Investigating the Relationship between Rooftop Reflectance and Zoning District in San Jose, California

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ABSTRACT

Urban heat islands are threatening metropolitan areas by impacting energy consumption, public health, and local climate systems. Cool roof systems can help mitigate the intensity of heat islands by providing solutions to these issues. Increasing rooftop surface reflectance reduces the amount of energy absorbed by building materials, thus reducing the amount of heat reradiated to indoor and outdoor environments. California's standards for rooftop reflectance are lenient and un-uniform between building types. The objective of this study is to quantify the mean solar reflectance of rooftops in San Jose, California, and to investigate the relationship between rooftop reflectance and zoning district. I investigated surface reflectance from remotely sensed, high-resolution, multispectral imagery using imagery processing software. The average surface reflectance for 300,000 buildings in San Jose is: 0.13 in red band, 0.13 green band, 0.09 in blue band, 0.18 in near-infrared band. The average nominal rooftop reflectance is 0.13, with about 90% of the rooftops being at, or below, this average. There is a highly significant difference in reflectance between zoning districts, with residential buildings having the lowest reflectance values. The results of this study indicate that San Jose rooftops have problematic surface reflectances, and that an increase to 0.5 (or higher) would provide significant benefits to San Jose. Targeting residential buildings for future policy change would result in the largest benefits to the city. This research directly pertains to increasing the sustainability of large urban areas, providing healthier city environments, and providing justification towards policy change.

KEYWORDS

Cool roofs, urban heat island mitigation, climate change, remotely sensed orthoimagery, GIS

INTRODUCTION

The heating of the Earth has become a major concern to today's global society, as populations and cities continue to grow and expand. Large urban areas contribute to increasing global temperatures because they can absorb large amounts of solar energy in their component construction materials. Cities are significantly hotter than the surrounding rural areas due to an increased amount of absorptive surface area, and dark surfaces such as asphalt. This phenomenon is known as the urban heat island effect (Sathaye et al. 2011). Increased temperatures have undesired effects on the habitability and energy consumption of a city, and can also aggravate local climate conditions (Rosenfeld et al. 1995). In hotter climates, the energy absorbed by a building's rooftop is a major factor that adds to the need for electric space cooling (Konopacki et al. 1999). This temperature increase can be offset by engineering building materials that have a high surface reflectance and can easily discharge absorbed heat (thermal emittance) (Akbari and Levinson 2009). A cool roof system is a prime example of the implementation of reflective surface materials. A cool roof can be a simple light colored paint coating or as sophisticated as thermally selective materials which reflect specific spectral wavelengths. Cool roofs retain low surface temperatures when exposed to the sun, which prevents excess heat from being absorbed and ultimately reradiated back into the building cavity and surrounding city environment. Reducing the amount of heat reradiated by building materials directly reduces indoor and outdoor air temperatures. Cool roofs are a cheap and effective option for mitigating urban heat islands, climate change, and even global warming (Akbari et al. 1997).

The implementation of cool roof systems has numerous benefits. By reducing the heat flow into a building the need for electric space cooling is drastically reduced. Space cooling accounts for nearly 10% of peak urban electric demand in the U.S (Rosenfeld et al. 1995). Nationally cool roofs could save an estimated $850 million in energy use, and reduce peak energy demand by 7.2 gigawatts (Konopacki et al. 1999). This energy savings corresponds to a 6.23 megatonne reduction of CO_2 annually, and could offset the emissions of 1.2 million cars (Akbari and Levinson 2009). Cool roofing systems also alleviate air pollution caused by heat islands (Sathaye et al. 2011). Decreasing urban air temperatures reduces the rates of heat-catalyzed, smog-forming reactions (Rosenfeld et al. 1995), resulting in cleaner, healthier air, as well as providing a more thermally comfortable city (Laaidi et al. 2012). Currently there are few regulatory requirements for buildings to maintain reflectance and thermal emittance values that cool roofs can achieve (Levinson, personal communication). A previous study by J. Jo et al. (2010a) revealed that 70% of the rooftops sampled in his study of Chandler, Arizona could drastically improve their surface reflectance.

California's policy and standards for residential rooftop reflectance are minimal, and the amount of cool roof systems currently installed in California is unknown. Initially proposed residential roof reflectance codes were set low in order to "get a foot in the door" with the intention to increase them in the future (Levinson, personal communication). However, these codes have seen little improvement since their adoption. California's Title 24 code ‘‘Building Energy Efficiency Standards for Residential and NR Buildings’’ does not include "prescriptive requirements for building envelopes" to have a cool roof system (or equivalent reflectance value), although certain building types do have stricter standards than others (Levinson et al. 2005). This allows building owners to not have to install a cool roof system for either new construction or regular maintenance. This is a non-trivial oversight because installing a cool roof system, or increasing rooftop reflectance, is more often a retrofitting process (Levinson et al. 2005). There is also a lack of city-wide building reflectance databases, which could be invaluable to climate modeling and sustainable urban development. Keeping records of urban land cover is important for understanding land-use patterns that have lasting impacts on the environment (Small 2005).

The objective of this study is to quantify the mean solar reflectance of building rooftops in San Jose, California, using remotely sensed data, as well as investigate the relationship between reflectance and zoning districts. What is the average rooftop reflectance for buildings in San Jose, and are there any differences in reflectance values between differing zoning districts? Based on current codes and standards, I hypothesize that commercial buildings with flat roofs will have a higher mean reflectance value than residential building types (Levinson et al. 2005, Sathaye et al. 2011). I also hypothesize that San Jose will have a high frequency of low reflectance rooftops.

