0.70)	7.27 (0.18)	9.86 (2.19)	10.46 (1.75)	11.45 (1.04)	12.20 (0.27)
Barren Land	2.10 (1.16)	2.73 (0.37)	2.89 (0.18)	2.76 (0.11)	3.14 (1.01)	3.59 (0.33)	3.68 (0.20)	3.53 (0.12)
Tree Cover	19.24 (3.95)	21.00 (1.07)	21.47 (0.64)	21.57 (0.38)				
Private Surfaces					0.63 (0.56)	0.46 (0.19)	0.35 (0.07)	0.29 (0.02)

4 Results from Salt Lake City, Utah

The areas selected for these flights were chosen to be representative of the primary urbanized land-uses in Salt Lake City. A variety of resources were used to help the selection process. A traditional map along with 1990 census data was used to identify the primary types of land-use in the city. Assistance from local authorities was also sought to acquire an understanding of the city's current state of development. Local authorities were able to identify trends in ongoing development and make recommendations on what areas would be useful to characterize in their local planning and in determining the fabric of the city. Hence, a combination of commercial, industrial, downtown, and residential areas was selected. Since the majority of the Salt Lake City metropolitan area is used for residential development, an accurate assessment of the range and coverage of surfaces in residential neighborhoods was necessary. Therefore, four residential areas were analyzed, varying in age, housing density, and level of vegetation. All of the areas are shown in **Figure 1** in their exact geographic positions. They are relatively small and widely dispersed throughout the metropolitan area.

4.1 Downtown Commercial (A1)

This area analyzed in downtown Salt Lake City is defined by the UTM coordinates (423400.0, 4513400.0) and (425400.0, 4511600.0) for its upper left and lower right corners, respectively. The total area studied is 2.0 km x 1.8 km and is shown in **Figure 2**. Near the upper left corner, Pioneer Park is the grassy area shown and in the lower right corner, the intersection of East 700 South Street and South 200 East Street is shown. The other vegetated block in this area contains city and county buildings. This area is primarily commercial and is classified in the USGS land-use/land-cover scheme as type 12, Commercial/Services.

As described previously, 400 random points were generated throughout the selected study area. Next, these points were located in the acquired imagery and visually 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 4** and **5**.

From these results it appears that the surface types with the greatest potential contribution to the heat-island effect in downtown Salt Lake City are paved surfaces, indicated by coverage of over 50 percent of the entire area. The above-the-canopy categories "Road" and "Parking Area" are both paved surfaces. Thus, the greatest benefits could be attained in downtown Salt Lake City by targeting paved surfaces for increases in albedo. Another man-made feature that affords the opportunity for heat-island reduction strategies is roof area indicated by its coverage of 23 percent of the study area. Alternatively, since the percentage of vegetation is quite low, there is also ample opportunity to increase vegetation. This option would be more difficult to implement, however, because this area is already completely developed, and it would be difficult or impossible to change surface types completely.

4.2 Downtown Mixed-Use (A9)

The other area analyzed in downtown Salt Lake City is irregularly shaped, located between (425399.0, 4512600.0) at its upper left corner and (426099.0, 4511162.0) at its lower right corner. Included in this 0.58-km^2 area are different types of developments common in high-density areas. The area analyzed is shown in **Figure 3**. Included in this area are several religious institutions and public spaces such as a cemetery and a community center. Many different types of residences are also shown. They range from single-family homes to multi-story apartment complexes. This area is composed of a mixture of commercial and residential developments and in the USGS land-use/land-cover scheme is classified as type 16, Mixed Urban or Built-Up Land.

Our analysis suggests that this is a unique land-cover type sharing characteristics of both residential and commercial land-covers. Similar to the downtown commercial area discussed earlier, this area has fairly high percentages of roof and road coverage, 22% and 21%, respectively. In contrast to a nearby commercial area with 13% vegetation cover (see section 4.4), this area has a high fraction of vegetation area (40%). This area balances both high-intensity usage and the preservation of vegetation.

4.3 Industrial Area (A5)

As shown in **Figure 4**, the selected Industrial Area has UTM coordinates of (417458.5, 4509647.50) for its upper left corner and (418314.5, 4508467.5) for its lower right corner. Its area is about 0.86 km x 1.2 km, or 1.0 km^2. It is located about 7 km southwest of downtown. This area includes a hazardous waste facility and several industries, including Huish Detergents, Inc. and Intermountain Design, Inc.

As in the downtown commercial area, paved surfaces are the dominant land-covers in this area. The total percentage of paved surfaces is 43 percent. The roof coverage is also quite high at about 19 percent. There is some undeveloped "Barren Land" in this area, but it is likely to be barren in anticipation of future needs for expansion. Therefore, the most effective method of lessening the heat-island effect in this area would be to target the paved surfaces for increases in albedo.

4.4 New Commercial Area (A3)

The New Commercial Area is 0.66 km^2. If the New Commercial Area were enclosed in a rectangle, the rectangle would be defined be the coordinates (426804.5, 4497607.5) and (428232.5, 4496779.5). As shown in **Figure 5**, this area is typical of many modern strip-mall type developments. These areas tend to be in suburban areas near major highways and are typified by large parking areas and warehouse-style buildings.

Similar to the Downtown Commercial and Industrial areas, the New Commercial Area has a high percentage of paved surfaces and roofs and a low percentage of vegetation. As expected for this sprawling type of commercial development, the "Road" percentage, at approximately 36%, is the highest of any of the areas studied (see Tables 4 and 5). Interestingly, the Old Commercial area, the Downtown Commercial area, and the New Commercial area have roughly the same percentages of roofs and pavements; only pavement distribution is different in the "Road" and "Parking Area" categories. Since this area is more oriented to the private, commercial sector than the downtown, civic-oriented area, it seems likely that the Downtown Area would have a higher percentage of vegetation. Surprisingly, the New Commercial Area has slightly more vegetative coverage than the Downtown Area, but the possibility of increasing this percentage does exist.

4.5 University Area (A7)

The University Area includes part of the traditional college campus of the University of Utah, as well as a research park, and the Stephen A. Douglas Armed Forces Reserve Center. This area is unique in its combination of research, commercial, and academic institutions. In fact, the research park was still being constructed at the time of the overflight. The area is 2.2 km^2 and is shown in **Figure 6.** The area selected for analysis is irregular in shape, so that only the "institutional" land-uses are selected. Therefore, the lower edge of the area follows 500 South Street. The left side of the image shows the traditional-style portion of the University of Utah, while the right side shows both the Reserve Center and the University's research park.

Like the more traditional commercial areas (Areas 1 and 3), the predominant university area land is covered with pavement (mostly parking areas). Unlike the traditional commercial areas, the vegetation percentages here are rather high, with about 41 percent vegetative coverage. Upon completion of the construction of the research park area, the vegetative cover will be even higher, as barren land will be planted with grass and trees. Also several of the large buildings in this area appear to have been built to take advantage of the benefits of high-albedo roofing materials.

4.6 Typical Residential Areas

In the Salt Lake City metropolitan area most of the land is used for residential development. Four residential areas were selected for this analysis ranging in age, housing density, and proximity to downtown. The oldest neighborhood is near downtown and was developed around the 1940s. The area farthest from downtown, a low-density residential, has the largest homes and some sections were developed in the 1980s, but since land is readily available on the urban fringe it was still being developed at the time of the data acquisition. Other areas studied include a medium-density residential development in the suburb of Sandy, Utah and a newer residential area that is typical of the style of current development most common in Salt Lake City.

4.6.1 Old Residential (A2)

This Old Residential area is an older, dense residential neighborhood approximately 3 km southeast of downtown. It consists primarily of single and multi-family housing. It also includes two schools (Whittier on the western edge of the area and Hawthorne near the center of the area) and several churches. **Figure 7** shows the area selected for this analysis.

The area analyzed extends from approximately the intersection of South 3rd East Street and Browning Avenue at its upper left corner to the intersection of South 9th East Street and Hollywood Avenue at its lower right corner. The UTM coordinates of the upper left corner of the selected area are (425400.0, 4510200.0) and the coordinates of the lower right corner are (427000.0, 4508800.0). The total area analyzed is 1.6 km x 1.4 km. The selected area includes only points classified as "Residential," code 11 in the USGS land-use/land-cover data used in the extrapolation detailed later in this report.

Based on a combination of census data (see Appendix B for the discussion of census data for this neighborhood) and imagery, this area has a mixture of single and multi-family structures. The size of the area is about 1,160 buildings per km^2 with an average lot size of approximately 860 m^2. This average lot size includes not only the standard lot surrounding a building, but also the roads and sidewalks servicing the lot. The average roof size in this area is 260 m^2 (2,840 ft^2) and the average paved area, including roads, parking areas, sidewalks, and driveways is 280 m^2 per lot (2,980 ft^2).

Although the paved area per lot is high, targeting them for albedo increases would not be as beneficial as one might expect. This is because in this residential area, much of the paved areas are concrete sidewalks or driveways (11.6%, as shown in Table 4). Therefore, they already have higher albedos than asphalt pavements. Hence, roofs are the surfaces that could be altered most effectively in this area. This area is also well vegetated, with coverage of 45 percent.