METHODS

Study Site

San Jose is located in Santa Clara County (37°20 N, 121°53 W), just below the southern tip of the San Francisco Bay and 45 miles inland from the coast. The city area is 466 km^2 and has a population of roughly 960,000, making it the third largest city in California and tenth largest in the U.S (Wikipedia contributors 2012). Mountains surround San Jose on three sides which shelter the city from rain and maintains an average of 300 days of sunshine annually (Wikipedia contributors 2012). This establishes a semiarid climate, and places San Jose in ASHRAE Climate Zone 4. Summers can be hot and dry with wide diurnal ranges where cooling would be necessary ("The Pacific Energy Center's Guide to: California Climate Zones and Bioclimatic Design" 2006). Winters are can be moderate to low in temperature where heating may be required. These climate conditions make San Jose an exceptional candidate for a rooftop reflectance study site.

Data Collection

I investigated surface reflectance using remotely sensed data collected by North West Geomatics. The dataset is high-spatial resolution (1m), 4-band, California National Agriculture Imagery Program (NAIP) orthoimagery. The four, narrow wavelengths include: red (608–662nm), green (533–587 nm), blue (428-292 nm), and near-infrared (833–887 nm) (Leica 2011). Each pixel in the imagery represents a "reflectance calibrated digital number" (RCDN), which is an amount of light that was returned to the aircraft sensor (Beisl 2010a). A pixel appears white if a higher percent of light has been reflected from the surface material, or black if less light is reflected. The imagery was processed using a bidirectional reflectance distribution function (BRDF) correction. The BRDF correction removes color distortion gradients caused by anisotropy of ground surfaces (Beisl 2010a, Beisl 2010b). I also obtained city-wide building outlines, San Jose city boundary, and municipal zoning district GIS files from the San Jose GIS Department. There are nearly 300,000 building outlines for all of San Jose, and 20 unique zoning districts (Table 1).

Table 1. San Jose Municipal Zoning Districts and reclassifications

Zoning District	Symbol	Reclassification
Agricultural	A	A
Rural Residential Residence (1 Dwelling unit/Acre /5 Acres)	R-1-RR	R
Residence (1 Dwelling unit/Acre)	R-1-1	R
Residence (2 Dwelling unit/Acre)	R-1-2	R
Residence (5 Dwelling unit/Acre)	R-1-5	R
Residence (8 Dwelling unit/Acre)	R-1-8	R
Residence (2 Dwelling unit/Acre)	R-2	R
Residence District (Multiple Unit/Lot)	RM	R
District (Mobile home parks, trailer parks)	R-MH	R
Office Commercial	CO	C
Pedestrian Commercial	CP	C
Neighborhood Commercial	CN	C
General Commercial	CG	C
Industrial Park	IP	I
Light Industrial	LI	I
Heavy Industrial	HI	I
Downtown Primary Commercial	DC	C
Downtown Commercial Neighborhood Transition	DC-NT1	C
Water	WATER	Removed
Open Space	OS	Removed

Analysis

I used GIS software, ArcMap 10.0, to process and analyze the orthoimagery (ESRI 2010). The imagery is divided into individual flightstrips from a composite mosaic for Santa Clara County. I used the San Jose city boundary to spatially select only the flightstrips that intersect with the San Jose city boundary (12 in total) (Figure1). I then loaded all four bands of the imagery, for each flightstrip, into the map layer (Figure 2) and overlaid the building outlines onto the imagery (Figure3). Buildings that were not fully contained by the San Jose city boundary were removed from my analysis.