4.6.2 Low-Density Residential (A4)

This Low-density Residential area is located about 21.5 km south-southwest of downtown Salt Lake City in the city of South Jordan. The rectangular area selected for analysis extends from approximately the intersection of Skye Drive and the West Jordan Canal at its upper left corner to just south of the intersection of 10400 South Street and South 2200 West Street at its lower right corner. This area includes schools, churches, and fields typical of a low-density residential area. The UTM coordinates defining the selected area are (418200.0, 4492000.0) at the upper left corner and (419800.0, 4490400.0) at the lower right corner. The analyzed area (**Figure 8**) is 1.6 km x 1.6 km, or about 2.6 km^2.

As expected the percentages of roads and roofs, 17% and 10%, were lower here than in the other residential areas. About 57% of the area under the canopy is grass and barren land. According to 1990 census data the homes in this area were built primarily during the 1980s. Also, the density of these homes is estimated to be 93 units per km^2 (240 units per mi^2). Thus, since these units are single-family residences, the average lot size should be approximately 10,800 m^2. Based on these data, the average roof area per home in this area should be 1,080 m^2 (11,600 ft^2). Since the homes in this area are obviously not that large, it is recognized that the 1990 data are insufficient for a current analysis of this area because of development in the area over the past ten years.

From observation of Figure 8, it is clear that some of the housing developments in this area are newly constructed. Therefore, in order to account for these new developments a lot size estimate is necessary based on visual inspection. All buildings in this area were counted; the resulting density is 270 homes per km^2. Thus, an average lot is about 3,700 m^2 and the average roof is 630 m^2 (6,800 ft^2). Since this area has several large fields, and areas that not primarily used exclusively for homes, a correction was applied to take into account these factors. In order to correct for these areas, those not exclusively used for analysis were selected and subtracted from the total area. To determine a more accurate housing density, the number of buildings in the non-housing area was totaled and subtracted from the total number of buildings in the area. After applying this correction, the housing density [(total area –non-residential area) / (total buildings –non-residential buildings)] is estimated to be 322 houses per km^2. Similarly, the estimated lot size is 3,100 m^2 and the average roof area is 600 m^2 (6,500 ft^2).

4.6.3 Medium-Density Residential (A6)

The rectangular area used for the analysis of the Medium-Density Residential area extends from (427922.5, 4493795.5) at its upper left corner to (429398.5, 4492515.5) at its lower right corner. Hence, the area analyzed is 1.9 km^2. The upper left corner is approximately at the intersection of East Cappella Way and South 1350 East Street; its lower right corner is at the intersection of East 9400 South Street and South Highland Drive. This area includes the large Falcon Park, the grassy area including a ball field near the center of the area, and Silver Mesa School above and slightly to the left of park (see **Figure 9**). This neighborhood is actually in the suburban city of Sandy and is about 19.5 km south-southeast of downtown.

Based on census data (see Appendix B), an average lot in this area is approximately 1,500 m^2 and the average roof area is 300 m^2 (3,300 ft^2). From the analysis of aerial photos the average lot size is 1,400 m^2 and the average roof area is 290 m^2 (3,100 ft^2). Thus, the 1990 census data are in agreement with the results of this study. This indicates that the area has not changed extensively over the past ten years and that census data in combination with an accurate average roof area estimate would give a good approximation of total roof area.

4.6.4 Newer Residential (A8)

The Newer Residential area is about 7 km south-southwest of downtown in West Valley City in the Redwood community. The analyzed area is shown in **Figure 10**. It extends from (420070.2, 4506321.7) at its upper left corner to (420553.7, 4505764.2) at its lower right corner. The intersection of West 3100 South Street and South 2050 West Street is shown in the upper left corner of the picture and South 1800 West Street and West 3350 South Street meet in the lower right corner of the picture. The Valley Fair Mall and Redwood Multipurpose Center are just outside the study area. The total area analyzed is 483.5 m x 557.5 m, or 0.270 km^2.

The selected area includes only single-family residences. From the aerial orthophoto for this area, we estimated a housing density of 993 housing units per km^2. Accordingly, each lot averages about 1,000 m^2, including roads and sidewalks, which comprise about 21 percent of the area (see Table 5). The average lot size excluding roads and sidewalks is about 780 m^2. The estimated average roof area is 280 m^2 (3,000 ft^2).

4.7 Summary

The results of this analysis are summarized in **Figure 11** (above-the-canopy view of the city) and **Figure 12** (under the tree canopy). In the commercial section of downtown Salt Lake City, the top view (above the canopy) shows that vegetation (trees, grass, and shrubs) covers 13% of the area, whereas roofs cover 23% and paved surface (roads, parking areas, and sidewalks) 55%. The under-the-canopy fabric consists of 65% paved surfaces, 24% roofs, and 3% grass. In the industrial areas, vegetation covers 25% of the area, whereas roofs cover 19%, and paved surfaces 46%. The surface-type percentages in the new commercial area were 19% trees and grass, 23% roofs, and 55% paved surfaces. Residential areas exhibit a wide range of percentages among their various surface-types. On the average, vegetation covers about 46% of the area (ranging from 44% to 52%), roofs cover about 20% (ranging from 15% to 24%), and paved surfaces about 25% (ranging from 21% to 27%).

5 Extrapolation to Metropolitan Salt Lake City

Table 6 summarizes the assignments of the observed land-use categories (OLUC) in Salt Lake City to the USGS Land-Use/Land-Cover (LU/LC) 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" and "other mixed urban or built-up land," we were uncertain regarding which categories to map. Therefore, they remained unchanged.

The average characteristics of various LU/LC categories are listed in **Table 7**. The USGS LU/LC categories presented in Table 7 are summarized in **Figure 13a**. The data clearly indicate that about 65% of the 560 km^2 analyzed in this study is residential. Commercial service and industrial areas taken together constitute another 22% of the total area.

There is some variation between the USGS LU/LC-observed land surfaces as determined for Sacramento (Akbari *et al.* 1999) and Salt Lake City. As shown in Table 7, tree cover in Salt Lake City is highest in the Residential land-use category (11), at 20.5%. It is followed by the Other Mixed Urban or Built-Up Land (17) and Mixed Urban or Built-Up Land (16) categories at 18.5% and 16.5%, respectively. [This is in contrast with Sacramento where the category 11 has tree coverage of 14.7% and categories 16 and 17 each have 26.8% of their areas covered by trees.] The percentage of roof coverage differs less than 5% for all of the land-use categories except for category 17. In the residential areas of both cities, roads covered 12–13% while in most of the other categories the percentage of road coverage was higher in Salt Lake City. This difference was most notable in the categories 13 and 15. Also notable is the high percentage of parking area in category 13 (Industrial) of Salt Lake City. Interestingly, in Salt Lake City the percentage of grassy areas is higher for all land-use categories.

Table 4 Above-the-canopy view of Salt Lake City, Utah. Entries are rounded to nearest 0.1%. Numbers in parenthesis show the standard deviations of the last 100 samples.

	Surface Type (percent of total cover)							
Area	Roof	Road	Parking Area	Sidewalk/ Driveway	Tree Cover	Grass	Barren Land	Misc.
1. A1: Downtown Commercial	22.5	24.7	26.5	4.3	10.9	2.3	5.8	3.0
	(0.2)	(0.4)	(0.8)	(0.2)	(0.6)	(0.1)	(0.1)	
2. A3: New Commercial	23.1	15.6	35.5	4.0	1.9	16.9	2.2	0.8
	(0.4)	(0.4)	(0.3)	(0.1)	(0.1)	(0.5)	(0.1)	
3. A5: Industrial Area	19.1	13.8	29.4	0.3	2.0	22.9	10.1	2.5
	(0.3)	(0.3)	(0.2)	(0.0)	(0.2)	(0.7)	(0.3)	
4. A9: Downtown Mixed-Use	21.5	20.7	11.4	2.7	16.5	23.1	2.7	1.6
	(0.6)	(0.4)	(0.4)	(0.1)	(0.2)	(0.3)	(0.1)	
5. A7: University Area	12.9	10.2	15.2	3.6	18.5	22.3	15.5	1.8
	(0.2)	(0.4)	(0.2)	(0.2)	(0.5)	(0.3)	(0.4)	
6. Typical Residential Areas								
a. A2: Old Residential	23.9	13.1	3.0	11.6	28.7	16.4	1.3	2.0
	(0.6)	(0.2)	(0.4)	(0.4)	(0.3)	(0.1)	(0.7)	
b. A4: Low-Density Residential	14.9	9.0	2.1	9.8	13.4	37.8	9.8	3.3
	(0.4)	(0.3)	(0.2)	(0.3)	(0.3)	(0.5)	(0.3)	
c. A6: Med-Density Residential	19.5	14.0	2.0	10.8	19.3	24.5	7.3	2.8
	(0.3)	(0.3)	(0.2)	(0.5)	(1.1)	(0.8)	(0.6)	
d. A8: Newer Residential	24.1	16.1	0.0	11.1	21.4	23.9	0.5	3.0
	(0.3)	(0.4)	0.0	(0.3)	(0.2)	(0.5)	(0.1)	

Table 5 Under-the-canopy view of Salt Lake City, Utah. Entries are rounded to nearest 0.1%. Numbers in parenthesis show the standard deviations of the last 100 samples.