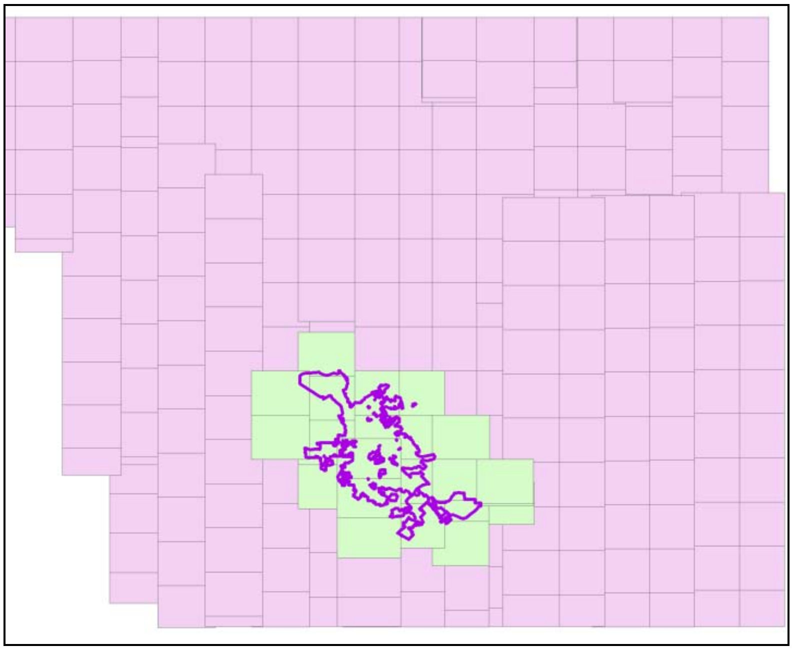

Figure 1. Process for selecting imagery flightstrips specific to San Jose

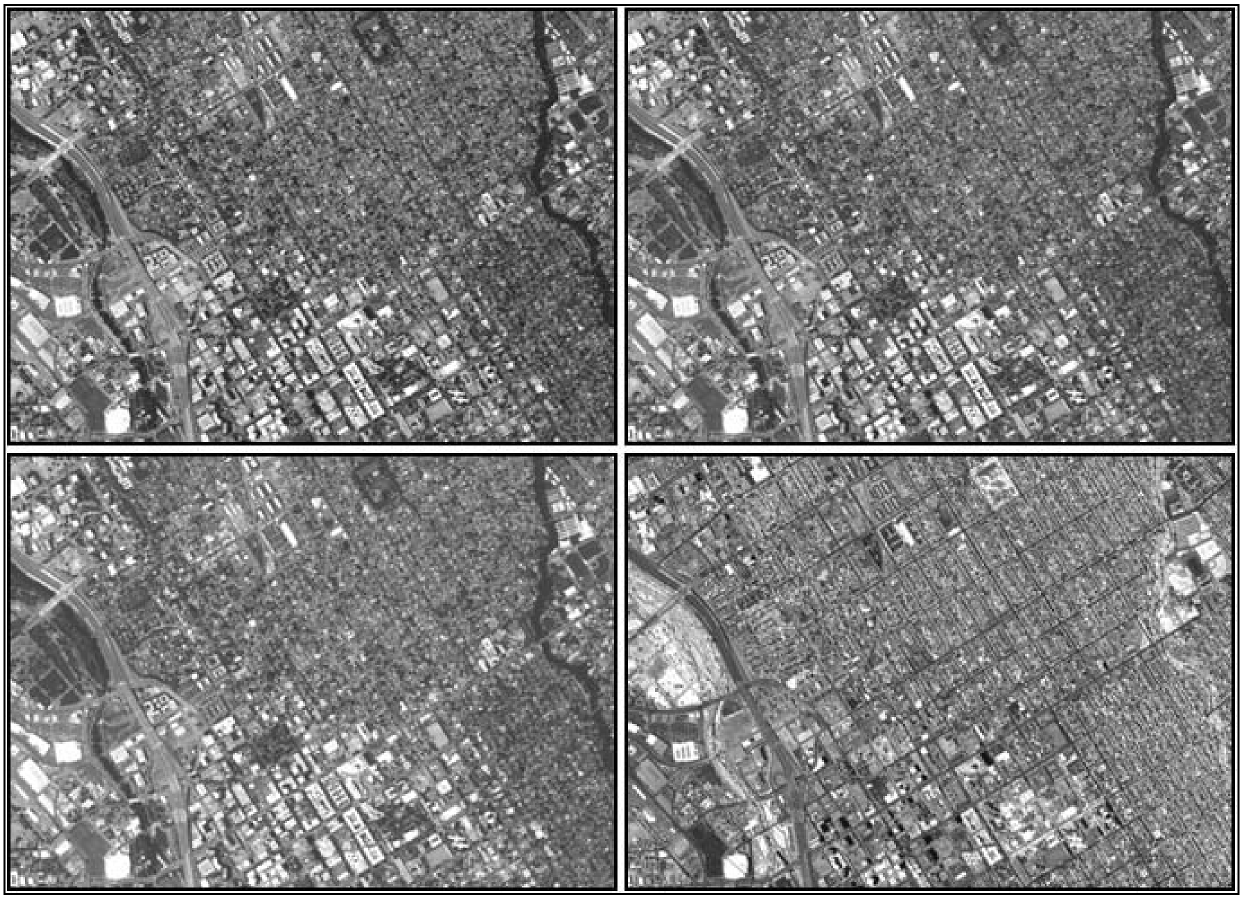

Figure 2. Sample images of each band. Top left: band 1 (red), top right: band 2 (green), bottom left: band 3 (blue), bottom right: band 4 (near-IR).

Figure 3. Sample of San Jose building outline shapefile

I divided the remaining building outlines into groups by their corresponding flightstrip location because analyzing the entire set of building outlines, at once, would require more computing power than I had available (Figure 4). This measure also ensured that every building outline was fully populated with pixels from the corresponding flightstrip and increases calculation accuracy. Lastly, I spatially joined the zoning data to building outlines, which assigned each building a zoning district in which the building was developed.

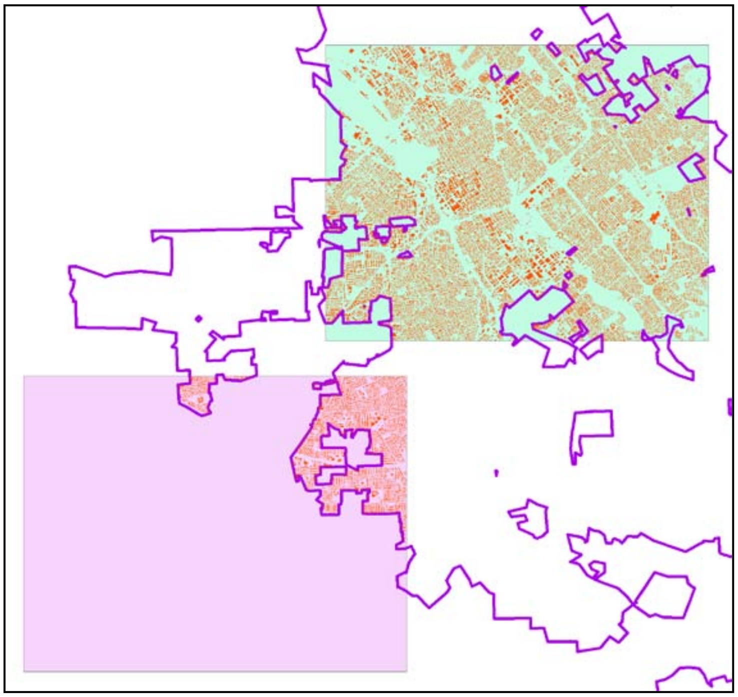

Figure 4. Process for grouping outlines specific to corresponding flightstrip

Using the zonal statistics tool in ArcMap, I calculated the mean surface reflectance for each building rooftop (ESRI 2010). The zonal statistics tool averages all pixels within a building outline and reports the RCDN in each band. The conversion from RCDN to reflectance is found in Equation 1 (Beisl 2010a).

$$Reflectance = RCDN/10,000 \quad (1)$$

I then averaged the reflectance values of all 4 bands to create a nominal, or proxy, surface reflectance. I used this strategy because the narrow bands only encompass small ranges of the total visible and near-IR spectrum, and a true total surface reflectance would only be obtainable through methods beyond the scope of this research (Brest and Goward 1987). Also, all flightstrips contain "edges" of 0 value pixels (black), which is a result of North West Geomatics processing (Figure 5). These values are unrealistic and if a rooftop contained a minimum value of 0, it is removed from the analysis of that flightstrip. This measure is justifiable because all flightstrips overlap at these edges, and roofs removed from one flightstrips analysis are included in the neighboring flightstrips analysis.