Area	Surface Type (percent of total cover)							
	Roof	Road	Parking Area	Side-walk	Private Surfaces	Grass	Barren Land	Misc.
1. A1: Downtown Commercial	24.2 (0.3)	27.8 (0.6)	31.1 (0.7)	6.6 (0.3)	0.3 (0.0)	3.3 (0.1)	5.8 (0.1)	1.0
2. A3: New Commercial	23.1 (0.4)	15.6 (0.4)	36.0 (0.3)	4.0 (0.1)	0.0 0.0	18.0 (0.5)	2.7 (0.2)	0.5
3. A5: Industrial Area	19.1 (0.3)	14.1 (0.3)	31.4 (0.2)	0.3 (0.0)	0.3 (0.1)	24.4 (0.6)	10.1 (0.3)	0.5
4. A9: Downtown Mixed-Use	21.8 (0.6)	22.3 (0.4)	12.5 (0.3)	2.4 (0.1)	1.1 (0.1)	30.8 (0.5)	2.7 (0.1)	6.6
5. A7: University Area	13.5 (0.3)	11.4 (0.5)	19.8 (0.3)	4.1 (0.3)	0.3 (0.0)	31.0 (0.6)	19.8 (0.4)	0.3
6. Typical Residential Areas								
a. A2: Old Residential	30.5 (0.6)	18.1 (0.3)	4.8 (0.6)	9.1 (0.4)	4.8 (0.2)	29.7 (0.5)	2.0 (0.2)	1.0
b. A4: Low-density Residential	17.0 (0.5)	10.0 (0.2)	3.3 (0.2)	4.9 (0.2)	7.5 (0.4)	46.3 (0.6)	10.5 (0.3)	0.5
c. A6: Med-density Residential	20.3 (0.3)	14.5 (0.3)	3.3 (0.2)	6.3 (0.3)	7.5 (0.2)	39.8 (0.6)	7.8 (0.5)	0.8
d. A8: Newer Residential	27.6 (0.4)	16.8 (0.4)	2.8 (0.2)	4.8 (0.3)	8.0 (0.3)	38.4 (0.6)	0.5 (0.1)	1.0

The areas for each LU/LC categories for the entire Salt Lake City region simulation domain were then calculated (See **Table 8**). Of the total domain area of approximately 9,000 km^2, about 560 km^2 are categorized as urban area, of which approximately 65% are residential. The total roof area as seen above the canopy comprises about 19% of the urban area (about 106 km^2), total paved surfaces (roads, parking areas, sidewalks) comprise 30% (about 170 km^2), and total vegetated area about 41% (230 km^2) (see **Figure 13b**). The actual total roof area as seen under the canopy comprises about 22% of the urban area (about 120 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) comprise 36% (about 200 km^2), and total vegetated area (only grass and bushes) about 33% (180 km^2) (see **Figure 13c**).

The potential for additional urban vegetation in Salt Lake City is large. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, and 30% of parking areas, they would add up to about an additional 13% tree cover for the entire city. An additional tree cover of 13% is about 70 km^2 of the urban area. Assuming that an average mature tree can have a horizontal cross-section of about 50 m^2, these calculations suggest a potential for an additional 1.4 million trees in Salt Lake City. As climate and air-quality simulations have indicated, 1.4 million additional trees can have a significant impact on cooling Salt Lake City and improving ozone air quality.

The potential is also very large for increasing the albedo of Salt Lake City. Impermeable surfaces (roofs and pavements) comprise about 49% of the total area of Salt Lake City. For illustration purposes, we calculate potentials for changing the albedo of Salt Lake City, assuming two different scenarios. One scenario assumes a modest change in the albedo of impermeable surfaces; the other assumes an aggressive increase in albedo of all surfaces. These scenarios are summarized in **Table 9**. The resulting change in the albedo of the city is summarized in **Table 10**. Under the low-albedo scenario, the overall residential and commercial albedos change by 0.052 and 0.107 respectively; the average albedo of the city increases by 0.067. For the high-albedo scenario, the overall albedo of residential and commercial areas changes by 0.117 and 0.192, and the average albedo of the city is increased by 0.135. 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 Salt Lake City (and Sacramento) overflights 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 photographs, USGS LU/LC, and satellite/aircraft data such as ATLAS or AVHRR.

Based on the studies performed for Salt Lake City and Sacramento, it is estimated that in cities the size of Salt Lake City and Sacramento between 10 and 50 km^2 of aerial photography would suffice. At a rate of $140–200 per km^2, the total cost of the flight and data would amount to about $7,000–10,000. For small data selections the per-km^2 price given here is not applicable because of fixed costs associated with overflights.

The companies that perform this type of data collection are flexible in dealing with and designing flight paths and selecting flight times. This permits better planning of the flight track and its timing, minimizing shadows and focusing 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 aspects.

Apart from the 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, the 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 the 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 LU/LC categories. We performed an analysis of this source of error using imagery from one of the areas acquired in the Salt Lake City flight. Appendix A discusses the details of this analysis and quantifies the magnitude of error for extrapolation. In addition to these two sources of error, potential errors relate to the accuracy of USGS LU/LC data are not addressed in this report. Finally, USGS data are older than aerial orthophotos, possibly introducing discrepancies between USGS data and aerial orthophotos.

Table 6 USGS LU/LC description for urban area and related observed land-use categories (OLUC).

USGS LU/LC	Description	OLUC Included
11	Residential	A2, A4, A6, A8
12	Commercial/Service	A1, A3, A7
13	Industrial	A5
14	Transportation/Communications	
15	Industrial and Commercial	A3, A5
16	Mixed Urban or Built-Up Land	A9
17	Other Mixed Urban or Built-Up Land	A7

Table 7 Calculated surface area percentages by USGS LU/LC categories.

USGS LU/LC	Tree Cover	Roof	Road	Side-walk	Parking Area	Barren Land	Grass	Misc.
11	20.5	19.7	12.3	10.8	2.2	5.8	26.1	2.7
12	10.4	19.5	16.8	4.0	25.7	7.8	13.8	1.9
13	2.0	19.1	13.8	0.3	29.4	10.1	22.9	2.5
14								
15	2.0	21.1	14.7	2.2	32.5	6.2	19.9	1.7
16	16.5	21.5	20.7	2.7	11.4	2.7	23.1	1.6
17	18.5	12.9	10.2	3.6	15.2	15.5	22.3	1.8

Table 8 Total surface areas (km^2) in metropolitan Salt Lake City (by Category).

USGS LU/LC	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.	Total
11	75.5	72.5	45.3	39.8	8.1	21.4	96.1	9.9	368.6
12	9.7	18.3	15.7	3.7	24.1	7.3	12.9	1.8	93.5
13	0.6	5.7	4.1	0.9	8.7	3.0	6.8	0.7	30.5
14									
15									
16	1.9	2.5	2.4	0.3	1.3	0.3	2.7	0.2	11.6
17	10.8	7.5	6.0	2.1	8.9	9.1	13.0	1.1	58.5
Total Urban Area									
	98.5	106.5	73.5	46.8	51.1	41.1	131.5	13.7	562.7
Total Urban and Non-Urban Area Simulated									**8977.5**

Table 9 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 10. Net change in the albedo of Salt Lake City for high- and low-albedo scenarios.

Area	High-Albedo Scenario	Low-Albedo Scenario
Residential	0.117	0.052
Commercial/Service	0.192	0.107
Industrial	0.185	0.103
Transportation/Communications		
Industrial and Commercial	0.207	0.115
Mixed Urban or Built-Up Land	0.172	0.094
Other Mixed Urban or Built-Up Land	0.122	0.068
Average over the Entire Area	0.135	0.067

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 characterize accurately the makeup of various urban surfaces. Of particular importance is the characterization of the area fraction of various surface-types and vegetative fraction. In this report, a method for developing data on surface-type distribution and city-fabric makeup (percentage of various surface-types) using aerial color photography is discussed. We devised a semi-automatic Monte-Carlo method to sample the data and visually identify the surface-type for each pixel. The color aerial orthophotos for Salt Lake City covered a total of about 34 km^2 (13 mi^2). At 0.5-m resolution, approximately $1.4x10^8$ pixels of data were available for analysis.

Results from this analysis suggest several possible land-use and surface-type classifications for the Salt Lake City area. We examined four major land-use types: 1) commercial, 2) industrial, 3) university-related, and 4) residential. 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 the area distributions.

In the commercial area of downtown Salt Lake City, a top-down view (above the canopy) shows that vegetation covers 13% of the area, whereas roofs cover 23% and paved surfaces (roads, parking areas, and sidewalks) 55%. The under-the-canopy fabric consists of 65% paved surfaces, 24% roofs, and 3% grass. In the industrial areas, vegetation covers 25% of the area, whereas roofs cover 19%, and paved surfaces 46%. The surface-type percentages in the new commercial area were 19% trees, 23% roofs, and 55% paved surfaces. Residential areas exhibit a wide range of percentages among their various surface-types. On the average, vegetation covers about 46% of the area (ranging from 44 to 52%), roofs about 20% (15–24%), and paved surfaces about 25% (21–27%). For the most part, trees shade the streets, parking lots, grass, and sidewalks. Under the canopy, the percentage of paved surfaces is significantly higher. In most non-residential areas, paved surfaces cover 25–37% of the area. In residential areas, paved surfaces cover an average of about 32% of the area.