Figure 5. Example of black, 0 value edges in imagery.

I reclassified the 20 original zoning districts into four general-use categories (San Jose, California Municipal Code § 20.20- 20.50): residential (R), commercial (C), industrial (I), and agriculture (A) (Table 1). Most zones contained a second entry which included a planned development (PD) symbol appended to the corresponding zone symbol. All zones with a PD symbol were grouped with the counterpart non-PD zone based on the intended territory zone use (San Jose, California Municipal Code § 20.10.070). Buildings in open Space (OS), and water zones were removed from the analysis, as were buildings that lacked zoning information. Using both the nominal reflectance and zoning data, I fit a linear model for reflectance as a function of zoning using R-project (R Development Core Team 2011). I used an analysis of variance to test for significant differences between the zoning re-categorizations. I then used a post-hoc Tukey HSD to test for significant, pair-wise differences in reflectance between zoning types.

RESULTS

Data Summary

The San Jose GIS Department building outline shapefile included approximately 300,000 building outlines, totaling 64 km^2 of rooftop surface area. This rooftop area accounts for 14% of the total surface area of San Jose. The average area of a building outline is 216 m^2. Of the total building outlines not excluded from my analysis, 41 km^2 is residential (63%), 11 km^2 is agriculture (18%), 7 km^2 is industrial (11%), and 3 km^2 is commercial (5%). Figure 6 illustrates the spatial distribution of zoning districts per building.

Each band contains a different range of minimum and maximum RCDN values. These values, when used with Equation 1, provide the reflectance of each pixel (Table 2). The maximum value represents the most reflective rooftop in San Jose, however all maximum values, for each band, are below 20% reflectance.