Land-use/land-cover (LU/LC) data from the USGS was used to extrapolate these results from neighborhood scales to metropolitan Salt Lake City. For an area of roughly 560 km^2, including most of metropolitan Salt Lake City, about 65% is residential. The total roof area as seen above the canopy comprises about 19% of the urban area (about 106 km^2), total paved surfaces (roads, parking areas, sidewalks) comprise 30% (about 170 km^2), and total vegetated area about 41% (230 km^2). The actual total roof area as seen under the canopy is about 22% (about 120 km^2), total paved surfaces (roads, parking areas, sidewalks, and private surfaces) 36% (about 200 km^2), and total vegetated area (only grass and bushes) about 33% (180 km^2).

The potential is large for additional urban vegetation in Salt Lake City. If we assume that trees can potentially shade 20% of the roof area, 20% of roads, 50% of sidewalks, and 30% of parking areas, they would add up to about 13% in additional tree cover for the entire city. An additional tree cover of 13% amounts to about 70 km^2 of the urban area. Assuming that an average mature tree can have a horizontal cross-section of about 50 m^2, these calculations suggest potential for 1.4 million additional trees in Salt Lake City. As climate and air-quality simulations have indicated, 1.4 million additional trees can have a significant impact on cooling Salt Lake City and improving ozone air quality.

The potential is also very large for increasing the albedo for Salt Lake City. Impermeable surfaces (roofs and pavements) comprise about 49% of the total area of Salt Lake City. For illustration proposes, if we assume that the albedo of residential roofs can increase by 0.10, commercial roofs by 0.20, roads and parking areas by 0.15, and sidewalks by 0.10, the albedo of Salt Lake City can then be increased by about 0.07. Like urban vegetation, increasing albedo would reduce ambient temperatures and in turn reduce ozone concentration in the city.

In Salt Lake City, there is a significant variation in the fabric of the neighborhoods selected for this analysis. Although an attempt was 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 construction (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 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 Chicago, Houston, and Baton Rouge, and to compare the results of this analysis with those obtained in the previous study of Sacramento, California.

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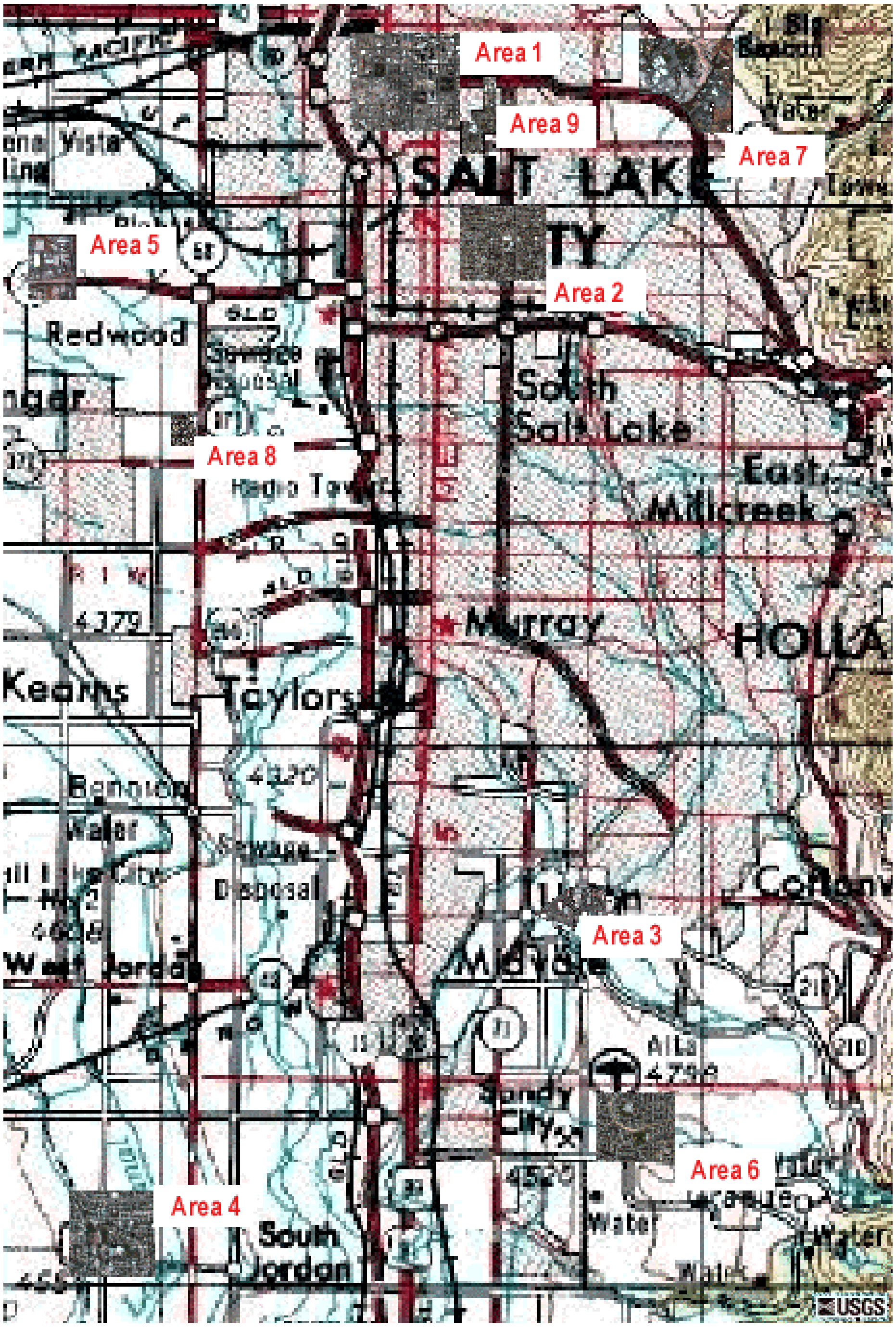


Figure 1 Digital aerial orthophotos taken for analysis in the Salt Lake City metropolitan area, overlaid on a map.

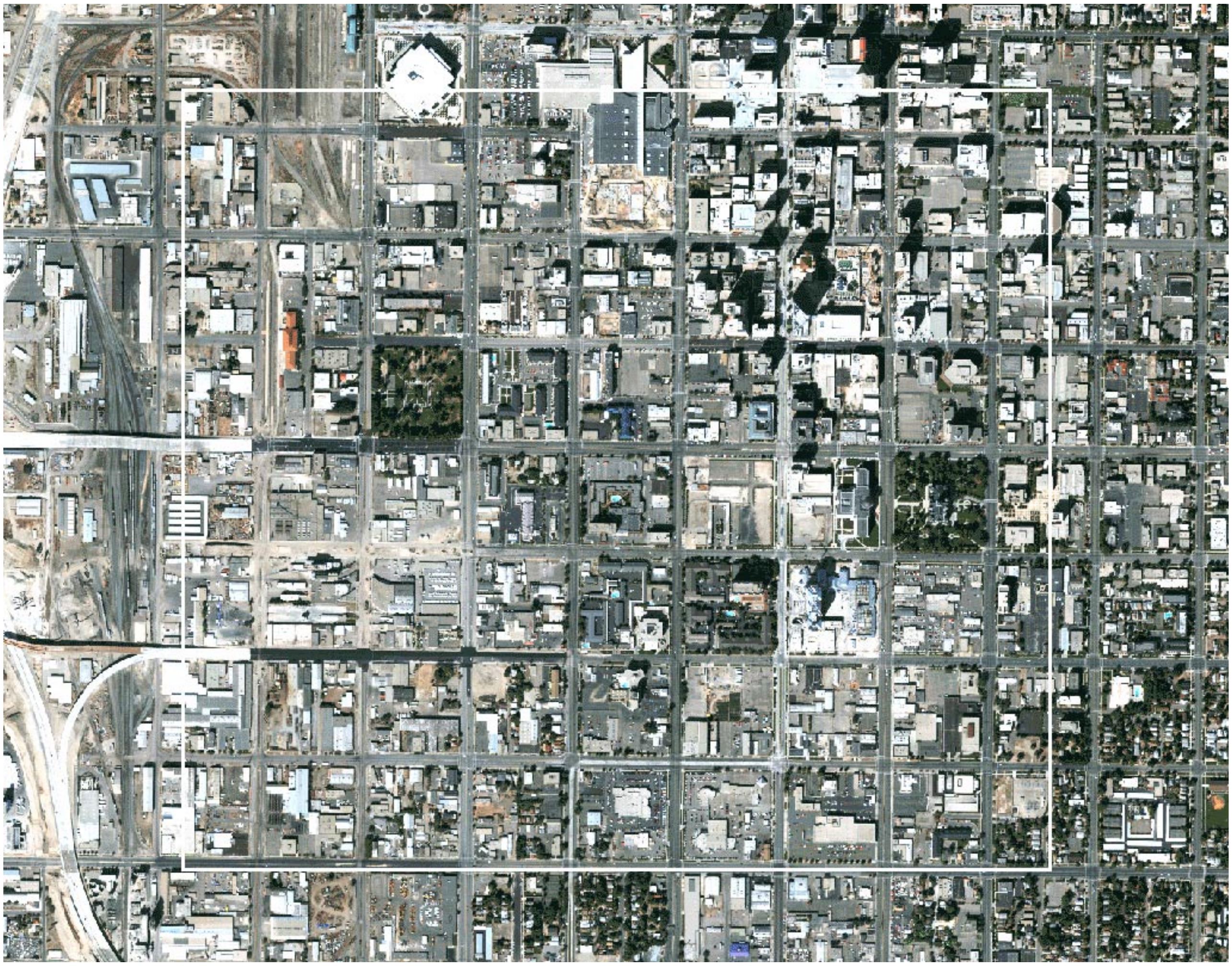


Figure 2 Aerial orthophoto of Downtown Commercial area in Salt Lake City.