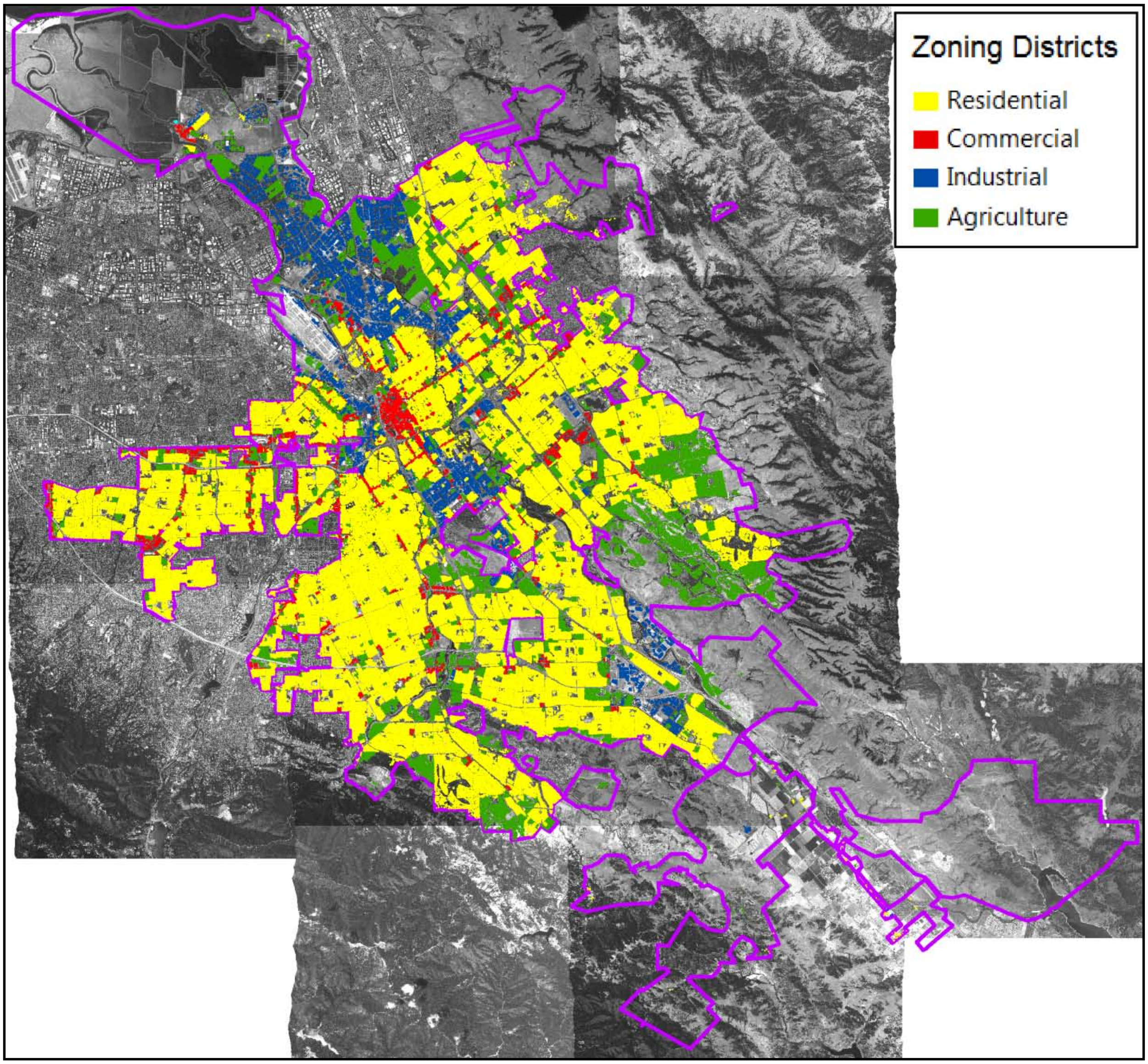

Figure 6. Map of building zoning districts

Table 2. Imagery reflectance ranges

Band	RCDN Range	Max Reflectance
1 (red)	0 - 14966	15%
2 (green)	0 - 18606	19%
3 (blue)	0 - 16302	16%
4 (near-IR)	0 - 15785	16%

Model Results

A mean rooftop reflectance for each of the 4 bands was calculated. The average percentage reflectance for each band is 13%, 13%, 9%, and 18% in band 1, band 2, band 3, and band 4 respectively. Figures 7-10 illustrate the distribution of reflectance values in each of the four bands. The average nominal rooftop reflectance for buildings in San Jose is 0.13 (or 13%) (Figure 11). A cumulative distribution plot for the nominal rooftop reflectance reveals that nearly 90% of all buildings in San Jose have a reflectance value of 13% or less (Figure 12). The map in Figure 13 illustrates the spatial distribution of reflectance using a color gradient (red to blue) of increasing surface albedo.

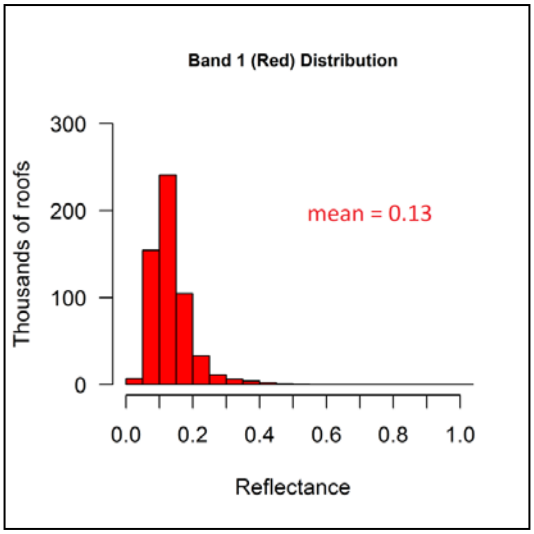

Figure 7. Band 1 reflectance distribution

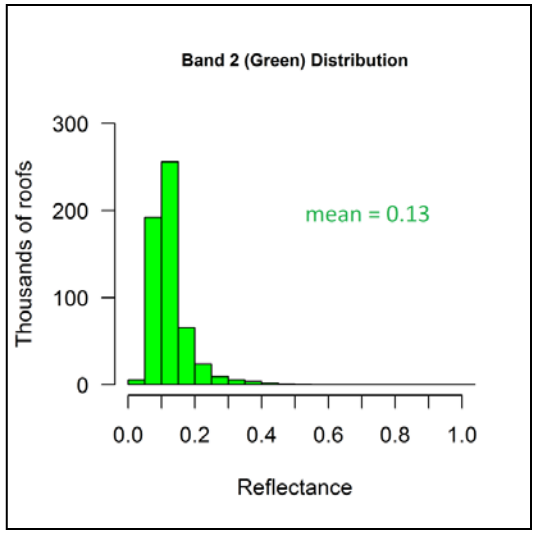

Figure 8. Band 2 reflectance distribution

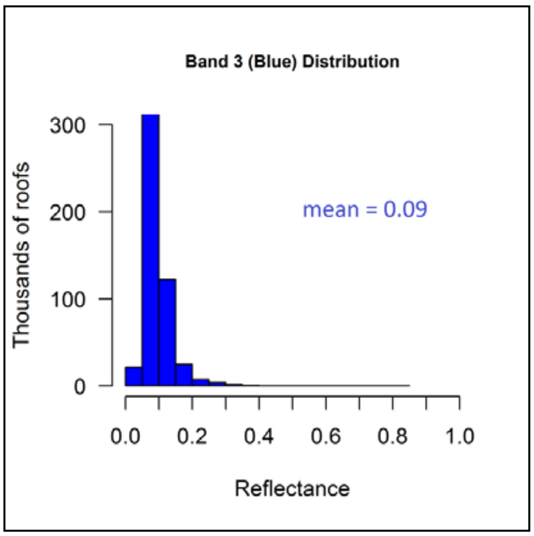

Figure 9. Band 3 reflectance distribution

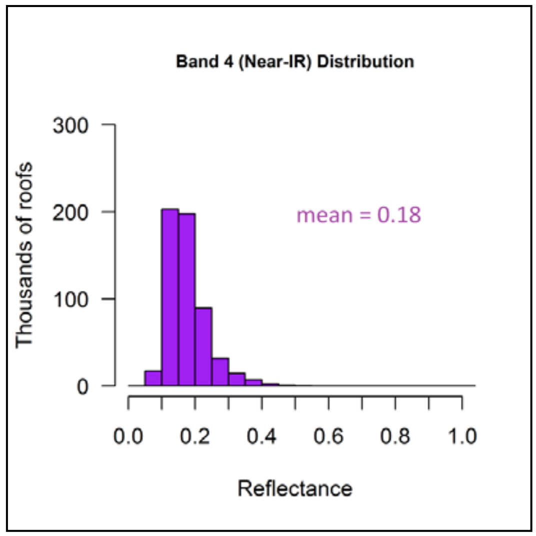

Figure 10. Band 4 reflectance distribution

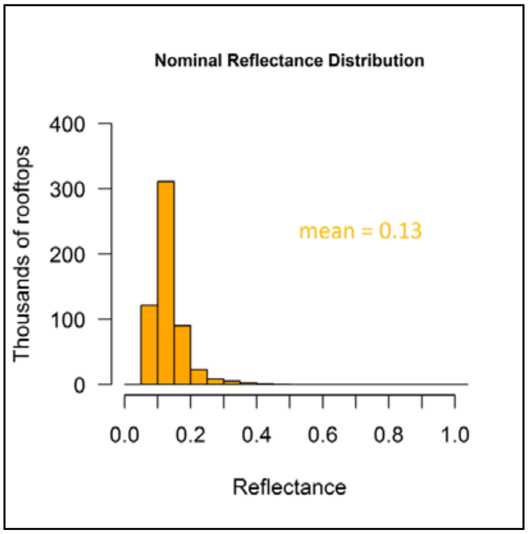

Figure 11. Nominal reflectance distribution

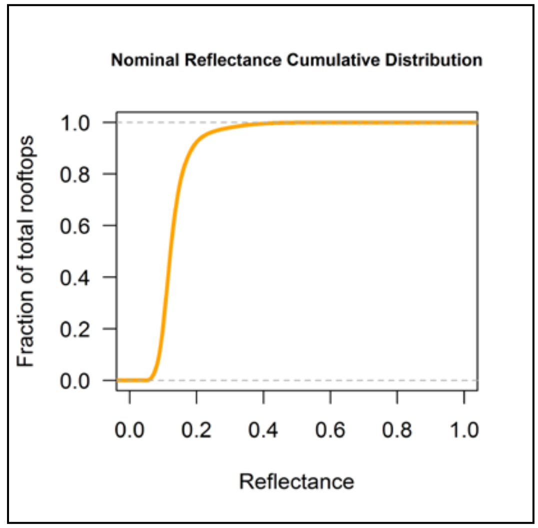

Figure 12. Cumulative distribution of nominal reflectance

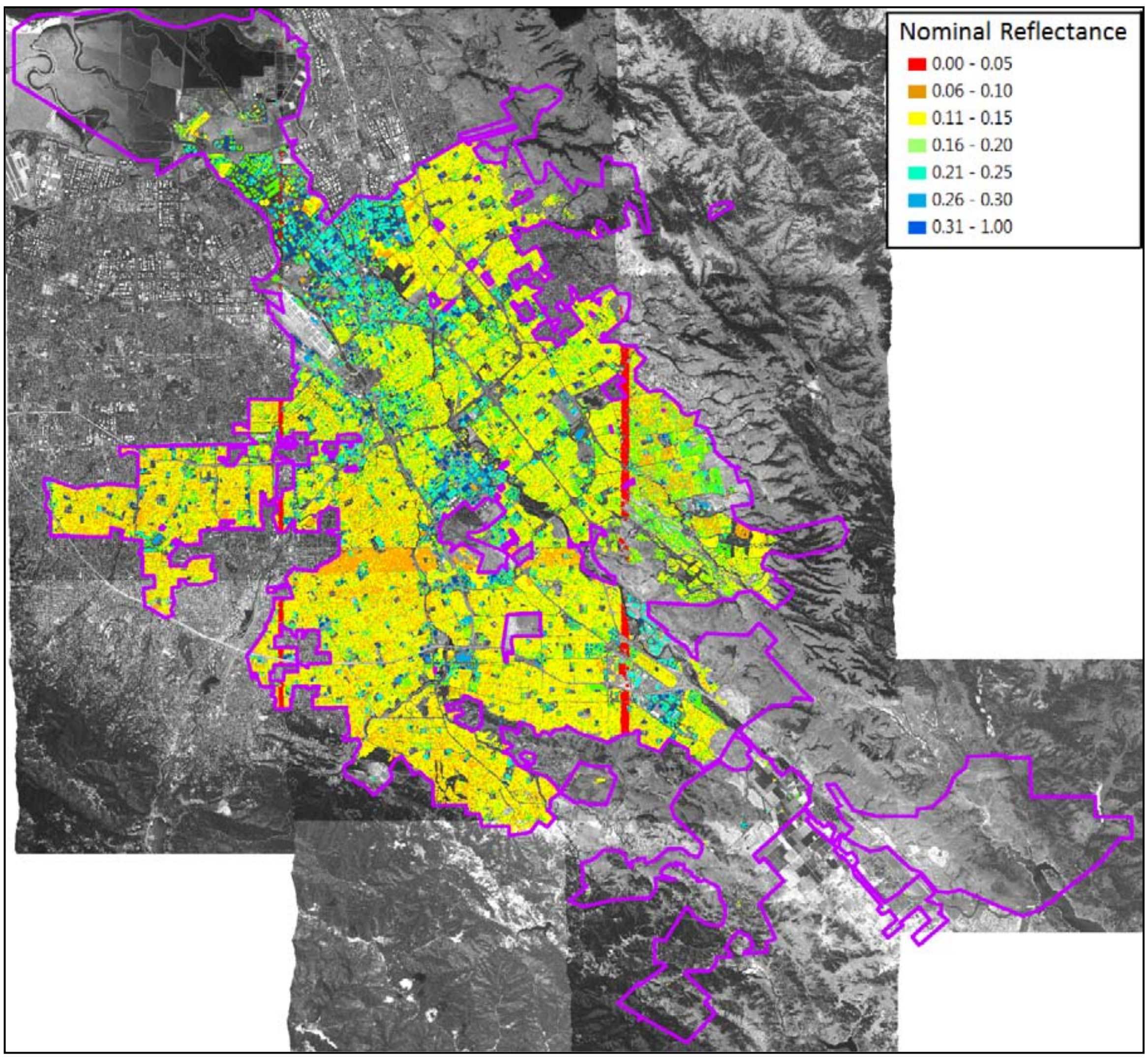

Figure 13. Map of nominal reflectance per building

My linear model for reflectance as a function of zoning type revealed a strong relationship between the two factors. The ANOVA results showed F-value =5847.6, $p = 2.2 \times 10^{-16}$, with 3 degrees of freedom. There was a significant difference between zoning types and reflectance (Figure 14). The results from the Tukey HSD test are outlined in Table 3, and it revealed a highly significant difference in reflectance between all zoning types within a 95% confidence interval.