Figure 3 Aerial orthophoto of Downtown Mixed-Use area in Salt Lake City.

Figure 4 Aerial orthophoto of an Industrial area in Salt Lake City.

Figure 5 Aerial orthophoto of New Commercial area in Salt Lake City.

Figure 6 Aerial orthophoto of University area in Salt Lake City.

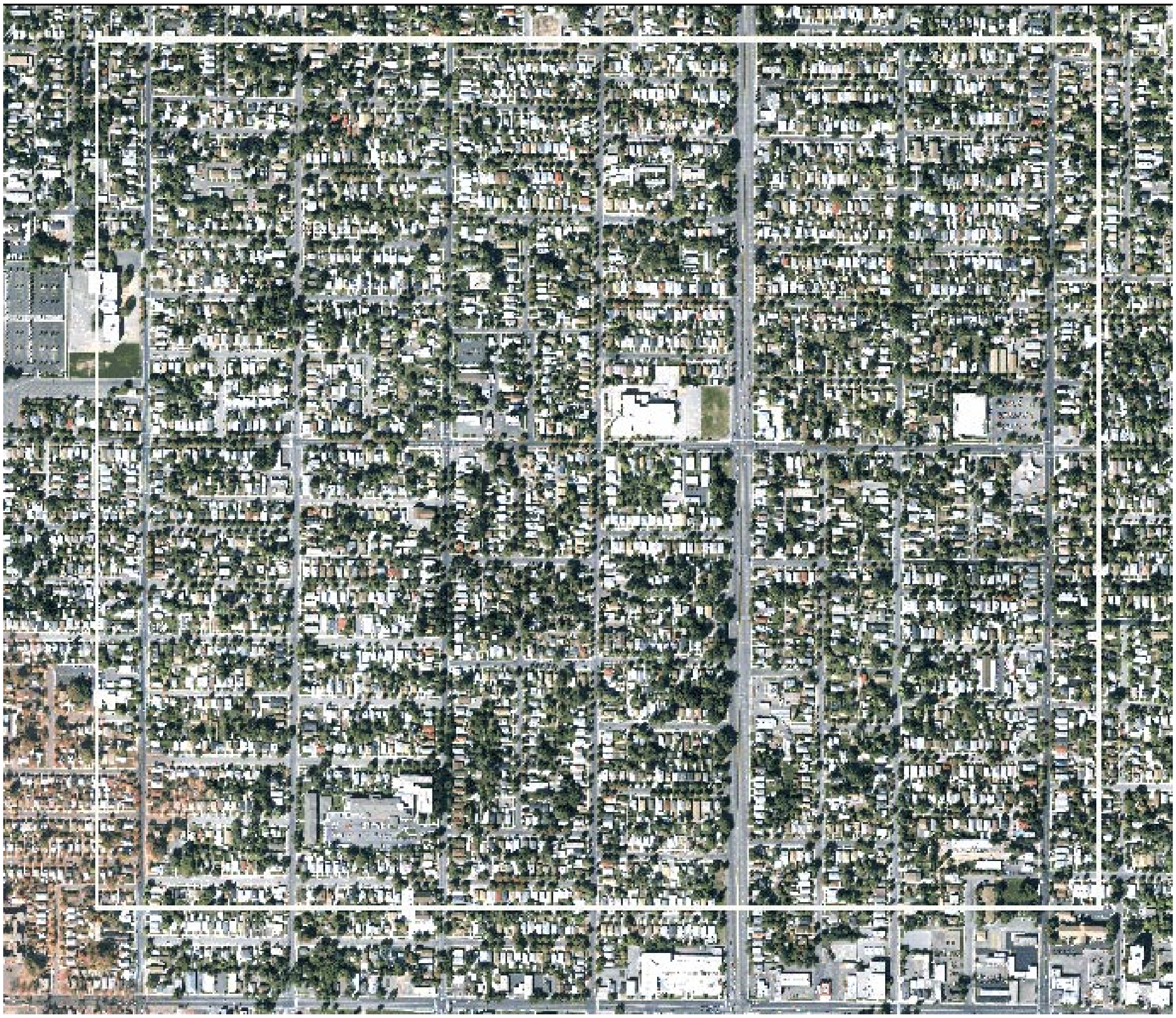


Figure 7 Aerial orthophoto of an Old Residential area in Salt Lake City.

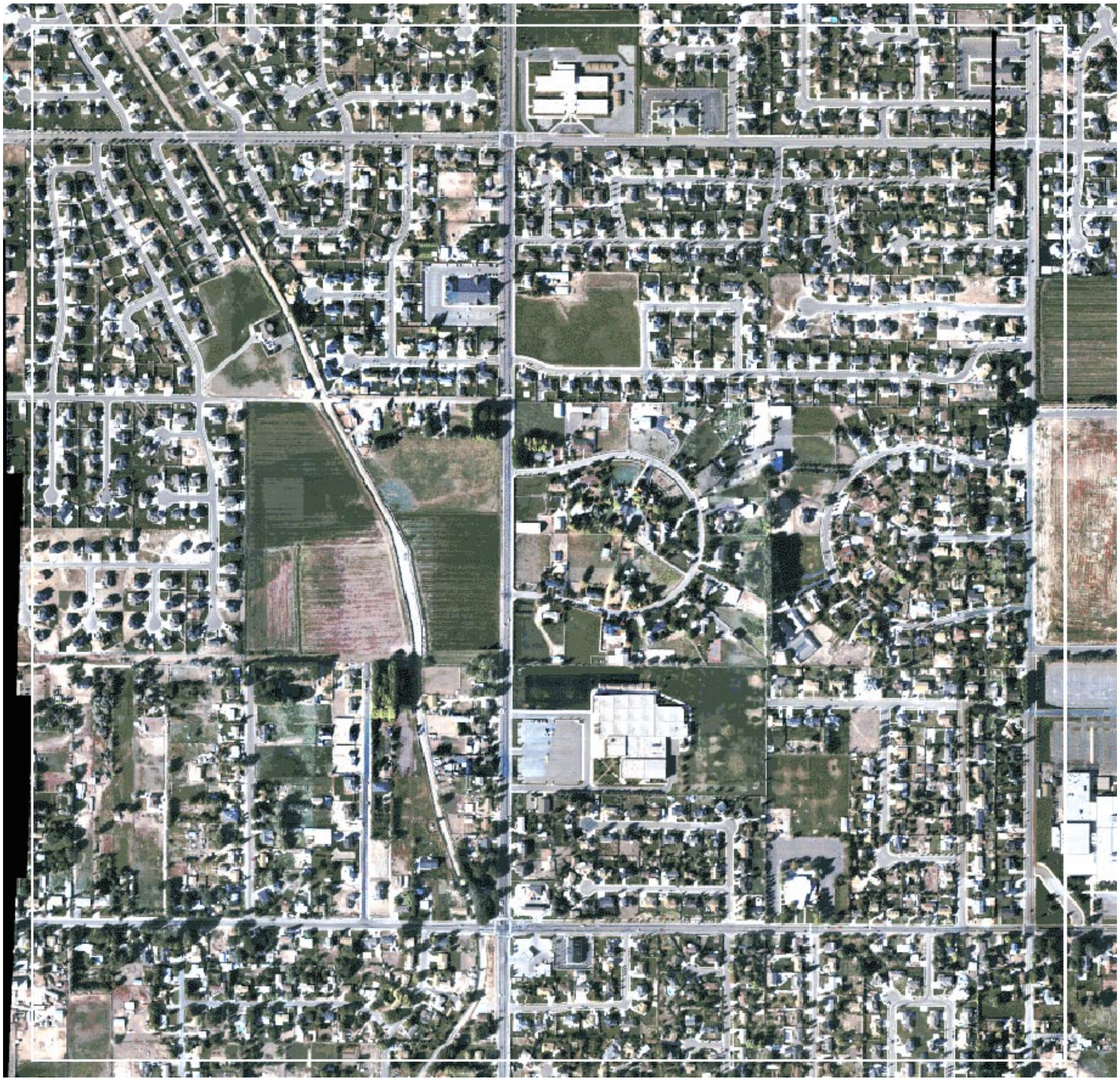


Figure 8 Aerial orthophoto of a Low-Density Residential area in Salt Lake City.

Figure 9 Aerial orthophoto of a Medium-Density Residential area in Salt Lake City.

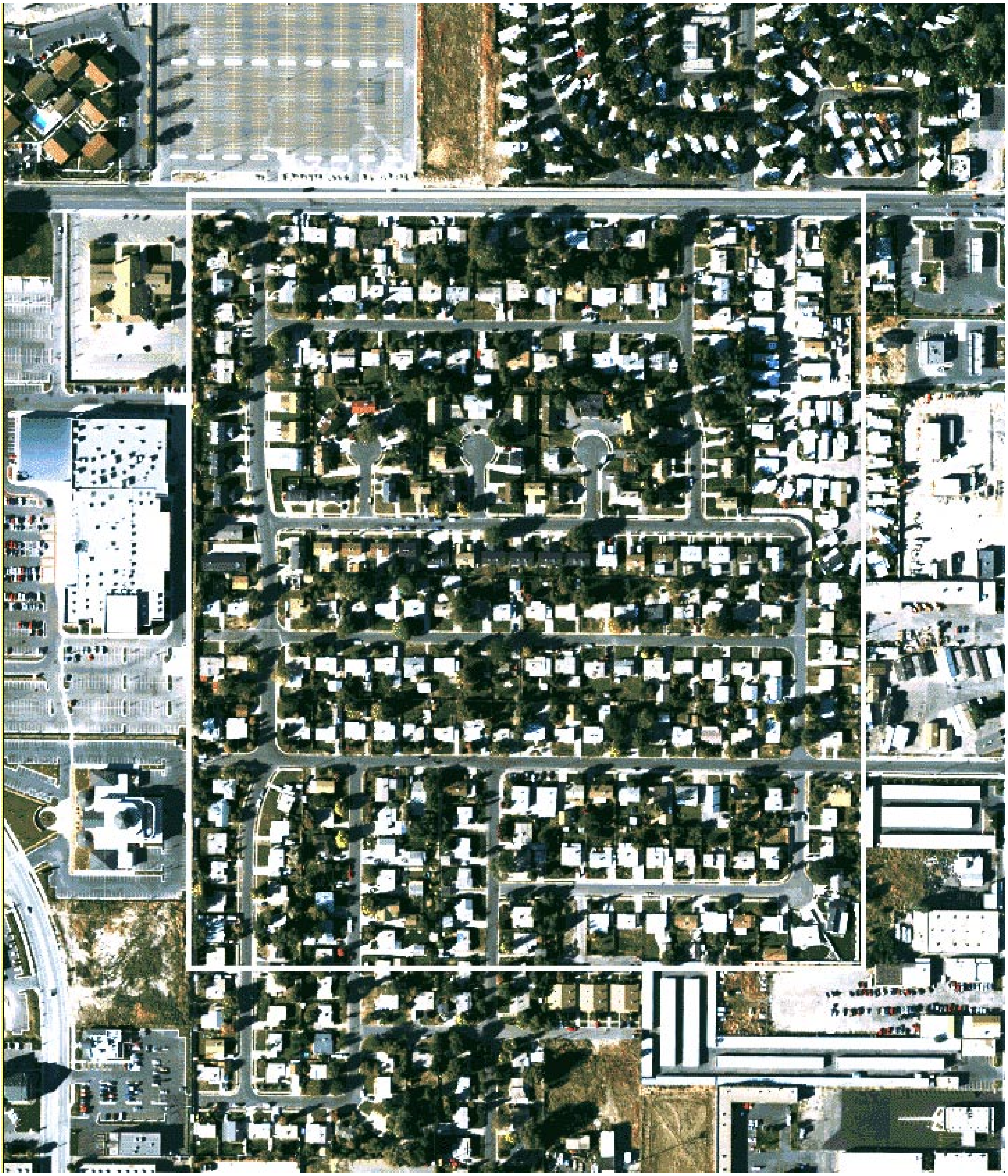


Figure 10 Aerial orthophoto of a Newer Residential area in Salt Lake City.

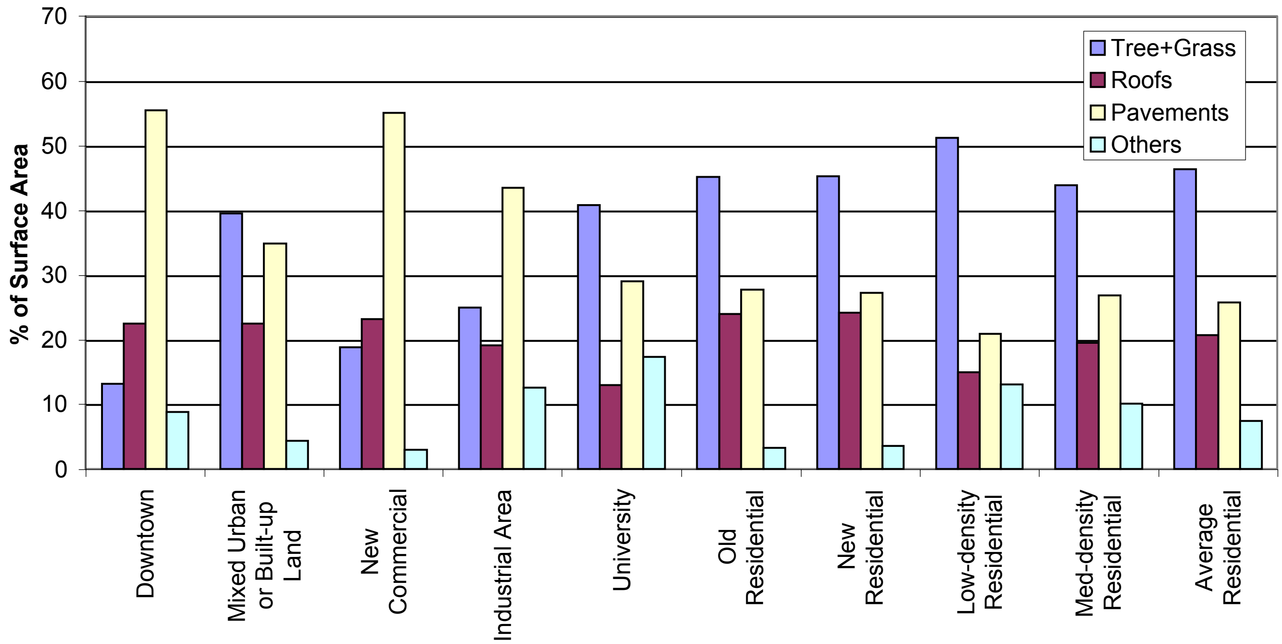


Figure 11 Above-the-canopy fabric of Salt Lake City, Utah.

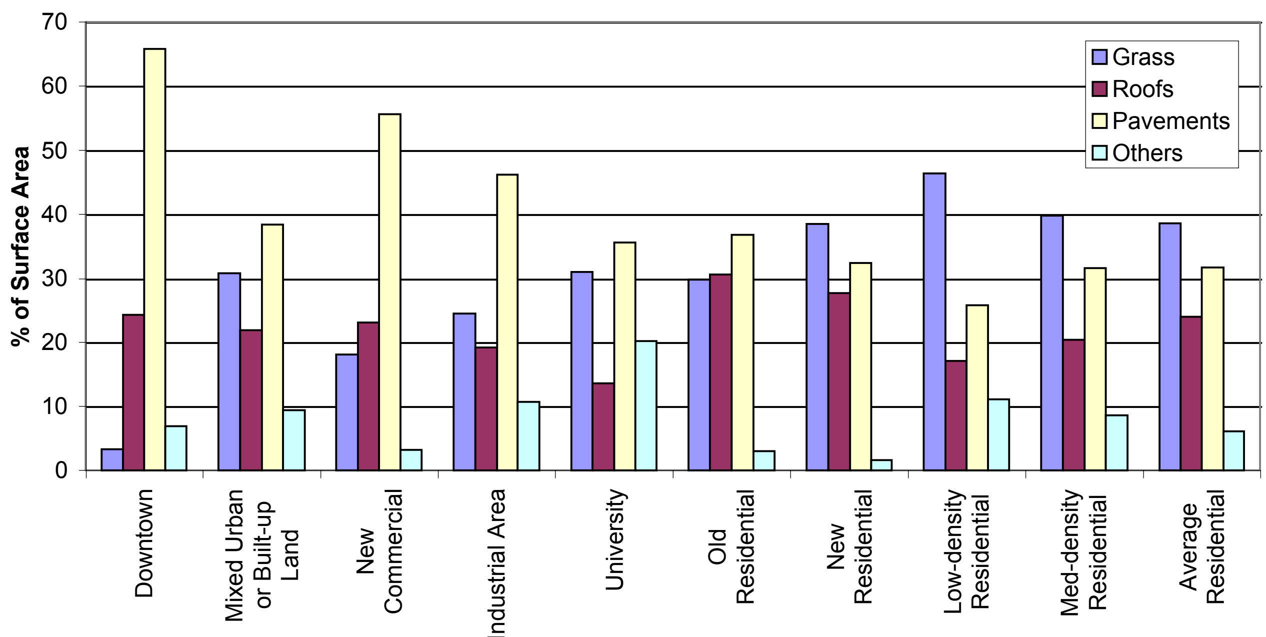


Figure 12 Under-the-canopy view of Salt Lake City, Utah.