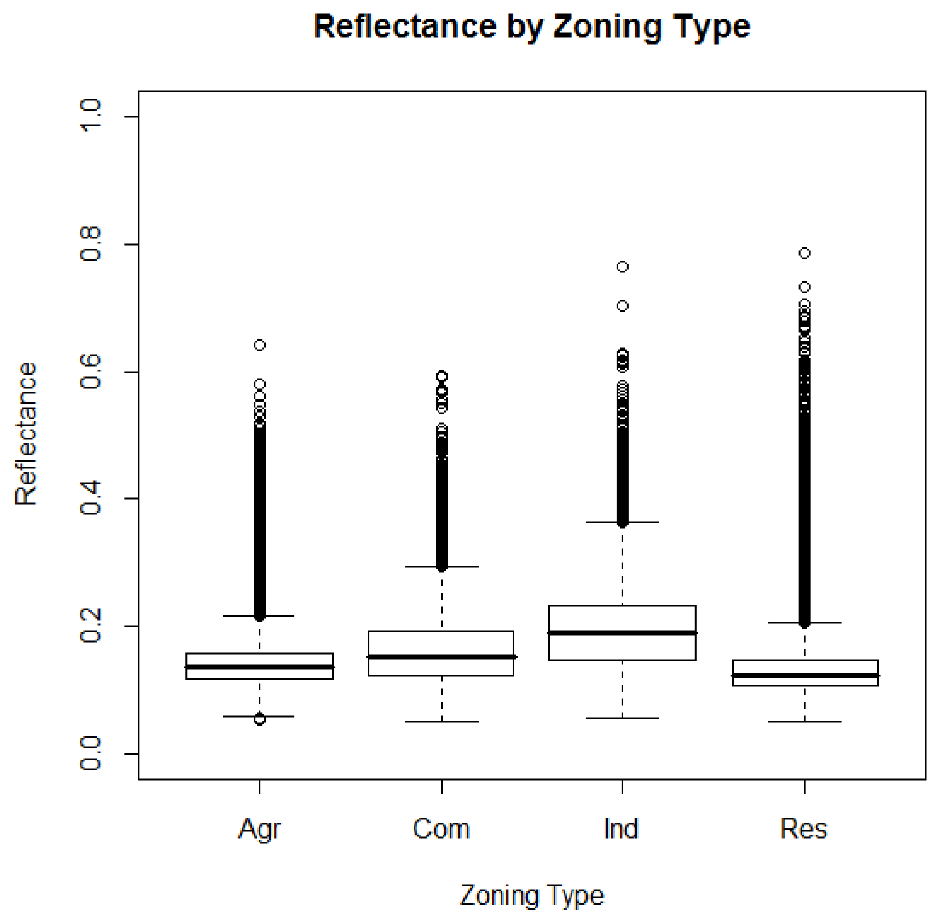

Figure 14. Box and whisker plot of reflectance for each zoning district

Table 3. Post-hoc Tukey HSD results

Zoning types	**Difference in percent reflectance**
Commercial - Agriculture	0.02
Industrial - Agriculture	0.05
Residential - Agriculture	-0.01
Industrial - Commercial	0.03
Residential - Commercial	-0.03
Residential - Industrial	-0.67

DISCUSSION

The high frequency of low reflectance rooftops in San Jose is an environmental, economic, and public health issue that has potential for tremendous improvements. Although this is a case study for one city in California, Akbari and Small promote the implementation of cool roofs nationally and globally because they would help alleviate the stresses caused by urban heat islands (1997; 2005). The solutions to increasing rooftop reflectance are simple and available, yet many cities have not widely adopted this practice (Akbari et al. 2008). The importance of this study is not only to quantify the mean surface reflectance of rooftops, but to emphasize the need for creating and maintaining city-wide building reflectance databases, and focus policy change to zoning districts that would result the largest benefits.

Result Interpretations

The results of this study indicate that San Jose building rooftops have a low average surface reflectance. These results are comparable to other urban reflectance studies that report most U.S and European countries have urban albedo values that range from 0.1 to 0.2 (Taha 1997). An increase in rooftop reflectance from 0.13 (observed) to 0.5 (or higher) would provide significant benefits to the San Jose (Millstein and Menon 2011). With residential buildings accounting for nearly 63% of the buildings in San Jose, improving residential codes and standards would provide the largest economic effects on both the city-wide and individual scale, as well as the greatest overall environmental improvements. Currently standards under California's Title-24 have no minimum value of surface reflectance or thermal emittance (Levinson et al. 2005). Based on my results, residential buildings have the lowest reflectance values, and standards for residential buildings must be raised accordingly. By highlighting the many benefits to residential home owners in terms of energy savings, and short payback period, the government can start trends towards wide scale cool roof adoption through increased standards (Jo et al. 2010a, Jo et al. 2010b).