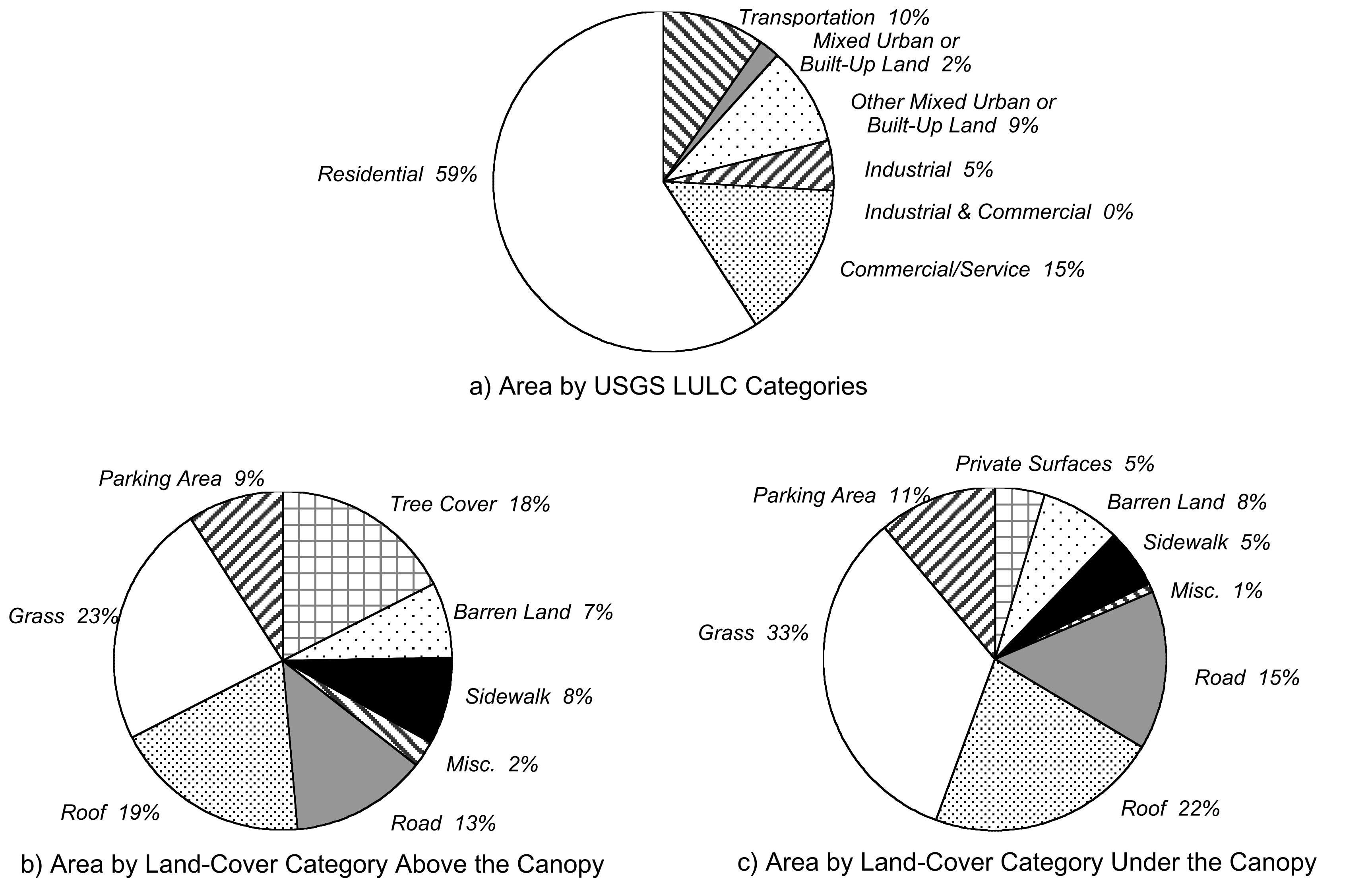


Figure 13 Land-use/land-cover of the entire developed area of Salt Lake City, Utah.

Appendix A
An Analysis of Potential Sources of Error in Extrapolating the Fabric Data to an Entire Metropolitan Area

Using imagery acquired from one of the areas in the Salt Lake City overflight, a study was performed of methods of extrapolation from small-scale, city-fabric data to larger areas to quantify sources of error in extrapolating the fabric data from the analysis of aerial orthophotos to the entire metropolitan area. In this analysis, a large set of random points (1000) was generated over an entire flight area, regardless of the specific land-uses it contained. The fraction of different land-uses were obtained using a Monte Carlo statistical analysis. The selected area contained several distinct land-uses (**Figure A.1**). The land-uses in the area were identified as single-family residential, multi-family residential, and commercial (**Figure A.2**). Then three independent sets of random samples were generated to characterize each area independently. Finally, the results for each of the land-uses were weighted according to their geographic coverage to generate results for the entire area. **Table A.1** compares the fabric results from the extrapolation method and the direct analysis of the entire area.

The results obtained agree fairly well for most surface types. The largest percentage of error occurs with the Barren Land and Vegetative (grass and tree) categories. The data suggest that significant errors occur in the identification of natural features as a result of the complexity of natural features both in their actual shapes and in their health. Errors occur in the tree-cover category because of the irregular shapes and complex structure of trees and their shades. A pixel is difficult to identify, for example, when it is situated on the fringe of a forested area or at the edge of a tree. In determining whether vegetation is dry, barren, or healthy, the near-infrared band is used in addition to the three visible bands. Even with the near-infrared band a determination is still more subjective than identifying a man-made feature. The average NDVI[1] (Normalized Difference Vegetation Index) of the area can be determined by taking advantage of the near-infrared and red bands of the data. This well-established calculation gives insight into the characteristics of vegetation in an area.

[1] The Normalized Difference Vegetation Index (NDVI) is a vegetation index that uses the light reflected in the near-infrared and visible bands of light to measure vegetative quantity. It is calculated as (Near Infrared Band -Visible Band) / (Near Infrared Band +Visible Band).