Unexpectedly there was a relatively small difference between residential and agricultural buildings reflectance. This could mostly be due to the fact that residential buildings are permitted to be built in agriculture zoning districts (San Jose, California Municipal Code § 20.20.100).

Quantifying the amount of buildings that are actually residential homes placed in agricultural zones would be especially difficult given the tools of my research methods. However, the very small reflectance differences between the two zones suggest that a large portion of the buildings categorized as agricultural may be residential buildings. Interestingly many of the other Tukey result differences are near a 5% difference in reflectance, or more. Realistically, a 5-10% change in reflectance could be a substantial increase in reflectance (Ban-Weiss, personal communication). Not unexpected was the very large difference between industrial type buildings compared to residential type buildings. Industrial building codes are stricter in terms of performance.

Economic Benefits

Buildings with higher rooftop reflectance have much lower cooling loads, and contribute less heat to the surrounding environment. By increasing a residential buildings rooftop reflectance to 0.6 (or 60% reflectance), homeowners could reduce annual energy costs by 4.5% (Jo et al. 2010a). This dollar value savings is slightly biased towards hotter, sunnier climates (Akbari et al. 1997). A cool roof will always have less of a cooling load, and reduced electric conditioning costs (Akbari and Levinson 2009). Cool roof systems can also be inexpensive. A white roof coating can range from $1.50 - $2.50, or white roofing membranes can range from $2.75 - $3.75 per square foot. There is a market for commercially available cool roof products, but there are also many simple solutions to creating a more reflective rooftop surface. Construction is typically unnecessary to retrofit a rooftop, where a film or paint coating can be highly effective, thus reducing the cost for installation. The payback period for a cool roof system can be as soon as 7 years after installation (Jo et al. 2010a).

Environmental Benefits

Cool roof systems have shown to be an effective mitigation technique for urban heat islands, reducing outdoor air temperatures and smog forming reactions, as well as energy consumption (Akbari and Levinson 2009). Based on Millenstein and Menons previous work (2011), daily San Jose outdoor air temperature would decrease by approximately 0.22°C in the summer and 0.18 ˚C in the winter if rooftop surface reflectance were increased to 0.6. The same increase in reflectance would offset ~3.3 Gt of Carbon, which corresponds to 175 kg CO_2 per square meter of rooftop area. With rooftops accounting for 64.32 square kilometers of surface area in San Jose, increasing the reflectance of rooftops to 0.6, through the use of cool roof systems, could equate to 11.3 Gt of CO_2 (Millstein and Menon 2011).

Global implementation of this practice would result in a negative radiative forcing on the earth equivalent to offsetting 44 Gt of $C0_2$ emissions (Akbari et al. 2008). This also results in the reduced emission of smog forming air pollutants, such as NO_x and SO_x, from power plants and buildings by reducing the peak demand of electricity (Rosenfeld et al. 1995) . Even a city scale increase in non-residential rooftop reflectivity could result in tremendous improvements to the air quality for public and environmental health (Akbari and Levinson 2009).

Limitations

The sources of data are very limited for this type of research, and much of the data used was collected from differing sources and for different purposes. The rooftop outlines for San Jose, obtained by a local agency, did not align perfectly over the imagery. Although this inaccuracy could be due to the resolution of the imagery, many outlines were not flush with the buildings visually identified, causing pixels that were not rooftop materials to be calculated in my results. Classifying rooftops through object based image analysis (OBIA) using commercially available image segmentation and classification software could also increase the accuracy of zonal statistic calculations. Another limitation is that investigating narrow band reflectance provides a very small view of the total reflectance of a rooftop. A linear average of the four bands is only a proxy for a material's total reflectance. Hyperspectral imagery would be necessary to more accurately determine the rooftop's reflectance throughout the visible and near-infrared spectrum. The process for obtaining a true surface reflectance from narrow band imagery is highly dependent on spatial, spectral and temporal aspects that are beyond the scope of this project (Brest and Goward 1987).

Future Directions

The methodology I used for my study can be easily adapted to other cities and locations. Automation of the process would allow any user with the correct software and datasets to create their own study and database for the city of their choice. Many local governments could provide a great resource to researchers by maintaining their own datasets of building outlines, which would be important for this area of research, as well as many other urban fabric studies. I plan to investigate other major cities in California using an automated version of the process described in this paper. Rooftop outlines will be obtained through local government agencies, or through OBIA classification software, such as eCognition.

This study is a preliminary phase to a larger project conducted by The Heat Island Group (HIG) at Lawrence Berkeley National Laboratory. San Jose is one of the seven major California cities chosen as a site to examine rooftop reflectance. The methodology developed in this paper will allow the group to investigate all other cities. HIG is also preparing to develop a methodology for obtaining a materials total spectral reflectance by mapping its narrow band reflectance to physical lab measurements of spectral reflectance. The group is also developing the automated process for extracting all reflectance data for each city.

Broader Implications

This research directly pertains to increasing the sustainability of large urban areas. The economic and environmental benefits are staggering for such a simple solution. Cool roofs offer the ability to reduce greenhouse gas emissions, provide cleaner healthier air, reduce energy consumption, and mitigate temperature fluxes of heat islands. The results from this study are only the launching point for the future of this field of research. Datasets of rooftop reflectance will be invaluable inputs towards future climate modeling relating to urban heat island mitigation. When a city's current average rooftop reflectance is known, simulations of increased reflectivity scenarios could be highly effective towards policy change, as well as community education. Standards can more accurately be designed to mitigate potential zoning types rather than building specifications. The ability to better understand the urban fabric and its interactions with a global environment would promote sustainable design and construction. Further studies, and maintenance of rooftop reflectance databases, will provide the tangible justification for significant and responsible building code improvements, policy change, and wide scale implementation of cool roof systems.

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