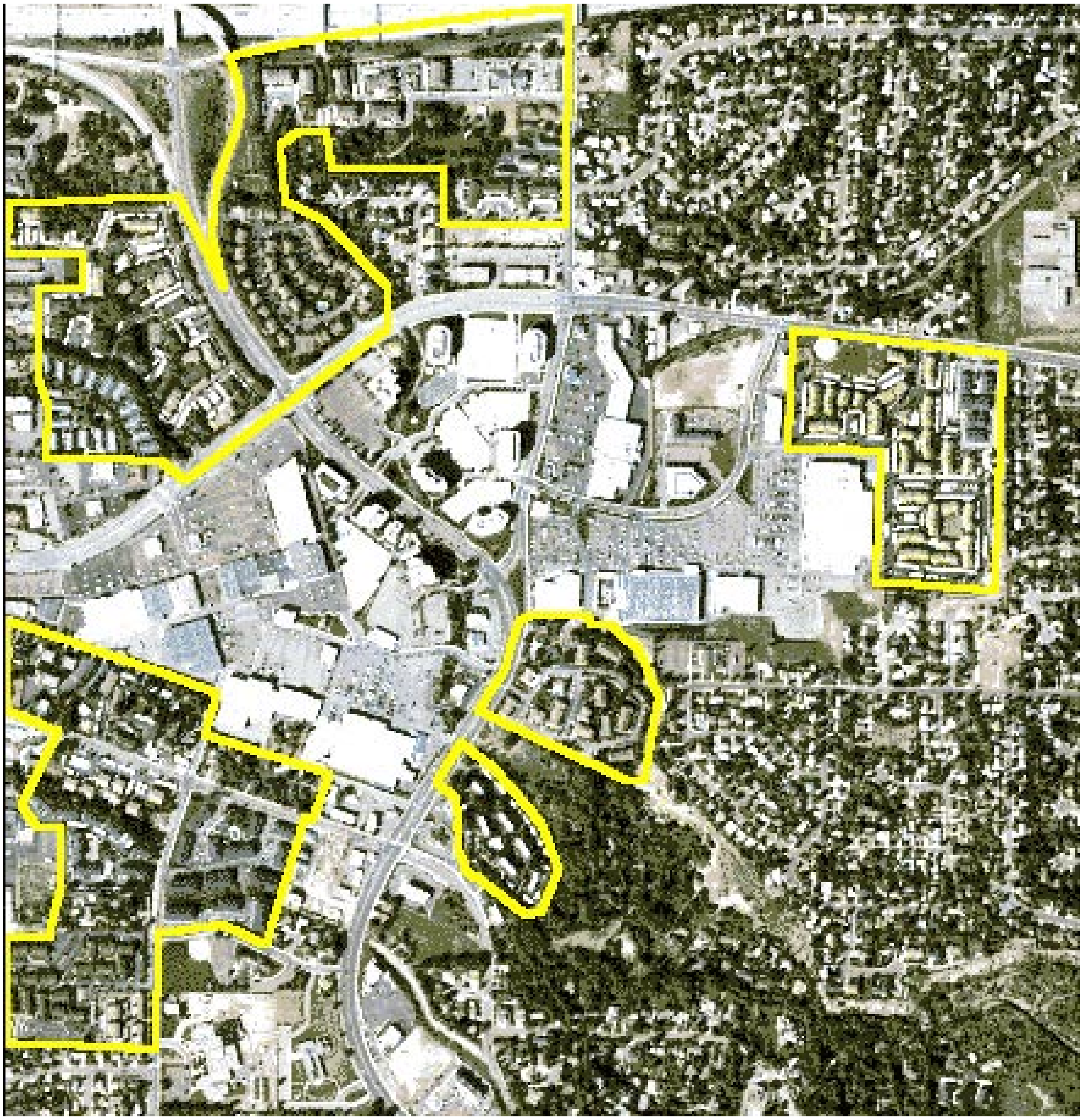
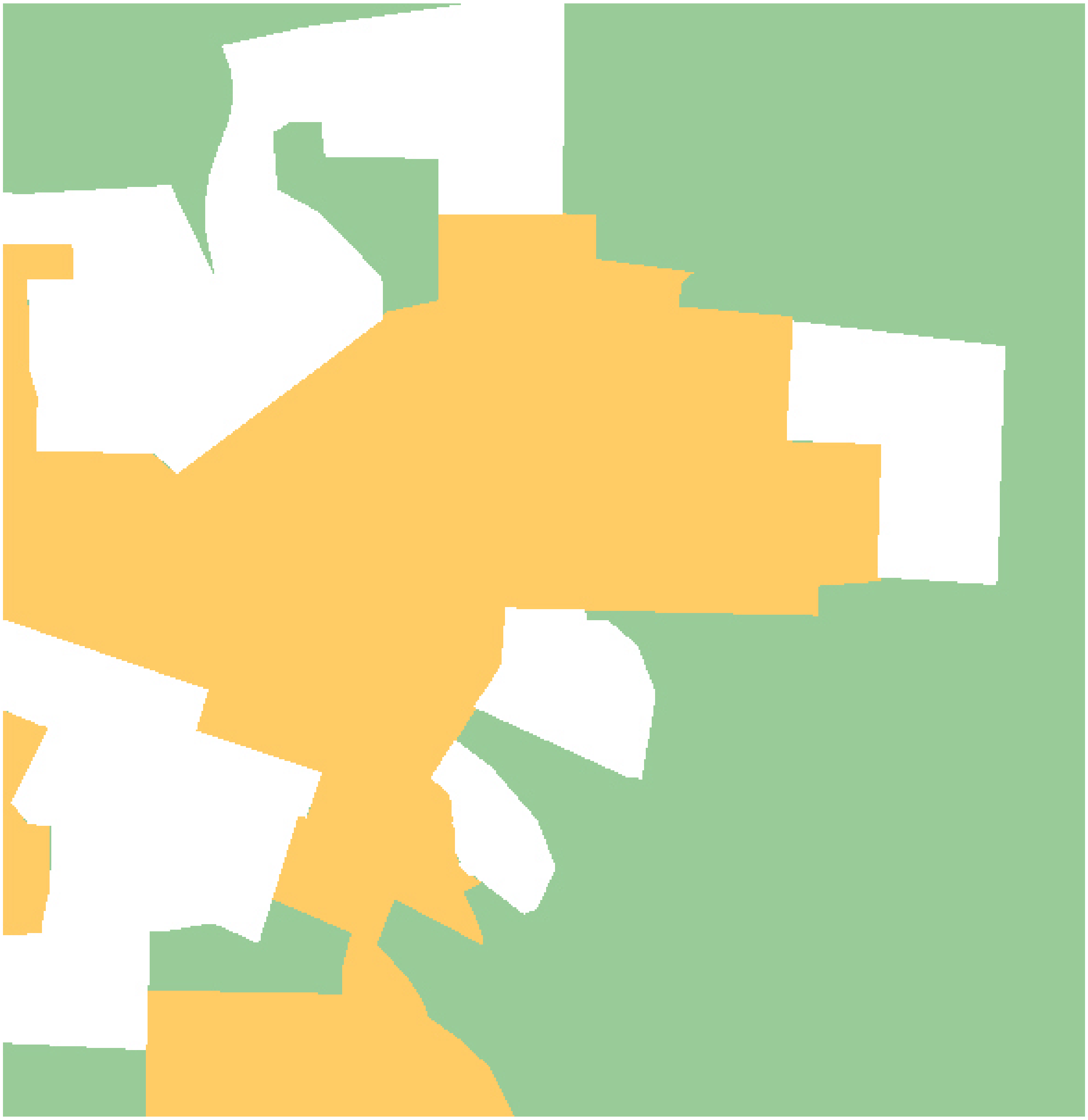


Figure A.1 Multi-land-use area selected for analysis of extrapolation errors.



Key
Green = Single-Family Residential
White = Multi-Family Residential
Brown = Commercial

Figure A.2 Land-use map created for the analysis of extrapolation errors.

Table A.1 Comparison of calculated area percentages obtained by extrapolation and by direct analysis of the entire data set.

Land-use	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.
Under the Canopy								
Multi-Family Residential	21.6	3.4	7.5	20.8	33.2	7.0	6.2	0.3
Single-Family Residential	11.3	0.5	13.9	2.1	53.2	10.8	4.4	3.9
Commercial	20.6	3.2	13.5	34.1	17.5	7.9	2.4	0.8
Weighted Average	16.5	2.0	12.3	15.9	37.9	9.1	4.2	2.1
Entire Area	16.4	1.9	12.8	15.6	35.8	13.5	1.5	2.7
Difference	–0.1	–0.1	0.5	–0.3	–2.2	4.4	–2.8	0.5
Above the Canopy								
Land-use	Tree Cover	Roof	Road	Sidewalk	Parking Area	Barren Land	Grass	Misc.
Multi-Family Residential	15.3	21.0	7.3	3.1	19.5	7.0	25.2	1.6
Single-Family Residential	23.9	11.1	12.6	3.6	2.1	10.0	35.2	1.5
Commercial	6.1	20.6	13.5	3.2	31.7	7.9	14.3	2.6
Weighted Average	16.6	16.2	11.6	3.4	14.9	8.7	26.7	1.9
Entire Area	13.1	16.1	12.6	4.5	14.7	12.2	25.6	1.2
Difference	–3.5	–0.1	1.0	1.1	–0.3	3.5	–1.0	–0.7

Appendix B

An Analysis of Characteristics of Residential Neighborhoods Using Census Data

By examining land-cover data in combination with census housing data it is possible to determine characteristics of individual lots in a neighborhood. Also, other information, such as the age of the houses can be used to estimate when roof repair or replacement might be needed, thus making implementation of albedo increases more effective. Using the imagery of the neighborhoods it is possible to count the actual number of buildings in a given area. By comparing the number of buildings with the number of Housing Units, some of the characteristics of residences in the area can be determined. As census data only includes housing units, whenever a storage building or garage is separate from a home on the same lot, only one building is counted.

1 Old Residential (A2)

There are six census block groups that cover the selected area (Table B.1). While these six block groups cover an area slightly larger than the area analyzed (2.4 km^2), they provide general information relevant to the study area because of homogeneity that exists over the entire area (Bureau of the Census 1990). Based on the census data, over half of the housing units in this area were built prior to 1941. The term "Housing Units" does not refer to separate buildings, but only separate living quarters. Therefore, these numbers alone do not give much information about the characteristics of the neighborhood.

Table B.1 Census data for the selected Old Residential area.

Block Group	Housing Units (HU)	HU Built Before 1940	Median Year HU Built	Area (km^2)
490351031-1	583	354	1939	0.41
490351031-2	703	393	1939	0.41
490351032-1	603	279	1941	0.36
490351032-2	711	398	1939	0.39
490351033-3	571	279	1941	0.44
490351034-3	606	326	1939	0.39
Totals	3,777	2,029	N/A	2.4

From aerial orthophotos, we estimated 1,157 residential buildings per km^2 in this Old Residential area. Census data indicate that there are approximately 1,695 Housing Units per km^2. Thus, assuming a mixture of single- and double-story housing units in this area, we estimate that at least 54% of the buildings in this area are single-family homes.

2 Low-Density Residential (A4)

According to 1990 census data, the homes in this area were built primarily during the 1980s. The density of these homes is estimated to be 93 units per km^2 (240 units per mi^2). Thus, since these units are single-family residences, the average lot size should be approximately 10,753 m^2. Based on these data, the average roof area per home in this area should be 1,075 m^2, or about 11,568 ft^2. Since the homes in this area are obviously not that large, it is recognized that the 1990 data are insufficient for a current analysis of this area because of new development over the past ten years.

3 Medium-Density Residential (A6)

Based on census data alone, only about 0.3 percent of the homes in this area were built before 1940; most were developed primarily in the 1970s and 1980s (see Table B.2). The housing density is estimated at 668 units per km^2 (1,731 units per mi^2). These data approximate an average lot to be about 1,498 m^2, making the average roof area 304 m^2 (3,270 ft^2).

Table B.2 Census data for the selected Medium-Density Residential area.

	Housing Units (HU)	HU Built Before 1940	Median Year HU Built	Area (km^2)
49035112608-1	357	0	1980	0.41
49035112608-2	405	0	1981	0.80
49035112608-3	444	0	1973	0.62
49035112608-4	421	5	1976	0.60
Totals	**1,627**	**5**	**N/A**	**2.43**

4 Newer Residential (A8)

The selected area includes only single-family residences. According to census data, 1967 is the median year these houses were built. Since the boundaries of the aerial photo for this area did not correspond well to the borders of any census block group, we did not estimate an average lot size from the census data.